Feasibility Evaluation of Fired Brick Technology as a Construction Material and Income-Generating Industry in Northern Ghana

by

Caroline Nijole Bates

B.Sc.E. Geological Engineering
Queen's University, 2007

Submitted to the Department of Civil and Environmental Engineering in Partial Fulfillment of the Requirements for the Degree of

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Signature of Author: ______________________________
Department of Civil and Environmental Engineering
May 21, 2014

Certified by: ______________________________
Susan Murcott
Senior Lecturer of Civil and Environmental Engineering
Thesis Supervisor

Certified by: ______________________________
Heidi M. Nepf
Chair, Departmental Committee for Graduate Students

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ABSTRACT

This work evaluates the potential to develop fired brick production in the Northern Region of Ghana. While several brick factories operate in southern Ghana, no factories are known to exist in northern Ghana, which remains economically depressed despite the fact that the World Bank now classifies Ghana as a lower middle income country. The development of a sustainable brick industry in northern Ghana could provide employment and stability to communities, a local source of construction material, and could support Pure Home Water in its aim of becoming locally and financially self-sustaining.

The evaluation includes visits to existing brick factories in southern Ghana, field investigations to evaluate the quality and quantity of clay-rich soil available for brick making, laboratory testing of soil and brick samples, consideration of brick production best practices, and a preliminary economic assessment of brick making in Ghana.

The study concludes that the Gbalahi Plot soils are most suitable for brick production using the existing intermittent kiln technologies in Ghana. However, given the intense energy requirements for fired brick production using intermittent kilns, alternative fuel sources and kiln technologies should be considered to reduce energy consumption and emissions and mechanization should be incorporated to reduce worker drudgery. Preliminary economic analyses show that brick production is profitable but that the industry is subject to inherent risks related to climatic and cultural factors in Ghana.

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Title: Senior Lecturer of Civil and Environmental Engineering

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1.0 Project Objectives

This thesis examines the potential for establishing a fired brick production capacity in the Northern Region of Ghana. Brick making is an industry that has been successful in the southern part of Ghana but no known manufacturing plants exist in the district of Tamale in the Northern Region. Pure Home Water (PHW), a Ghanaian non-profit organization based in Tamale, is keen to explore brick making as a potential extension to their community work and as a potential income-producing activity to support PHW's humanitarian work.

The evaluation of fired brick potential in the Northern Region comprises several components, including:

- Assessment of the quality and quantity of source clay material available;
- Evaluation of best practices for brick production; and
- Preliminary economic assessment.

The ultimate goal of the thesis is to produce a technical recommendation on whether a fired brick production capability at the PHW factory is feasible and sustainable for the local communities and if it can be a source of revenue to support PHW's goal of becoming financially and locally self-supporting.

2.0 Country Overview

2.1 Demographics and Climate

The Republic of Ghana is located in West Africa along the Gulf of Guinea (see Figure 1). With a population of just over 25 million people (The World Bank, 2014), the country comprises an estimated 75 ethnic groups (Ghana Embassy, 2014). English is the official language, however many local languages of the Niger-Congo language family are spoken. The country is divided into ten administrative regions (see Figure 2), with the majority of the population centered in the southern part of the country. The population is densest in the Greater Accra Region; the Northern Region is the least densely populated.

Ghana's climate is tropical (although regional variations occur across the country) and is strongly influenced by the West African Monsoon (Lizcano, 2013). The south-western part of the country is distinctly more humid, receiving an average annual rainfall of between 1500 mm to over 2000 mm (Gumma and Pavelic, 2013). The northern part of the country is the driest, with pronounced dry and wet seasons and an average annual rainfall between 800 mm and 1500 mm (Gumma and Pavelic, 2013).

FIGURE 1: LOCATION MAP OF GHANA (UNITED NATIONS, 2005)

FIGURE 2: ADMINISTRATIVE REGIONS OF GHANA (IAEA, 2012)

2.2 Pure Home Water

The work presented in this thesis was done in partnership with Pure Home Water (PHW), a registered non-profit organization based in Tamale, Northern Region. Founded in 2005, the organization aims to:

1) Provide safe drinking water, sanitation, and hygiene (WASH) in Ghana, with a particular focus on northern Ghana; and
2) Become locally and financially self-sustaining.

Through the production and distribution of their *AfriClay Filter*, PHW has reached over 100,000 people in Ghana. The organization employs approximately 20 Ghanaians, has established a training center, a laboratory, an office, a filter production plant, and a pilot tree farm, and is actively involved in ongoing research and development work through collaboration with the Massachusetts Institute of Technology (MIT) (Pure Home Water, 2013).

The PHW filter production plant, located in the village of Taha, 8 kilometers east of Tamale, covers an area of approximately 2.5 acres. The facility is fully roofed but open to the air via windows and doors, with one large, open work space on the eastern side of the building. The western side of the building comprises a recent extension and will include laboratory and office space. Three kilns exist at the plant; the largest is dedicated to filter production but the two smaller kilns are not in regular use. Given the available space and two unused kilns, PHW would like to evaluate if fired brick production could be a viable enterprise at its filter production plant by providing employment and resources to the community and supporting the organization's goal of becoming locally and financially self-sustaining.

2.3 Focus on the Northern Region – Challenges and Opportunities

Although Ghana has experienced increasingly stable democratic governance and is now classified as a lower middle income country by the World Bank, many development challenges persist (UNDP, 2013). Poverty remains endemic in the country as economic growth has been primarily focused in extractive and capital intensive sectors, which do not have a direct poverty-reducing effect (UNDP, 2013).

Poverty is particularly pronounced in the northern regions, where poverty rates are two to three times higher than the national average (IFAD, 2013). Although the largest of the ten regions of the country by landmass (Government of Ghana, 2013), the Northern Region is much less densely-populated than the southern portion of the country, in part due to a significantly drier climate whose landscape is characterized by grassland and savannah plains. The main economy is agriculture, however due to the dry climate, a lack of irrigation systems, and nutrient-poor soil, the growing season is short and usually limited to one harvest per year (Government of Ghana, 2013).

Despite the reliance on agriculture, poor farming practices are common and pervasive. Bushfires are set throughout the northern savannah during the dry season to clear fields to allow hunting of rodents, encourage the productivity of Shea trees, stimulate fresh vegetation shoots for grazing animals, and facilitate tilling of the ground for agriculture (Asante, 2005). Seventy five percent of Ghana's land surface is deforested, as fuel wood and charcoal (produced from burning felled trees) represent 75% of Ghana's fuel consumption (First Climate, 2014). These practices result in extensive deforestation, degradation of soil, and lowered agricultural productivity (Asante, 2005).

Unemployment, particularly amongst the youth, continues to be an issue in the Northern Region (Adusei, 2012). Much of the country's economic activity is focused in the southern part of the country, including mineral resources and oil reserves, manufacturing, and the more lucrative agricultural industries, such as cocoa cultivation (The Herald, 2010). As a result, skilled workers migrate to the southern regions in search of work (The Herald, 2010).

A 2011 report, jointly authored by the Stockholm International Peace Research Institute and the West Africa Civil Society Institute on governance and security in Ghana, states that, "There is a lack of a systematic structural and operational strategy that can transform the socio-economic conditions of the citizens of Northern Ghana." The long-standing political and chieftaincy disputes in the north are exacerbated by the high level of poverty, unemployment, and inequality, which in turn threatens the stability of the region (Adusei, 2012).

The development of ancillary industries (other than agriculture) in the Northern Region that are less vulnerable to climate variations and seasonal limitations would provide increased stability and security for local communities. One such possible industry that could make use of abundant natural resources and the growth boom in Tamale and vicinity is fired brick manufacturing.

3.0 Overview of Brick Making

Fired brick technology, which involves moulding and firing clay-rich soil into blocks for use in construction, dates back several millennia. The Indus Valley Civilization, a Bronze-Age Civilization of the Indian subcontinent, is thought to have produced the first baked bricks as early as 2800 B.C. (Khan and Lemmen, 2013). The Romans used bricks extensively and introduced them to many parts of Europe through their conquests (Heierli, 2008). Since then, the technology has endured and flourished in all inhabited continents of the globe due to the strength, durability, simplicity, versatility, and beauty of bricks.

3.1 Advantages of Bricks

There are numerous advantages to using fired bricks in construction. The process of firing bricks induces physical and chemical changes to the soil mineral structure which dramatically increase the material strength. Bricks vary in compressive strength due to the differing qualities of the parent materials but compressive strengths can range from 5 MPa to 100 MPa with common house bricks having values between 20 MPa and 40 MPa (Gorse et al., 2012). For comparison, compressive strength values in the 20 MPa to 40 MPa range correspond to concrete and rocks such as shale, coal, siltstone, and schist (Hoek and Brown, 1997).

The durability of fired bricks is a distinct advantage. Bricks generally require very little maintenance and do not fade, twist or warp, rot or decay, and they are not attacked by termites (Boral, 2002). The thermal performance of bricks also makes them desirable for both hot and cold climates alike. Brick buildings have excellent thermal mass, which means they are able to retain heat energy and resist changes in temperature (Boral, 2002). For hot climates such as Ghana, this means that the solar energy is absorbed by the bricks, keeping the inside of the building cooler during the hottest part of the day. Superior acoustic performance is another benefit attributed to bricks. The density of bricks compared to other, more lightweight materials results in less external noise being transferred to the interior of the building and internally between rooms (Boral, 2002).

The most basic of bricks are made with only two materials, clay-rich soil and water. This simplicity means that they can be produced wherever clay-rich soil is abundant and at relatively low cost. Bricks can also be moulded into different shapes and sizes, imparting a versatility that allows for different practical applications. Finally, the rich and varied colour of bricks offers an aesthetic appeal that has attracted architects and home-builders alike for centuries, despite a wealth of modern construction material options.

3.2 Fired Brick Making Procedure

Brick making comprises five basic steps:

1) Winning – Clay-rich soil is extracted from the ground manually (by hand-digging) or mechanically (with an excavator or back hoe). Material appropriate for bricks is selected by visual and manual inspection.
2) Preparation – The soil is worked to remove large particles and bring it to a desired consistency for moulding. This could involve placement in a soaking pit to soften the soil, physical kneading to mix and homogenize the soil, and grinding.

3) Moulding – The soil is pounded into a mould and extruded manually or passed through a machined head of a given geometry and cut to the desired dimensions. The newly formed block is termed a green brick.
4) Drying – The green brick is dried for several days to weeks under controlled conditions, usually on drying racks or under plastic tarps. If dried too quickly or under direct sunlight, the bricks will deform excessively and crack.
5) Firing – The dried bricks are gradually heated to high temperatures (usually between 800^{o}C and 1200^{o}C) in kilns or in self-supporting stacks (called clamps). Firewood, coal, oil, sawdust, and natural gas are common sources of fuel for firing.

As technology has improved and machinery has replaced manual labour in higher income countries, brick making has been mechanized and optimized with the addition of additives for increased strength and performance. However, the manual fired brick making procedure outlined above is still practiced throughout lower income countries and in particular, in the brick plants visited in Ghana.

3.3 Firing Technology

Several different firing technologies have been developed and continue to be used throughout the brick industry. The most rudimentary systems are considered intermittent kilns, where bricks are fired in batches. Bricks are generally stacked in layers and the entire batch is fired together (Heierli, 2008). Once the firing process is finished, all of the bricks are allowed to cool and the kiln is unloaded, refilled, and the process continues with a new batch. Intermittent kilns are considered the least energy-efficient kilns as most of the heat is lost in the hot flue gases, in the fired bricks when they are removed, and in the kiln structure (Heierli, 2008). Examples of intermittent kilns include clamp, scove, scotch, and downdraught kilns (Heierli, 2008). The use of intermittent kilns is widespread in Asia, Africa, and South and Central America and to a limited extent in some European countries (Heierli, 2008). All five of the brick plants visited in Ghana use intermittent kilns to produce their fired bricks, either in the form of clamps or downdraught kilns.

Continuous kilns operate using a fire that is always burning and bricks are cycled through different parts of the system in various stages of warming, firing, and cooling. Continuous kilns are more energy-efficient as the heat in the flue gases is used to heat and dry green bricks and the heat in the fired bricks is used to preheat air for combustion (Heierli, 2008). Several different types of continuous kilns have been developed and are categorized into two broad categories, moving-fire kilns and moving-ware kilns (Heierli, 2008). In moving-fire kilns, the firing source moves through a closed kiln circuit and the bricks remain stationary. The kiln circuit geometry is ovular, rectangular, or circular (Heierli, 2008). The Bull’s Trench Kiln (BTK), used extensively in South Asia, is an example of a moving-fire kiln. In moving-ware kilns, the fire remains stationary and the bricks and air move in counter-current paths (Heierli, 2008). The bricks generally are moved on cars through a long horizontal tunnel or vertically through the kiln shaft. The cars can be moved continuously or intermittently at fixed intervals. Continuous kilns inherently require different management, often requiring 24-hour/day supervision. Examples of moving-ware kilns include tunnel kilns (the technology used most extensively in large, commercial operations), and the Vertical Shaft Brick Kiln (VSBK) that was developed in China.

3.4 Soil Properties and Brick Making

Because bricks are primarily composed of soil, the type of soil used for brick making is an important consideration. The soil properties affect the mouldability of the green bricks, the behaviour of bricks during drying and firing, and the ultimate strength of fired bricks.

3.4.1 Grain Size Distribution

Of particular interest are the grain size distribution and the plasticity of a soil. The grain size distribution of a soil provides information on the range of individual grain sizes present and the proportions of the various grain sizes. Four classes of soil are defined in the United Soil Classification System according to grain size: gravel is material that is between 4.75 mm and 75 mm; sand is material that is between 0.075 mm and 4.75 mm; silt-sized material is between 0.002 mm and 0.075 mm; and clay-sized material is less than 0.002 mm (see Table 1) (Germaine and Germaine, 2009). For bricks, it is desirable to have a mixture of clay, silt, and sand, however the exact proportions of each soil type vary considerably.

TABLE 1 - GRAIN SIZE BOUNDARIES

Grain Size Diameter	Particle Name
<0.002 mm	Clay
0.002 – 0.075 mm	Silt
0.075 – 0.425 mm	Sand (fine)
0.425 – 2 mm	Sand (medium)
2 – 4.75 mm	Sand (coarse)
4.75 – 19 mm	Gravel (fine)
19 – 75 mm	Gravel (coarse)
75 – 300 mm	Cobbles
>300 mm	Boulders

Clay particles are elongated, platy particles that interact with each other and water in such a way that imparts cohesive strength to the soil. Therefore the clay portion provides the plasticity and strength that is required for moulding green bricks and the ultimate strength of fired bricks. Literature on brick making suggests that the clay content of soil suitable for bricks can vary substantially (between 15% and 80%) (Chisholm, 1910). The amount of clay present will affect the workability of the green bricks and the ultimate performance of fired bricks. Too little clay will result in weaker bricks that are difficult to mould, but too much clay will cause excessive shrinkage and cracking during the drying and firing phases of brick production (Mueller, 2008).

Sand grains are generally equidimensional particles whose behavior is dominated by physical contact forces between similar-sized particles. They do not exhibit the attractive and repulsive forces exhibited by clays. The presence of sand in soils used for brick making is important for several reasons. Sand improves the workability of the soil by lowering the soil plasticity. This means the soil does not stick to surfaces as readily as a pure clay soil would. In addition, unlike clay particles, the sand particles do not adsorb water which results in less water within the soil skeleton. As a result, the bricks are less likely to crack or deform as water is expelled during the drying and firing phases (Mueller, 2008).

Silt particles generally behave as sand particles but are smaller in size. They contribute both cohesive and frictional strength to soil. In brick making, silt serves as the intermediary between clay and sand particles. The silt reduces the plasticity of clay material and its intermediate particle size creates a well graded soil that contributes to brick homogeneity and high fired strength (Mueller, 2008).

3.4.2 Soil Plasticity

Qualitatively, the plasticity of a soil is a measure of how easily it can be moulded or shaped. In soil mechanics, the plasticity of a soil is formally defined as the range of water contents over which the soil exhibits plastic behavior. The minimum water content at which a soil exhibits plastic behavior is referred to as the plastic limit and the maximum water content at which a soil exhibits plastic behavior is referred to as the liquid limit. Below the plastic limit the soil will behave as a semi-solid material, and above the liquid limit, the soil will behave as a fluid (Germaine and Germaine, 2009). Low plastic soils are defined as those with a liquid limit below 50% and high plastic soils are defined as those with a liquid limit above 50%. These limit states were defined by Dr. A. Atterberg in 1911 to classify agricultural soil, but remain as fundamental index parameters in soil science and engineering (Germaine and Germaine, 2009).

The plasticity of a soil is most dominantly affected by the amount and types of clay particles present. Certain clay minerals, such as montmorillonite, take up a lot of water into their particle structure and are therefore called high plastic clays. Other clay minerals, such as kaolinite, take up less water and are therefore called low plastic clays.

The plasticity of a soil influences its suitability for brick making. Non-plastic soil will be difficult to mould into green bricks with sufficient strength and very high plastic soil will require a long time to dry, will be very sticky and difficult to handle, and will be prone to cracking and large deformations during drying and firing. Despite the importance of sourcing soil of appropriate plasticity for brick making, prescriptive quantitative guidelines for the plastic limit and liquid limit are difficult to find in brick making literature. Smith (1984) recommends a liquid limit between 30% and 35% and Mueller (2008) generally recommends low plastic clays as the ideal brick making material. However both sources document specific types of bricks and a wider range of plasticity is observed to be used in practice.

4.0 Brick Making in Ghana

4.1 Overview of Existing Plants and Locations

Several operating brick factories are known to exist in Ghana in the southern part of the country. Five factories were visited during the month of January 2014 and are indicated on Figure 3.

FIGURE 3 - LOCATIONS OF EXISTING BRICK FACTORIES (MODIFIED FROM CIA, 2007)

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4.1.1 Daniel Osei-Bonsu's Factory

The first factory visited (referred to herein as the Osei-Bonsu Factory), owned by Daniel Osei-Bonsu, is located near the village of Adansi Asokwa, 12 kilometers outside of Obuasi in the Ashanti Region. The plant produces approximately 30,000 bricks per month using both clamp and downdraught kilns and employs 20 to 25 full-time staff. Locally sourced firewood is used for firing the kilns. Approximately three Kia truckloads of hardwood or four Kia truckloads of softwood are required for a single kiln firing. Two downdraught kilns are present on the property. The smaller downdraft kiln is approximately six feet in diameter (inner diameter) and can hold approximately 3,000 bricks per firing. The larger downdraught kiln was recently constructed and has not yet been used for brick production. It has an inner diameter of approximately 12 feet and is estimated to hold approximately 20,000 bricks (see Figure 4).

The clay-rich soil used for brick production is sourced on-property from a 15 acre deposit (see Figure 5). The clay-rich soil is extracted from three pits by an excavator in batches and is stockpiled for future use. Excavating in batches allows for cost savings, requiring excavator rental only intermittently. Stockpiling also exposes the soil to increased weathering, which is thought to improve its suitability for brick production. Once exhausted, the clay pits are shaped and will be used in the future as fish ponds for aquaculture (Mr. Osei-Bonsu is looking into the regulatory requirements for aquaculture). Workers transport the clay-rich soil to the factory by wheelbarrow for brick making when required. A perennial stream separates the brick plant from the clay deposit, providing a constant water source for plant operation.

Bricks are produced using a semi-automated system where the soil is loaded manually into a pug mill powered by a diesel-run tractor (see Figure 6). Once the soil is mixed and broken up to the required consistency, bricks are moulded by an extruder attached to the pug mill and are cut manually using wire. Bricks are dried in the covered facility on pallets that are stacked to allow for more efficient storage and to promote air flow (see Figure 7).

FIGURE 4 - LARGE DOWNDRAUGHT KILN

FIGURE 5 - CLAY-RICH SOIL BORROW PLOT

FIGURE 6 - PUG MILL USED TO MIX SOIL FOR BRICK MAKING

FIGURE 7 - DRIED GREEN BRICKS

4.1.2 Adam Braimah's Factory

The second factory visited (referred to herein as the Adams Factory), owned by Adam Braimah, is located near the village of Asante Akropong, 40 kilometers outside of Sunyani, in the Ashanti Region. The plant uses firewood to fire a clamp kiln, where the green bricks are stacked outside into a self-supporting structure and fired in-place. Bricks are produced using a semi-automated process, where the soil is loaded into a crusher initially to break down the soil. The material is then transferred to an electrically-powered pug mill using a conveyor (see Figure 8), where the soil is further worked to the desired consistency and extruded into solid bricks.

Approximately ten staff members were observed to be working at the plant during the impromptu visit. The clay-rich soil is sourced locally from a river deposit, but the size and location are not known, nor was it visited. The soil is transported to the brick factory using a tractor and wooden trailer (see Figure 9).

FIGURE 8 - CRUSHER AND CONVEYOR SYSTEM USED TO MOVE CLAY-RICH SOIL TO PUG MILL

FIGURE 9 - TRACTOR AND TRAILER USED FOR HAULING SOIL

4.1.3 Obeng Akwasosem's Factory in Asante Akropong

The third factory visited (referred to herein as the Obeng 1 Factory), owned by Obeng Akwasosem but operated by his wife Nana Ama Akwasosem, is located near the village of Asante Akropong, 40 kilometers outside of Sunyani in the Ashanti Region. The plant produces between 30,000 and 40,000 bricks per month using clamp kilns (see Figure 10) and employs approximately 35 part-time and full-time staff. Locally-obtained firewood is used to fire the three clamp kilns observed at the factory.

The soil used for brick making is sourced locally from a river deposit but the size and location are not known, nor was it visited. Two tractors are used transport the clay from the deposit to the brick making plant. The soil is kneaded manually and bricks are formed in groups of five using wooden moulds (see Figure 11). Sawdust is sprinkled on the surface of the mould and on the soil before placement in the mold to prevent the soil from sticking to the mould upon extrusion. Green bricks are placed on wooden planks and dried in the open (see Figure 12).

FIGURE 10 - PARTIALLY DECONSTRUCTED CLAMP KILN

FIGURE 11 - HAND MOULDING GREEN BRICKS

FIGURE 12 - GREEN BRICKS DRYING IN THE OPEN AIR

4.1.4 Obeng Akwasosem's Factory in Acherensua

The fourth factory visited (referred to herein as the Obeng 2 Factory), owned and operated by Obeng Akwasosem, is located near the village of Acherensua, 40 kilometers outside of Sunyani in the Brong Ahafo Region. The plant produces between 20,000 and 30,000 bricks per month using clamp kilns and employs approximately 25 full-time staff. Both men and women are employed at the factory, which uses firewood to fire the kilns.

The soil used for brick production is sourced from a 500 acre floodplain deposit within five kilometers of the brick factory (see Figure 13). The soil is extracted manually using shovels and pickaxes into small stockpiles for future use (see Figure 14). The soil is transported to the brick factory using a large truck. Access to the soil deposit can be compromised in the rainy season due to flooding.

Bricks are produced using a semi-automated system where the soil is loaded manually into a pug mill powered by a diesel-run tractor. Once the soil is mixed and broken up to the required consistency, bricks are moulded by an extruder attached to the pug mill and are cut manually using wire. Bricks are dried in the covered facility on wooden planks placed on racks to promote air flow for even and quicker drying (see Figure 15). Due to space limitations, green bricks are also dried in the open air on raised soil beds (see Figure 16). Plastic tarps are used to cover the bricks to optimize drying and to protect the bricks against rain and direct sun.

FIGURE 13 - CLAY-RICH SOIL RIVER DEPOSIT

FIGURE 14 - STOCKPILING OF SOIL

FIGURE 15 - DRYING GREEN BRICKS ON SHELVES

FIGURE 16 - DRYING GREEN BRICKS IN OPEN AIR

4.1.5 Peter Tamakloe's Factory

The fifth factory visited (referred to herein as the Tamakloe Factory), owned and operated by Peter Tamakloe, is located in Mongotsonya along the Dodowa-Afienya Road, in the northeastern part of greater Accra. The factory is substantially larger than those previously described and produces approximately 70,000 bricks per month. The factory has a very large, ten chamber brick kiln; each chamber holds approximately 10,000 bricks. The bricks are fired in separate chambers using firewood and residual oil that is piped to the chambers from a storage tank and then sprayed into the chamber from the top via a vertical shaft.

Bricks are produced using a semi-automated system where the soil is loaded onto a conveyor that is connected to a pug mill. Green bricks are extruded from the pug mill and cut using wire. Bricks are dried in the covered facility in stacks or on the ground. The soil used for brick making is sourced locally, but the location and size of the deposit are unknown and the site was not visited. No pictures are available from the visit to the Tamakloe Factory.

4.2 Technical Considerations

4.2.1 Kiln Technology

All five brick factories visited employ intermittent kiln technology for brick production. Four of the five brick plants utilize clamp kilns as their primary production kiln. Because clamp kilns are constructed outside, are temporary structures that can be moved if required, and are built only out of the bricks that need to be fired, clamp kilns are the most rudimentary type of kiln and offer small-scale producers the most flexibility with the lowest capital investment. However, clamp kilns also have the highest specific energy consumption. Table 2 presents the energy requirements for different kiln technologies, as summarized by Heierli (2008). It is important to note that the energy requirements presented in Table 2 are in terms of coal consumption; however it seems reasonable to expect similar relative requirements of firewood between technologies, which is the main fuel source in four of the five brick plants visited in Ghana.

TABLE 2 - COMPARISON OF KILN TECHNOLOGY ENERGY REQUIREMENTS (HEIERLI, 2008)

Type of kiln	Specific Energy Consumption (MJ/kg of fired brick)	Specific coal consumption (tons/100,000 bricks)
VSBK (India, Nepal, Vietnam)	0.7-1.0	11-16
Fixed chimney BTK (India)	1.1-1.5	17.5-24
Moveable chimney BTK (India)	1.2-1.75	19-28
Tunnel kiln (Nam Dinh, Vietnam)	1.4-1.6	22-25
Modern tunnel kiln (Germany)	1.1-2.5	17.5-40
Clamp and other batch kilns (Asia)	2.0-4.5	32-71

During the January 2014 factory visit, Daniel Osei-Bonsu anecdotally stated that producing bricks in his six foot inner diameter kiln required only half the amount of firewood required for production with the clamp kiln, as a substantial amount of heat is lost to the environment. However, it is unclear if the statement accounted for similar quantities of bricks (clamp kilns can hold between 7,000 to 20,000 bricks (Akwasosem, 2013) and the six foot diameter kiln can hold only 3,000 bricks). Osei-Bonsu also stated that the clamp kiln produces inconsistently fired bricks and a greater amount of broken bricks. In clamp kiln firing, some bricks are optimally fired, some are under-fired, and some are over-fired due to the uneven heat distribution (Osei-Bonsu, 2014). Although inconsistently fired bricks are not ideal, Mrs. Akwasosem contributed that bricks of different degrees of firing can still be sold, albeit at a lower price For example, under-fired bricks can be used for brick oven construction.

Only the Tamakloe Factory makes exclusive use of a downdraught kiln but the large scale of the kiln and operation are beyond what is deemed reasonable for capital investment at PHW.

4.2.2 Fuel Source

Approximately half of the production cost of brick making is related to the fuel source for firing (Osei-Bonsu, 2014). Firing is also the largest energy-consuming and emissions-producing step in the brick making process (Heierli, 2008). Therefore selection of fuel source is a major consideration for brick production, as it has both financial and environmental ramifications.

In Ghana, the dominant fuel source for brick production is firewood. Four of the five brick plants visited utilize firewood exclusively; only the Tamakloe Factory uses a combination of firewood and residual oil. In the savannah landscape of the Northern Region, tree cover is much sparser than in the tropical climate of southern Ghana. This is in part due to extensive deforestation in Ghana, which at a rate of 2% annually, is considered one of the highest in Africa (United Nations Environment Programme). Therefore in evaluating the feasibility of setting up a brick factory in northern Ghana, alternatives to firewood must be considered.

Mr. Akwasosem and Mr. Osei-Bonsu both suggested that sawdust and residual oil were practical alternatives to using firewood as a fuel source. Sawdust is an abundant waste product of wood processing facilities in Ghana and is considered to be of negative value as resources must be expended for disposal (Atakora, 2000). Residual oil, otherwise known in Ghana as waste oil or dirty oil, is oil that is removed during vehicular oil changes and machinery maintenance. It is commonly disposed of in large barrels and can be obtained at a very low cost or for free in the country (Anyekase, 2014). Therefore, both sawdust and residual oil are known by brick manufacturers to offer a very low cost or no cost alternative to firewood use. However, most plants in Ghana do not use either product and the Tamakloe Factory only uses residual oil in conjunction with firewood. This apparent contradiction can possibly be explained by the large capital investment required to set up more complex firing systems and will be further discussed in Section 4.3.

Two other very commonly used fuel sources for brick making are coal and natural gas. Coal is used as the dominant fuel source for brick making in much of Asia (Heierli, 2008). However, given the environmental concerns surrounding its use and the absence of coal reserves in Ghana and other West African countries, it is not considered a potential fuel source for brick making in Ghana (Iddrisu, 2014). Natural gas is the most common fuel source for large brick making industries in Europe and North America. Ghana has proven natural gas reserves, although it does not currently produce natural gas and instead imports natural gas from Nigeria (U.S. Energy Information Administration, 2013). No natural gas infrastructure exists in the village of Taha and therefore this fuel source would be prohibitively expensive.

Bio-fuels and methane gas generated from landfills are other possible fuel sources, but would require significant capital investment for appropriate infrastructure and are currently outside the expertise available in-country.

4.2.3 Brick Shape

The shape of a brick is another important consideration as it will impact the moulding, drying, and firing process substantially. Bricks produced by manual moulding offer the least flexibility and are generally solid, which means the full brick volume is composed of clay and must be dried and fired. Solid bricks take longer to dry and require more fuel in the firing process as there is more material in a given brick.

Bricks produced using an extruder offer more flexibility. Different extrusion heads can be mounted on the pug mill, allowing a variety of shapes to be produced, including hollow bricks. Hollow bricks offer several advantages to solid bricks. With horizontal or vertical holes ranging from 10% to 40% of the brick volume, hollow bricks dry quicker and require less fuel during the firing process (Heierli, 2008). In addition, they require less clay material and are lighter than solid bricks. Furthermore, the voids provided by the holes within the bricks improve the thermal insulation of a building by provided pockets of air that buffer temperature changes (Heierli, 2008). Lastly, during building construction, the holes are partially filled with mortar which increases the shear resistance and strength of the building by interlocking (Akwasosem, 2014).

4.2.5 Weather

Small-scale brick making is strongly influenced by the weather and by the seasons. According to Mr. Akwasosem, work during the rainy season is slower for several reasons:

- It is difficult to extract material from the clay borrow pit due to road access issues and flooding of the deposit;
- During heavy rains, stones are mixed into the clay at the borrow pit which degrades the quality of the material;
- It takes significantly longer to dry green bricks before they can be fired; and
- Outdoor clamp kilns will fire much less efficiently if it is raining.

The Northern Region of Ghana experiences a distinct wet season during the months of May through October and a distinct dry season during the months of November through April (Government of Ghana, 2013). Therefore any brick making operation undertaken in the Northern Region will need to be robust enough to operate during the rainy months. Daniel Osei-Bonsu stated that the security of his brick manufacturing plant lies in the downdraught kiln, as clamp firing is too weather dependent (Osei-Bonsu, 2014). A large, covered working space is also essential to allow for stockpiling of clay material and drying of green bricks during the rains.

4.3 Other Considerations

During the course of the visits to the brick factories, several observations were made that could influence the viability of brick production in the Northern Region.

4.3.1 Dominance of the Cement Manufacturing Industry

Daniel Osei-Bonsu stated that in the past, many more brick factories had existed in the southern part of Ghana. However in recent decades, both large- and small-scale operations had been closing down to the point where very few brick producers remain. One of the reasons stated by Osei-Bonsu was related to the rise of the cement industry in Ghana. Cement is used widely in the production of concrete blocks, the favoured construction material in Ghana. Osei-Bonsu felt that unsupported, the brick industry could not compete with the cement industry in the country. Although several cement manufacturers exist in in Ghana, the largest is Ghacem Limited, a partnership between the Government of Ghana and Norcem AS of Norway (Ghacem, 2012).

4.3.2 Financing

Brick making is a capital intensive industry. To generate product, skilled workers must be trained, equipment such as trucks, tractors, and pug mills is required, and land for the production facility and soil extraction must be leased or purchased from local chiefs. Furthermore, equipment must be maintained and upgraded to expand the business.

Financing for small- and medium-sized enterprises is difficult to obtain in Ghana. The Omidyar Network report on Accelerating Entrepreneurship in Africa summarized findings from six Sub-Saharan African countries, including Ghana. The report found that self-financing and family loans are the main sources of funding and when exhausted, entrepreneurs face the challenge of finding other sources of funding. The situation is plagued by a dichotomy; entrepreneurs complain of a limited supply of capital, but financiers feel that many projects are not fundable due to poor book-keeping and a lack of business planning (Omidyar Network, 2013). The report also states that although entrepreneurs are aware of possible sources of funding, financing is often cost prohibitive, with some banks requiring 150% of the borrowed amount in collateral, which disqualifies many from funding eligibility (Omidyar Network, 2013). The challenges in accessing financial resources are further compounded by corruption. Entrepreneurs report that legitimate government support is nearly impossible to access without engaging in corruption; patronage and nepotism are cited as the most common forms of corruption in the country (Omidyar Network, 2013).

Brick producers often find themselves unable to keep up with market demand due to lack of funds to pay workers, purchase fuel, and repair chronically malfunctioning equipment. While visiting Mr. Akwasosem's plant in Acherensua, a customer who had been waiting for pre-ordered and partially pre-paid bricks for several weeks, visited to inquire on the status of production. In this particular instance, Mr. Akwasosem's entire operation was shut-down due to a broken-down truck, the vehicle used for transporting clay from the borrow source to the production plant. Another potential customer inquired about bricks and was told that partial payment was required upfront to finance the production. Prepayment and long lead times for the product can deter potential customers and are difficult to manage for the brick plant owners.

4.3.4 Local Unfamiliarity with Brick

Ghana has the second-largest economy in West Africa and recent decades have seen a major construction boom in the housing industry (Omidyar Network, 2013; Bank of Ghana, 2007). The dominant source of construction material in Ghana is concrete block. While travelling in Ghana in January 2014, brick structures were rarely observed and tended to occur in close proximity to the operating brick plants when they were spotted.

Daniel Osei-Bonsu commented that marketing of brick products was critical to expanding his business as many Ghanaians are unfamiliar with the benefits offered by bricks (outlined in Section 3.1). Furthermore, Mr. Akwasosem stated that 60% of his customers purchased bricks because they were a cost-effective alternative to concrete blocks, 30% purchased bricks because they appreciated their aesthetic beauty, and only 10% purchased bricks because they understood the quality of the material and its advantages as a construction material. At the Tamakloe Factory in the outskirts of Accra, the factory manager stated that most of the plant's customers were foreigners living or working in the country as Ghanaians were not accustomed to building with bricks.

These anecdotal statements suggest that demand for bricks in the Northern Region may take some time to develop and that a well-structured marketing strategy that educates communities on the benefits offered by bricks may be required.

4.3.3 Working Conditions

The small-scale brick production observed throughout southern Ghana involves a significant amount of manual labour. Extracting the clay-rich soil from borrow pits, hand-kneading soil and moulding bricks, loading soil onto conveyors or into the pug mill, stacking and unstacking bricks into kilns before and after firing, and transporting bricks by hand, all involve significant human strength and drudgery. The manual labour inherent in small-scale brick production will provide highly-sought after employment for community members, but where possible, mechanization of the most arduous tasks should be considered to minimize occupational hazards such as heat exposure, repetitive strain injuries, and dust inhalation.

4.4 Facilities and Equipment

From the operations observed in southern Ghana, small-scale brick production requires at a minimum a large covered workspace, access to water, and a kiln for firing bricks. The PHW factory in Taha possesses all of these assets and is therefore well-poised to commence brick production if decided. The current factory layout has a covered work space where the soil can be mixed and moulded with storage racks for ceramic filters that can be used for drying green bricks under cover. The village of Taha and the PHW factory are connected to a piped water supply which provides intermittent access to water. PHW has also recently purchased a pug mill and is looking into purchasing a hammer mill; this equipment could possibly be incorporated into the soil processing necessary for brick production. The factory also has three kilns of various sizes that can be used immediately for pilot trials or for initial production. However, the available kilns may not be ideal for full-scale brick production. A large truck owned by PHW that is used to transport soil between the borrow source and the factory could serve the same purpose for brick production.

Additional equipment to reduce the drudgery associated with brick production could supplement existing resources. This could include, a backhoe or bulldozer for clay extraction, a kiln designed for brick firing, a pug mill fitted with a head that allows for mechanical extrusion of bricks, and a conveyance system for soil loading into the pug mill. Should brick production be undertaken in earnest, facility requirements will evolve with time; additional space and equipment will likely be required as production increases. The costs involved with purchasing equipment for short-term and long-term production are included in Section 9.0.

5.0 Site Investigation

5.1 Geology of Ghana

5.1.1 Bedrock Geology

The bedrock geology of Ghana is characterized by two distinct zones as shown in Figure 17. The southern part of the country is dominated by low grade metamorphic rocks of the Birimian volcanic sequence (Bates, 1955). These volcanic belts trend northeast to southwest and host the majority of Ghana's mineral deposits. The northern portion of the country is dominated by Voltiain sedimentary deposits of Obosum and Oti bed shales and basal sandstones (Bates, 1955).

5.1.2 Surficial Geology

The surficial geology of Ghana is characterized by two distinct zones as shown in Figure 18. The southern part of the country is dominated by Forest Ochrosols, which are deeply weathered soils found in the semi-deciduous forest and parts of the forest-savannah transition agro-ecological zones of Ghana (Adjei-Gyapong and Asiamah, 2002). They characteristically show a marked concentration of organic matter in the upper layer (topsoil) (Obeng, 2000). The subsoil is strongly leached with significant clay accumulation and can be more than 120 cm thick with variable colour and texture (Obeng, 2000; Adjei-Gyapong and Asiamah, 2002). Forest Ochrosols are suitable for a wide range of crops, including lucrative tree crops such as cocoa, coffee, oil palm, para-rubber, and citrus, however agriculture is somewhat limited by soil erosion due to removal of vegetative cover on moderately steep to steep slopes (Adjei-Gyapong and Asiamah, 2002).

The northern part of the country is dominated by Savannah Ochrosols and Groundwater Laterites. Savannah Ochrosols are moderately deep to deep soils similar to Forest Ochrosols except that they occur in savannah landscapes with semi-arid conditions. As a result, the upper, most weathered part of the soil profile is thinner with less topsoil than the Forest Ochrosols (Adjei-Gyapong and Asiamah, 2002). Ironstone concretions and rock fragments are common and may form as much as 40% of the soil mass (Adjei-Gyapong and Asiamah, 2002). Some Savannah Ochrosols show development of an ironpan at approximately 60 cm depth (Obeng, 2000). Savannah Ochrosols support the majority of Ghana's food crops (Adjei-Gyapong and Asiamah, 2002).

Groundwater Laterites are shallow to moderately deep soils that occur on gently sloping topography in a plain landscape (Adjei-Gyapong and Asiamah, 2002). The soil typically contains between 10% to 40% ironstone concretions and nodules to a depth of approximately 60 cm which is underlain by sheet ironpan or boulders of ironpan (Adjei-Gyapong and Asiamah, 2002). Groundwater Laterites are poorly draining soils that induce temporal water logging conditions during heavy rains (Adjei-Gyapong and Asiamah, 2002).

Both Forest Ochrosols and Savannah Ochrosols are in the Latosol soil group family, whose clay fraction is dominated by 1:1 phyllosilicates (kaolinitic clays), and iron and aluminum oxides (Adjei-Gyapong and Asiamah, 2002). The PHW plots are expected to be either Savannah Ochrosols or Groundwater Laterites (see Figure 18). If the PHW plots are Savannah Ochrosol soils, kaolinite-dominated clay fractions should be expected.

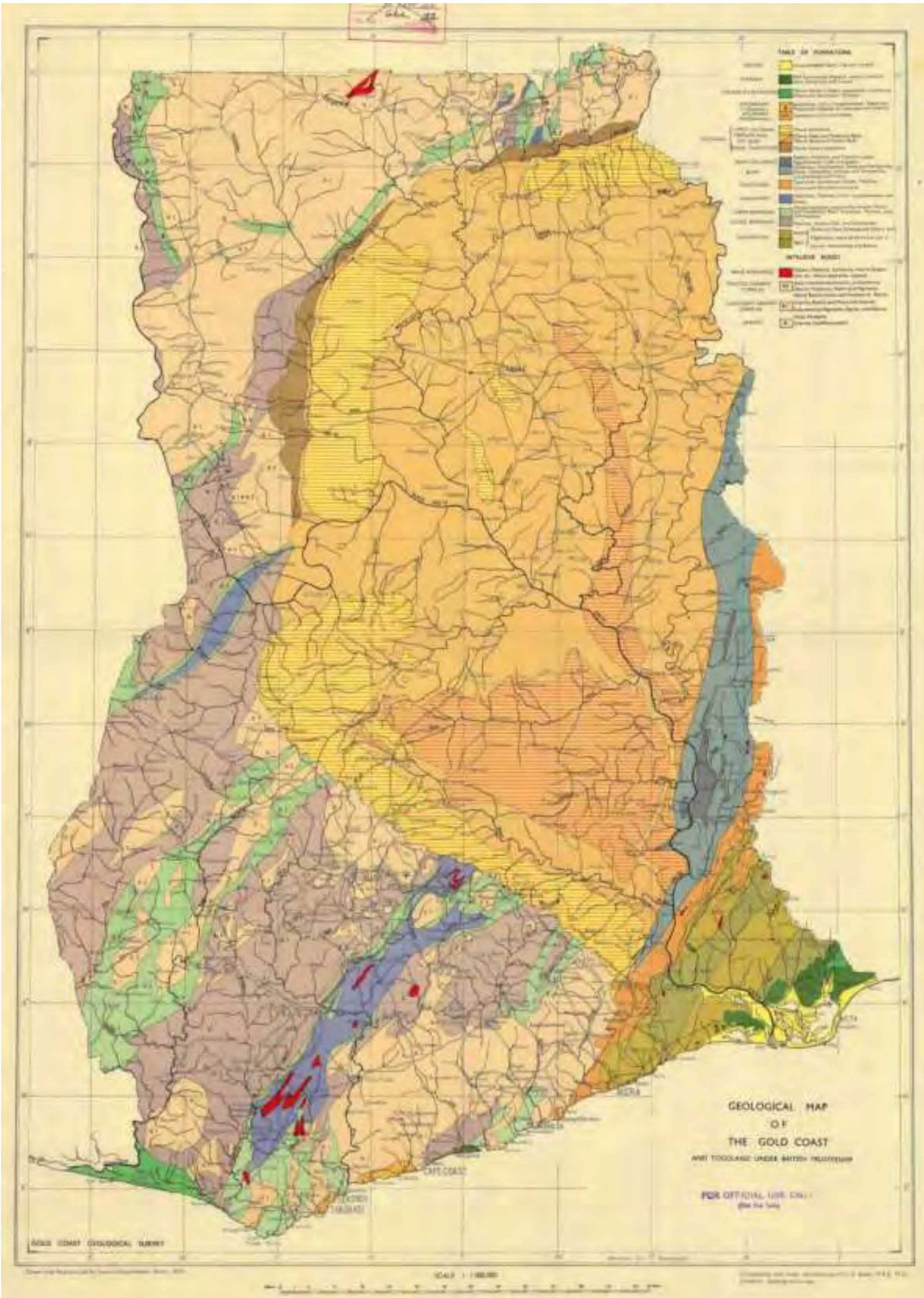

FIGURE 17 - BEDROCK GEOLOGY MAP OF GHANA (BATES, 1955)

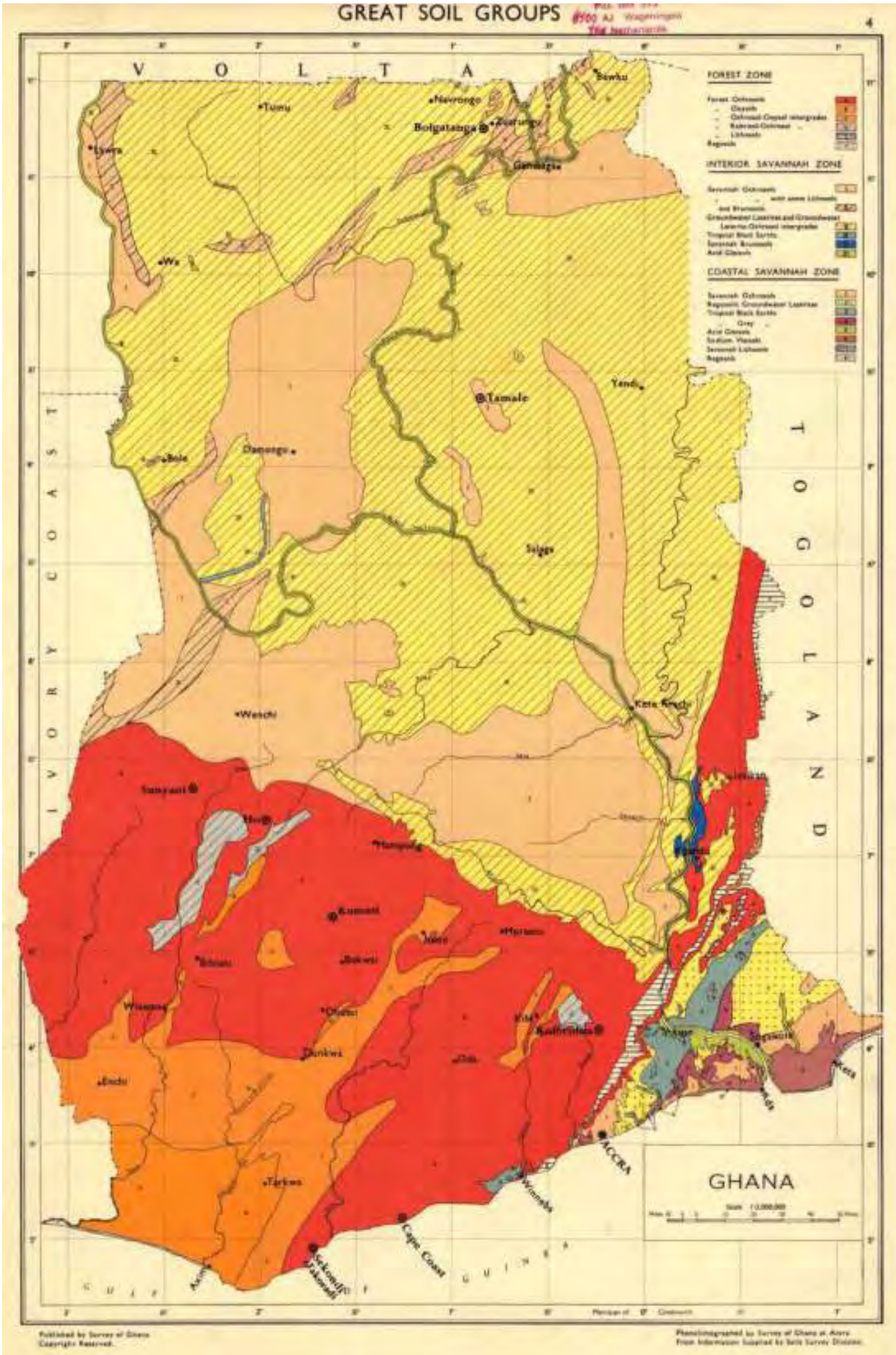

FIGURE 18 - SOIL MAP OF GHANA (SURVEY OF GHANA, YEAR UNKNOWN)

5.2 Description of PHW Plots

As part of the fired brick study, ground investigations were completed at five plots that PHW currently has access to, in order to evaluate the suitability of the local soils for brick making. This investigation was undertaken as the soil map shown in Figure 18 suggests a distinct difference in soil type between the soils in the south, where existing brick factories exist and the soils in the north, where the potential for brick production is being evaluated.

The Gbalahi Plot is located 10 km northeast of Tamale in the Gbalahi Village. The property covers an area of approximately 30 acres and is owned and managed by the chief of the village. The site is located on a flat plain with minor vegetation (see Figure 19). The area has been stripped of surface gravel for use as construction material and clay has also been excavated from select dugouts. The Gbalahi Plot clay deposit is used for traditional pottery by Gbalahi women and is the principal clay source for PHW's filter production plant in Taha. It is considered the most promising borrow plot (a term used in construction to describe an area where material, usually soil, has been dug for use at another location) for fired brick production.

The Kpaumo Plot is located 8 km northeast of Tamale and 1 km northwest of Taha Village, which is the site of PHW's filter factory. The property covers an area of approximately 1.5 acres and is currently under a 99-year land lease by PHW. The site is located on a gently undulating plain with sparse vegetation, including grass shrubs and small trees (see Figure 20). The area has been stripped of surface gravel; in some areas the original ground surface is over a meter above the existing ground surface. PHW has excavated a small amount of clay from the plot for use in their filter production. The Kpaumo Plot is considered to be a promising borrow plot for fired brick production.

FIGURE 19 - GBALAHI PLOT LOOKING WEST

FIGURE 20 - KPAUMO PLOT LOOKING SOUTHWEST

The Wayemba Plot is located 11 km north of Tamale along the Tamale-Navrongo Road. The property covers an area of approximately 1 acre and is currently under a 99-year land lease by PHW. The site is located on a flat plain with grass cover (see Figure 21). PHW has excavated a small amount of clay from the plot for use in their filter production; the land appears to have had no other development. Due to land use restrictions, the Wayemba Plot is not considered to be a promising borrow plot for fired brick production.

FIGURE 21 - WAYEMBA PLOT LOOKING SOUTH

The Gburma Plot is located 13 km northeast of Tamale in the Gburma Village. The property covers an area of approximately 10 acres and is currently under a 99-year land lease by PHW. The site is located on a flat plain that is vegetated with grasses and a variety of tree species (see Figure 22). PHW has invested in the Gburma Plot as an experimental tree farm to provide a renewable source of fuel for filter production at the factory in Taha. Because it is intended for tree harvesting, the Gburma Plot is not considered to be a promising borrow plot for fired brick production.

The Taha Plot is located 8 km northeast of Tamale in the Taha Village. The property covers an area of approximately 2.5 acres and is currently under a 99-year land lease by PHW. The site is located on a flat plain that is vegetated with grasses and sparse trees. The PHW filter factory is located on the Taha Plot (see Figure 23). Because it is principally used for filter production, the Taha Plot is not considered to be a promising borrow plot for fired brick production. However, it was investigated and sampled by the author in order to further characterize the soils in this area.

FIGURE 22 - GBURMA PLOT LOOKING NORTHEAST

FIGURE 23 - TAHA PLOT LOOKING NORTHWEST

5.3 Test Pit Excavation

Holes were excavated at all five PHW plots to investigate the suitability of the soils for brick making. Three test pits were excavated at the Gbalahi Plot; two test pits were excavated at the Kpaumo Plot; two test pits were excavated at the Wayemba Plot; one test pit was excavated at the Gburma Plot; and one recently excavated hole was examined at the Taha Plot (see Figure 24). Test pits were excavated manually with pickaxes and shovels by teams of between two and four local labourers.

Tests pit depths ranged from 4.0 ft. to 5.0 ft. and measured approximately 5.0 ft. by 5.0 ft. Test pits were generally dug beyond the soil horizon suitable for brick making and were terminated when digging became inefficient and very difficult due to hard ground conditions.

5.3.1 Field Logging Methods

Test pit lithologic logs were completed for all excavated holes and include descriptions of encountered subsurface conditions. Materials were characterized using a logging system, described in Appendix A; individual test pit logs can be found in Appendix B.

Test pits were named using the following naming convention: TP-PHW14-xxx. TP signifies test pit; PHW14 signifies test pits completed at PHW in the year 2014; and the xxx is sequential starting from 001 and is unique to each test hole.

5.3.2 Sample Collection

Samples were collected from different soil horizons in all excavated test pits for laboratory testing. During test pit excavation, collected samples were placed into two double-zipper Ziploc bags to preserve the in-situ moisture content and were transported to the PHW laboratory/office in Tamale for storage and laboratory testing.

Samples were named using the convention G1, G2, etc. to signify that grab samples were taken. The depths of collected samples for each test pit are indicated on individual test pit logs included in Appendix B.

FIGURE 24 - IMAGE SHOWING PHW PLOT LOCATIONS (GOOGLE EARTH, 2013)

5.3.3 Field Observations

Gbalahi Plot

The three test pits excavated at the Gbalahi Plot were completed in the centre of the plot (see Figure 25 and Figure 26) and showed a similar stratigraphy. The subsurface is characterized by a 0.5 ft. to 1.0 ft. thick layer of fine gravel which is underlain by a low to high plastic clay deposit that is between 1.0 ft. and 3.0 ft. thick. The clay unit is mottled orangish brown and grey, dry to moist, moderately to strongly cemented, shows no discernable structure, and requires moderate to significant hand pressure to break down lumps within the soil to create homogeneous material. With depth, the clay content decreases, the soil becomes more difficult to work due to the presence of rocky clumps, and grades into weathered rock. Figure 27 shows a typical soil profile for the Gbalahi Plot and Figure 28 shows the rocky nature at depth. The red line on Figure 25 outlining the plot limits was drawn using Google Earth imagery, which shows the extent of denuded land affected by surface gravel extraction.

FIGURE 25 - APPROXIMATE OUTLINE OF THE GBALAHI PLOT AND TEST PIT LOCATIONS (GOOGLE EARTH, 2013)

FIGURE 26 - ZOOMED IN IMAGE OF TEST PIT LOCATIONS (GOOGLE EARTH, 2013)

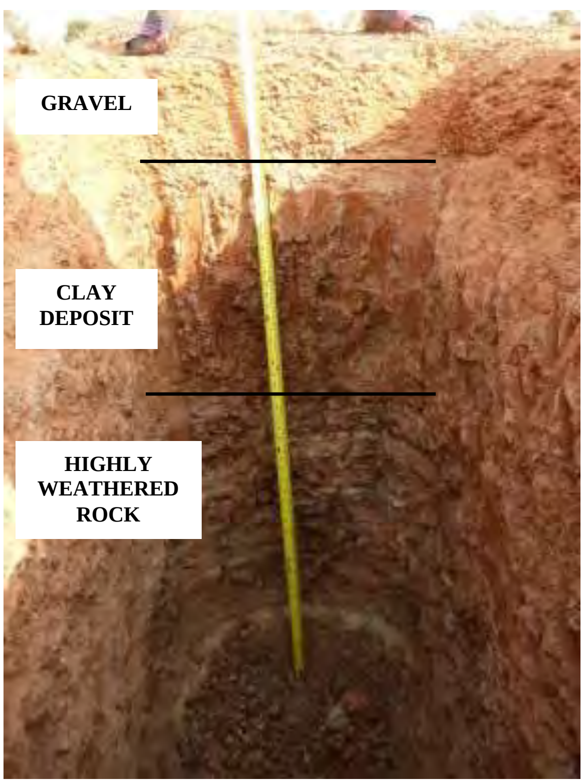

FIGURE 27 - SOIL PROFILE AT TP-PHW14-003

FIGURE 28 - COARSE GRAVEL-SIZED ROCK PIECES AT DEPTH

Kpaumo Plot

The two test pits excavated at the Kpaumo Plot were completed in the centre of the plot (see Figure 29 and Figure 30) and showed a similar stratigraphy. The subsurface is characterized by a 0.8 ft. to 1.5 ft. thick layer of fine gravel which is underlain by a high plastic clay deposit that is between 1.5 ft. and 2.0 ft. thick. The clay unit is greenish grey with reddish brown and orangish brown mottles, dry to moist, weakly to moderately cemented, shows no discernable structure, and requires moderate to significant hand pressure to break down lumps within the soil to create homogeneous material. With depth, the clay content decreases, the soil becomes more difficult to work due to the presence of rounded rocky concretions, the material shows cm-scale bedding, and grades into weathered rock. Figure 31 shows a typical soil profile for the Kpaumo Plot and Figure 32 shows the rounded concretions at depth.

FIGURE 29 - APPROXIMATE OUTLINE OF THE KPAUMO PLOT AND TEST PIT LOCATIONS (GOOGLE EARTH, 2013)

FIGURE 30 - ZOOMED IN IMAGE OF TEST PIT LOCATIONS (GOOGLE EARTH, 2013)

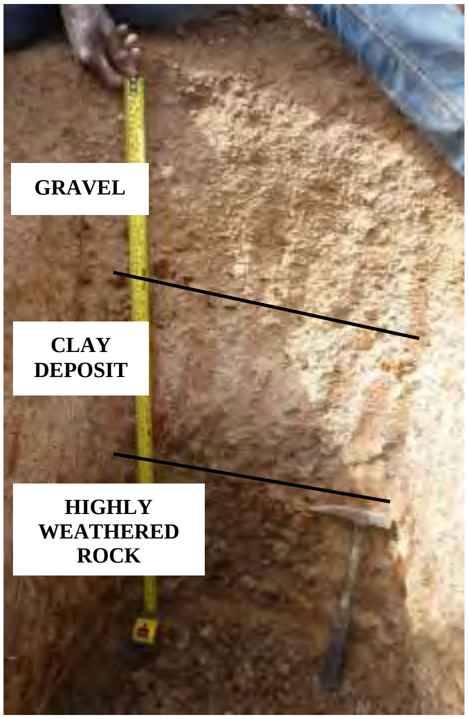

FIGURE 31 - SOIL PROFILE AT TP-PHW14-005

FIGURE 32 - IMAGE SHOWING DARK REDDISH BROWN ELLIPTICAL CONCRETIONS PRESENT AT DEPTH

Wayemba Plot

The two test pits excavated at the Wayemba Plot were completed in the northwestern and southeastern corners of the plot (see Figure 33) and showed slightly different stratigraphy. TP-PHW14-006, located in the northwestern corner of the plot, contains loam at surface overlying a deposit of strongly cemented clay that is extremely difficult to work due to hard concretions throughout. The test pit was terminated in rock at depth. Figure 34 shows the soil profile at TP-PHW14-006.

TP-PHW14-007 is characterized by a 0.5 ft. thick layer of loam at surface which is underlain by a low plastic silt/clay deposit that is 2 ft. thick. This silt/clay unit is light orangish-greyish brown, weakly cemented, and is easy to work by hand. The third unit observed is a brownish orange, high plastic clay that shows weak to moderate cementation. The clay unit can be worked relatively easily by hand but contains rocky seams. The test pit was terminated in rock at depth. Figure 35 shows the soil profile at TP-PHW14-007.

FIGURE 33 - APPROXIMATE OUTLINE OF THE WAYEMBA PLOT AND TEST PIT LOCATIONS (GOOGLE EARTH, 2013)

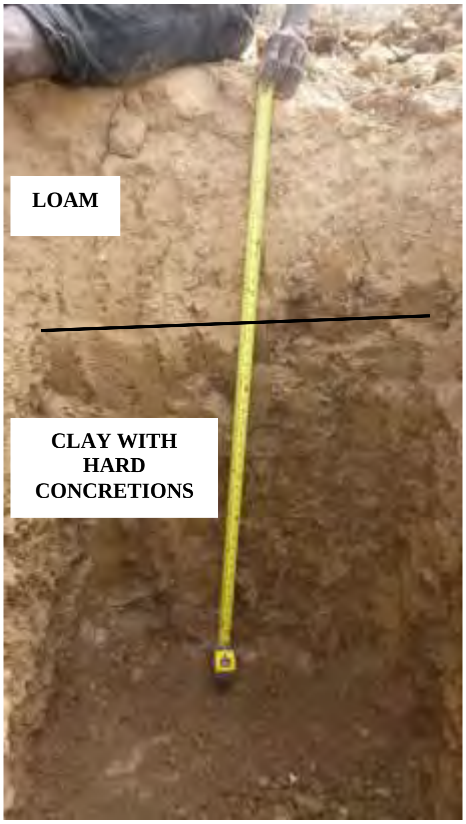

FIGURE 34 - SOIL PROFILE AT TP-PHW14-006

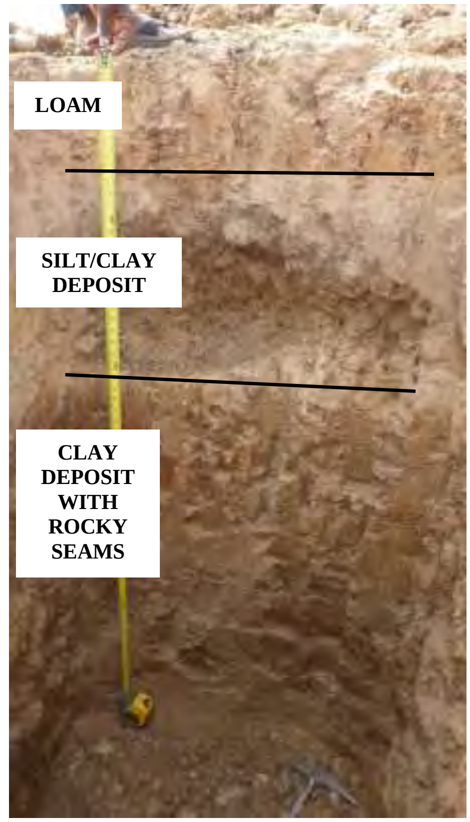

FIGURE 35 - SOIL PROFILE AT TP-PHW14-007

Gburma Plot

The test pit excavated at the Gburma Plot was completed at the southern end of the plot (see Figure 36). TP-PHW14-008 is characterized by a 0.5 ft. thick layer of porous loam at surface which is underlain by a porous, low plastic, sandy clay deposit that is approximately 3 ft. thick, orangish brown, moderately to strongly cemented, and relatively easy to work by hand. The third unit observed is an orangish brown, low plastic clay that is strongly cemented and very difficult to work by hand. Figure 37 shows the soil profile at TP-PHW14-008. Figure 38 shows the porous texture of the soil.

FIGURE 36 - APPROXIMATE OUTLINE OF THE GBURMA PLOT AND TEST PIT LOCATION (GOOGLE EARTH, 2013)

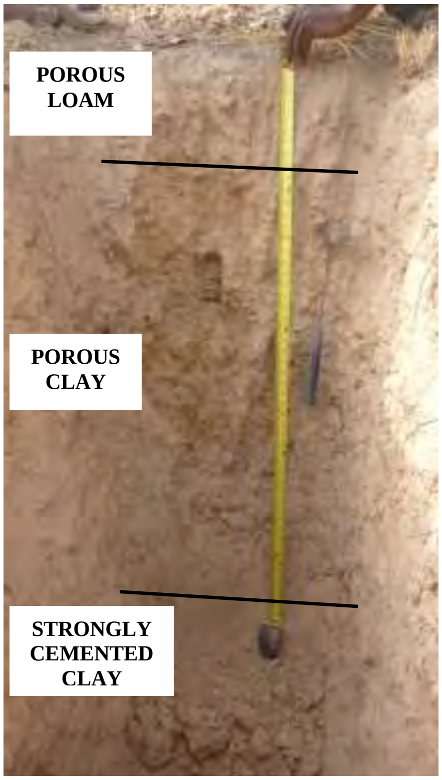

FIGURE 37 - SOIL PROFILE AT TP-PHW14-008

FIGURE 38 - POROUS TEXTURE OBSERVED IN LOAM AND TOP CLAY UNIT

Taha Plot

Prior to arriving in Ghana in January 2014, a 7 ft. deep excavation was completed adjacent to the PHW filter factory on the Taha Plot for a septic tank installation (see Figure 39). The excavation sidewalls had been exposed to the sun for several weeks prior to examination and had completely dried out.

The excavation shows a thin surface layer of fine gravel, underlain by loam. Below the loam is a low plastic, silty clay unit. A high plastic clay unit is observed from approximately 4.0 ft. to 5.0 ft. depth, which is further underlain by a strongly cemented unit that is extremely difficult to work by hand. Figure 40 shows the soil profile at the Taha site.

FIGURE 39 - APPROXIMATE OUTLINE OF THE TAHA PLOT AND EXCAVATION LOCATION (GOOGLE EARTH, 2013)

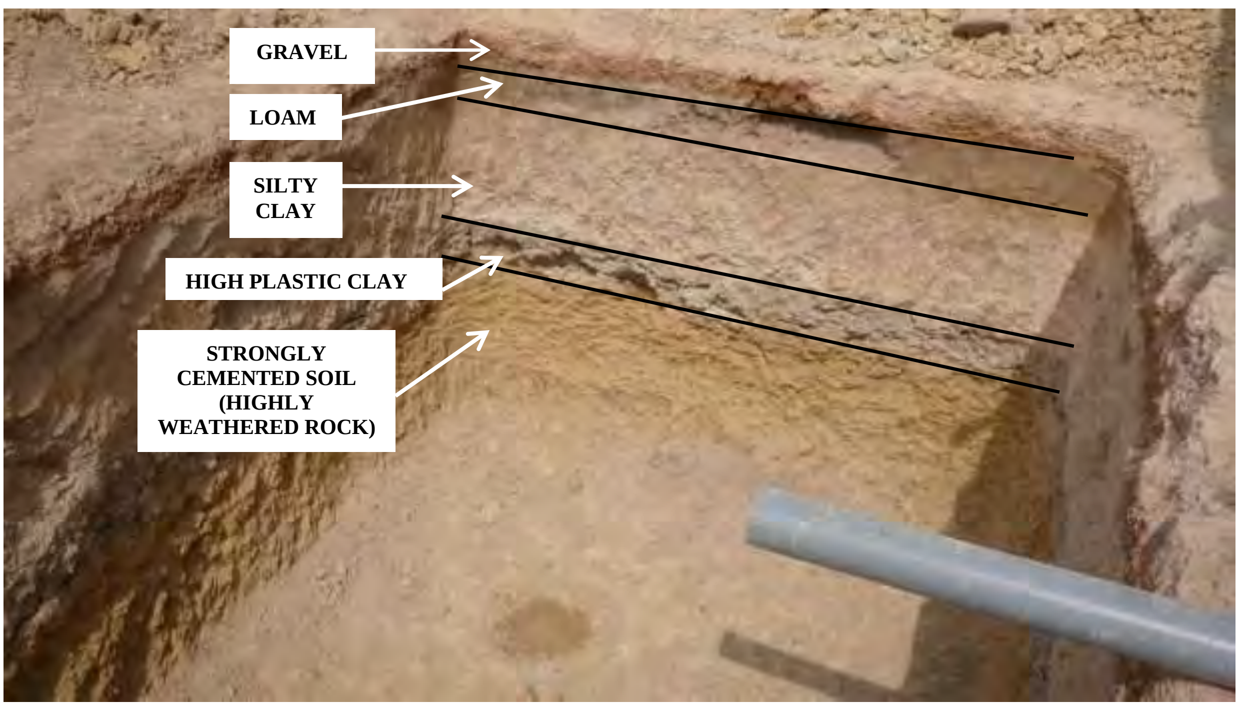

FIGURE 40 - SOIL PROFILE AT THE SEPTIC TANK EXCAVATION ADJACENT TO THE PHW FACTORY

General Soil Classification

The soils observed at all five PHW plots appear to reflect the characteristics of Savannah Ochrosols. This agrees with the interpretation presented on the Ghana soil map in Figure 18, where the soils of Tamale and its immediate environs are shown as a small zone of Savannah Ochrosols surrounded by extensive Groundwater Laterite deposits. No ironpan was observed in the soils, which is characteristic of the Groundwater Laterite great soil group. The presence of Savannah Ochrosols also suggests that the clay fraction of the soils is dominated by kaolinitic clays (Adjei-Gyapong and Asiamah, 2002), which is promising for brick production.

6.0 Laboratory Testing

6.1 Soil Testing

6.1.1 Index Testing

Laboratory testing to determine basic soil properties is an important component of assessing whether the PHW soils will be suitable for brick making. Therefore a program of index testing was undertaken on samples collected from the five PHW plots. Index testing was also completed on soil samples obtained from the existing brick factories in Ghana for comparison.

All index testing was completed during the month of January 2014, in Ghana at the PHW office/laboratory in Tamale. A large table was set up on the porch of the house which served as a storage site for the samples as well as a work space for the testing.

Moisture Content

The moisture content of a soil is important for classification purposes, describing soil consistency, and can be used with empirical relationships to infer strength, compressibility, and flow characteristics of a soil (Germaine and Germaine, 2009). It is also a very simple test, requiring only an oven and scale, and results are obtained within 24 hours. For brick making, the natural moisture content of a soil will provide some guidance on how much effort and water will be required to work the material into bricks.

The moisture content is defined as the weight of water divided by the weight of the solids in a given soil sample and is determined according to ASTM standard D2216 (ASTM International, 2010). The sample is collected from the field and placed in a sealed container to preserve the moisture content for testing. The sample is placed into an oven at 110^{o}C +/- 5^{o}C for 24 hours. The weight of the soil before and after heating in the oven is measured; the difference normalized by the weight of the solids is the moisture content.

Moisture content tests were performed on samples collected from all five PHW plots and three of the brick factories. No moisture content tests were performed on material from the Osei-Bonsu Factory because the soil was stockpiled and not in-situ. Moisture contents performed on samples from the Taha Plot excavation are lower than in-situ values as the excavation was open for several weeks and exposed to the drying action of the sun.

Figure 41 shows the moisture content versus depth profile for the five PHW plots. Where samples were taken at several depths in a given test pit, a general trend can be observed. At surface, a lower moisture content zone is observed. This can be explained as the test holes were dug in the dry season and the surface has been dried out. With depth, the moisture content increases, reflecting the reduced drying effect from the sun and heat. At some depth, the moisture content then decreases due to a reduction in fines content and an increase in rocky or gravelly soil.

By comparing this moisture content profile with the test pit logs provided in Appendix B and the field observations described in Section 5.0, some general conclusions can be made relating the moisture content and the presence of material suitable for brick production. In general, a higher moisture content reflects a higher clay percentage, as clay particles interact with water differently than the larger particle sizes (see Section 3.4) and retain more water than the larger particles under similar conditions. Therefore, where the moisture content decreases at depth, it is generally an indication that the soil has less clay and more of the coarse soil fraction. The lower moisture content at the examined sites generally coincides with more rocky seams in the soil profile, indicating that the material will be difficult to work and process for brick making.

Table 3 below summarizes the average moisture content at each of the sites investigated. The average moisture contents of the soils at the brick factories are significantly higher than those of the PHW plot soils. This reflects the location of the sites: all of the PHW plots are located in the drier Northern Region and all of the brick factories are in the more tropical climate of southern Ghana. This difference in moisture content will affect how easily the soil is extracted from the ground and how much mechanical effort will be required to mix and temper the soil for brick making. The soils at the PHW plots will require more effort to reach the required consistency for moulding bricks.

It should be noted that the average moisture content for the Taha site is artificially low due to drying as the excavation was open for several weeks. The surface of the Wayemba site was charred black during test pit excavation as a bush fire had recently occurred. This could have affected the moisture content of the soils closest to the ground surface. The upper soils of the Gburma Plot were sandy and very porous; this could explain the very low average moisture content at the site. It is unclear if the soil sample obtained from the Obeng 1 Factory was at its natural moisture content or if water had been added to temper the soil for brick making. It is known however, that the soil used for brick making at the Obeng 1 Factory is from a river deposit, as is the material used at the Adams Factory, and therefore the presented value is reasonable due to similar depositional environments.

TABLE 3 - AVERAGE MOISTURE CONTENT AT VARIOUS SITES

	PHW Plots					Brick Factories		
Site	**Gbalahi**	**Kpaumo**	**Wayemba**	**Gburma**	**Taha**	**Adams**	**Obeng 1**	**Obeng 2**
Average Moisture Content (%)	17	22	16	9	7	32	38	30

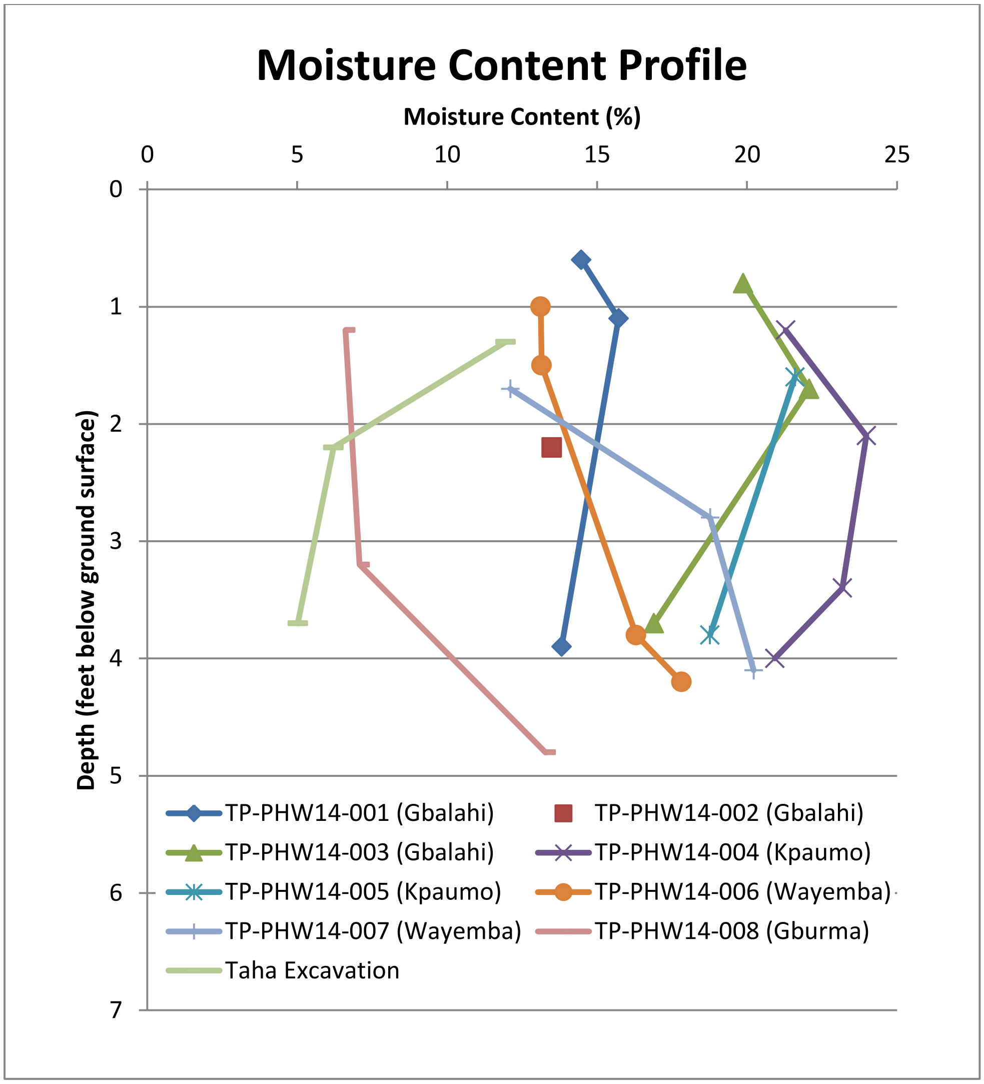

FIGURE 41 - MOISTURE CONTENT PROFILE FOR PHW PLOTS

Atterberg Limits

Atterberg limits are standard index tests performed on fine-grained soils according to ASTM D4318 (ASTM International, 2010). The limits are moisture contents at conceptual boundaries between various states of material behavior involving a mixture of soil particles and water (Germaine and Germaine, 2009).

The two limits of particular interest are the plastic limit and the liquid limit. The plastic limit defines the boundary between semi-solid and plastic mechanical behavior and is determined by measuring the moisture content at the point where soil crumbles when rolled into a 3.2 mm diameter string (Germaine and Germaine, 2009). The liquid limit defines the boundary between plastic and fluid-like behavior and is determined by measuring the water content where soil exhibits fluid behavior under a standard dynamic shear stress (Germaine and Germaine, 2009). A soil with a liquid limit of above 50% is considered to be a high plastic soil; one with a liquid limit below 50% is considered to be a low plastic soil.

The plastic limit and liquid limit are used to calculate the plasticity index, another value that is used to characterize material behavior. The plasticity index is defined as the moisture content at the liquid limit minus the moisture content at the plastic limit. The plasticity index is a measure of how strongly the particles interact with the water and quantifies the range in moisture contents over which a soil exhibits plastic behaviour (Germaine and Germaine, 2009).

The Atterberg limit test is performed on material passing the 0.425 mm (No. 40) sieve, which requires that clumps of clay and silt be disaggregated to pass through the sieve. However, some soil materials, particularly those found in tropical and hot environments, contain bonded aggregates that are very sensitive to mechanical breakdown to smaller grain sizes. The amount of mechanical effort put into disaggregating the soil can drastically affect material behaviour in these soils. Furthermore, drying the soils can significantly alter their structure and physical behavior (Fookes, 1997). ASTM D4318 outlines two preparation methods, namely the dry preparation method and the wet preparation method (ASTM International, 2010). The wet preparation method involves passing the material through the No. 40 sieve in the wet state and is used to help disaggregate clay and silt while minimizing mechanical breakdown of chemically bonded aggregates. The soil is maintained at its in-situ water content until testing commences and is never dried. Given that Ghana has a hot climate and some soils were from tropical areas, all samples were tested using the wet preparation method.

Atterberg limit tests were completed on samples collected from all five PHW plots and four of the brick factories. All Atterberg limit tests were completed in Ghana at the PHW office/laboratory in Tamale. Due to time and labour limitations, the clay-rich soil horizons were targeted for testing, as these horizons would be the most promising for brick production. However, seams that were deemed to contain more silt from the Wayemba and Taha plots based on manual-visual classification tests in the field were also tested for calibration of field classification and to provide comparative materials.

Figure 42 is a plasticity chart, which is a standard graphical presentation of Atterberg limit test results. All of the materials tested plot either as low plastic clays or as high plastic clays. The samples from the existing fired brick factories are generally observed to cluster in the centre of the data with liquid limit values between 37% and 58%. The samples from the PHW plots show a larger scatter and span liquid limits between 27% and 69%.

Table 4 below summarizes the average plastic limit, liquid limit, and plasticity index values for each site. The sites are listed in order of decreasing liquid limit, with the high plastic soils at the top and the low plastic soils at the bottom.

As a first attempt at delineating material suitable for brick making, it would seem reasonable to select those soils with plastic limit, liquid limit, and plasticity index values within the range of the values exhibited by the soils of the existing brick plants. The average plastic limit, liquid limit, and plasticity index of the Gbalahi clay and Wayemba clay fall within the range of the values for the existing brick plants. This suggests that they display favourable properties for brick making using the technologies practiced in Ghana. The Taha silty clay unit, the Wayemba silty clay unit, and the Gburma material fall below the range of values for the existing brick plants; their low plasticity may correlate to decreased mouldability and lower strength in brick production. The Kpaumo material falls above the range of values for the existing brick plants; its high plasticity may correlate to difficulty during moulding, high shrinkage rates, and cracking during firing.

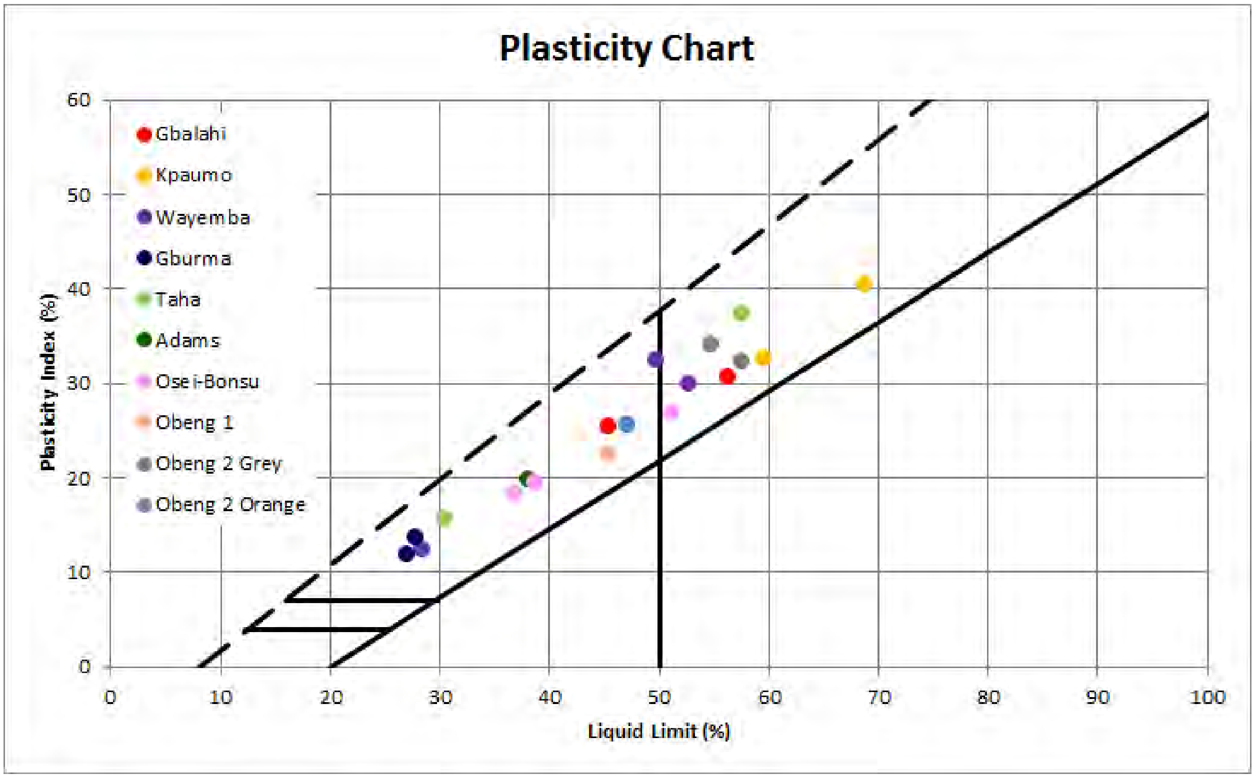

FIGURE 42 - PLASTICITY CHART SHOWING TESTED MATERIALS

TABLE 4 - SUMMARY OF ATTERBERG LIMIT TESTING

	Site	Average Plastic Limit (%)	Average Liquid Limit (%)	Average Plasticity Index (%)
High Plastic Clays	Kpaumo (PHW)	28	64	36
	Taha clay unit (PHW)	20	58	37
	Obeng 2 Factory	22	53	31
	Wayemba clay unit (PHW)	20	51	31
	Gbalahi (PHW)	23	51	28
Low Plastic Clays	Obeng 1 Factory	23	45	22
	Osei-Bonsu Factory	21	42	22
	Adams Factory	18	38	20
	Taha silty clay unit (PHW	15	31	16
	Wayemba silty clay unit (PHW)	16	28	12
	Gburma (PHW)	15	27	13

Simple Sedimentation

Grain size analyses are performed on soils to understand the relative amounts of the different sized particles. The distribution of particle sizes within a soil provides important information relating to soil classification and behaviour.

Sedimentation methods are used to determine the grain size distribution of fine-grained soils (Germaine and Germaine, 2009). Sedimentation is based on the principle that larger particles will settle more quickly in a column of water and that the density of the water at a given time reflects the grain size of the particles at a particular horizon in the fluid column. Calculation of the particle sizes using sedimentation is based on Stoke's Law, which expresses the hydrodynamics of a single spherical particle falling in a stationary fluid (Germaine and Germaine, 2009). There are several assumptions inherent in the application of Stoke's Law, including that the particles are spherical and smooth, there is no interference between particles, no side wall effects, all particles have the same density, and flow is laminar (Germaine and Germaine, 2009).

Simple sedimentation is used when the amount of material greater than 75 μm will be quantified, but the grain size distribution will not be determined for this coarser portion. The analysis is completed using the hydrometer method on the fine-grained portion passing the No. 10 sieve (2.00 mm). Sodium hexametaphosphate at a concentration of 5 g/L is added to the distilled water and soil mixture to deflocculate the clay particles.

Simple sedimentation tests were completed on samples collected from two of the PHW plots and three of the brick factories. All simple sedimentation tests were completed in Ghana at the PHW office/laboratory in Tamale in accordance with ASTM standards D2217 and D422 (ASTM International, 1998; 2007). Due to time and labour limitations, only the clay-rich soil horizons from the most promising PHW plots for brick production were targeted for testing.

Figure 43 below shows the grain size distribution curves for the six completed simple sedimentation tests. The six soils show relatively similar grain size distribution curves with clay percentages between 40% and 50%. This indicates that relatively little variation in grain size exists between the southern Ghana and northern Ghana soils. As outlined in Section 3.4, the percentage of clay in bricks can vary between 15% and 80% (Chisholm, 1910). Therefore the tested soils from the PHW plots and the brick factories show clay percentages within acceptable limits for brick making. Furthermore, the similarity in clay percentage between the PHW plots soils and the brick factory soils bodes well for brick production in the north. Table 5 below summarizes the clay percentages for the various soils.

TABLE 5 - CLAY PERCENTAGES OF TESTED SOIL SAMPLES

	PHW Plots		Brick Factories			
Sample	Gbalahi	Kpaumo	Obeng 1	Obeng 2 – soil 1	Obeng 2 – soil 2	Adams
Clay Percentage	46%	48%	40%	49%	44%	43%

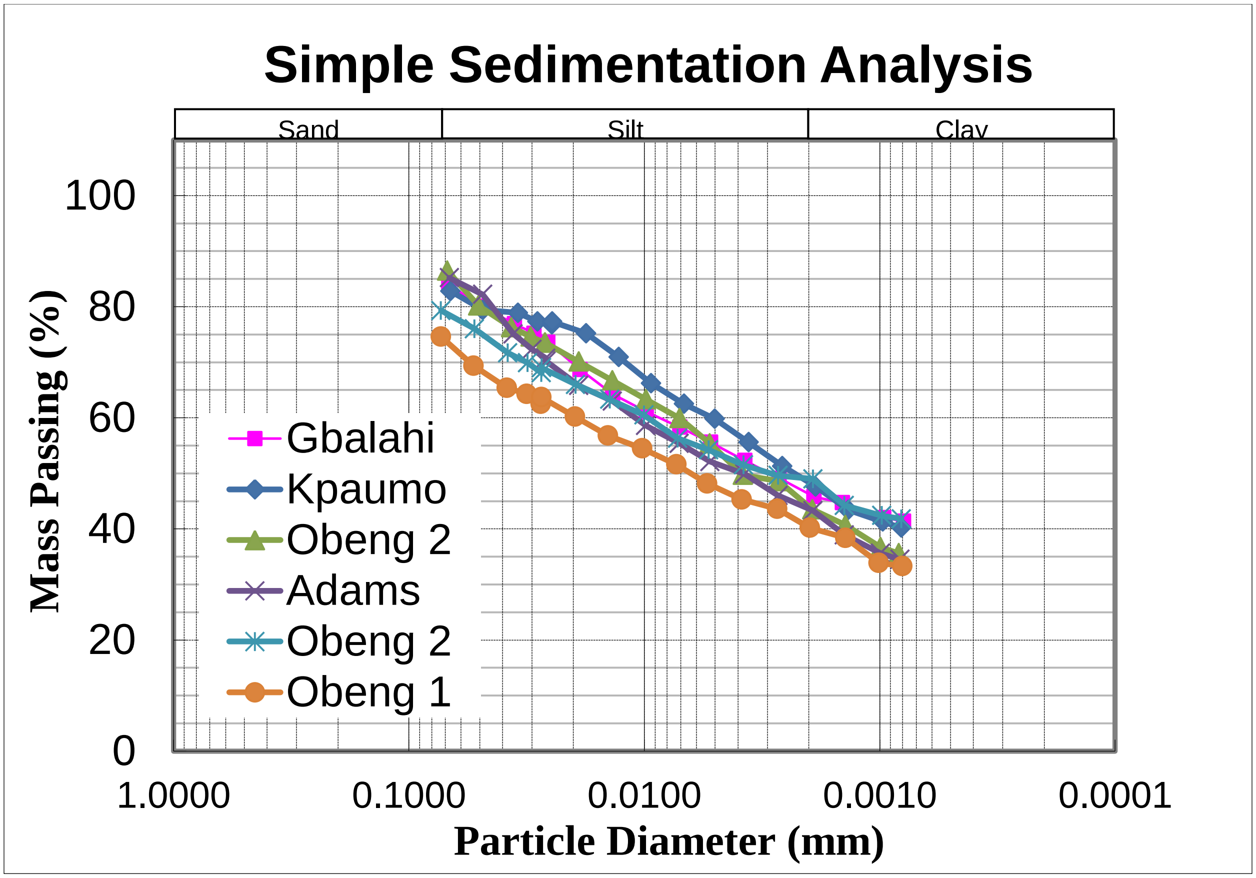

FIGURE 43 - GRAIN SIZE DISTRIBUTION CURVES FOR SIMPLE SEDIMENTATION ANALYSES

6.1.2 X-Ray Diffraction Testing

The physical and chemical properties of a soil are controlled to a large degree by the minerals that make up the soil, and particularly those that make up the clay fraction (Whittig, 1965). X-Ray diffraction testing is a technique that allows for the identification of the individual minerals that constitute a given soil.

The intensity of the diffraction pattern from a particular mineral is affected by several factors, including concentration of the mineral, crystal size, and crystal perfection (Whittig, 1965). Many clays produce broad, diffuse, and poorly defined diffraction peaks due to their small particle size, a poorly ordered nature, and/or interstratification (Ozalas and Hajek, 1996). Therefore the correct identification of the minerals that make up the clay fraction requires the application of several complementary analyses.

Analysis of the bulk soil sample mineralogy is completed on a randomly-oriented powder sample. However minerals that produce stronger diffraction patterns will tend to mask the diffraction signatures of the clay minerals. It is therefore necessary to segregate the fine fraction of the soil using sedimentation or centrifugation. Once the clay fraction of interest has been separated from the bulk sample, an oriented clay mineral aggregate can be prepared on a glass slide or other substrate. Several techniques are available to prepare the oriented clay mineral aggregate, including the glass slide mount, the smear mount method, the Millipore filter transfer method, and the centrifuged porous plate method (Moore and Reynolds, 1997). The prepared films should be analysed in an air-dried condition, an ethylene glycol-solvated condition, and after enough heating to collapse any expandable layers. These supplemental analyses are required to identify certain clay minerals, such as the smectite clay mineral montmorillonite, that could be confused with other clay minerals with similar diffraction patterns.

Seven samples were prepared for testing; three samples were from the PHW plots and four samples were from the brick factories. The first set comprised randomly-oriented powder samples of the bulk soil. The second set comprised oriented clay mineral aggregates on a silicone slide substrate, air dried at room temperature. The glass slide mount method was used with silicone slides in place of glass slides to produce a better diffraction pattern. The third set comprised oriented clay mineral aggregates on a silicone slide substrate, air dried at room temperature and then ethylene glycol salvated at $60^{o}C$ for a minimum of eight hours. No official standards exist for clay X-ray diffraction; guidelines from Moore and Reynolds (1997) and the United States Geological Survey website were followed as appropriate, with consultation from Dr. John Germaine in the Civil Engineering Department at MIT (USGS; Germaine, 2014).

The randomly-oriented powder samples were prepared by sieving through a 325 mesh (44 μm) and were packed into stainless steel sample holders provided by the MIT CMSE XRD laboratory. The clay fraction (2 μm and finer) for the oriented aggregates was separated by sedimentation in test tubes. The sieved soil was added to distilled water at a concentration of 30 g/L with 5 g/L of sodium hexametaphosphate as a dispersing agent. The soil-fluid suspension was allowed to settle for approximately three hours and the 2 μm clay fraction was removed with a glass eye-dropper from the appropriate horizon. The fluid was placed on a silicone slide and allowed to air dry (generally overnight). For ethylene glycol salvation, the samples were placed in a desiccator containing liquid ethylene glycol. The samples were supported by a ceramic platform and did not come into direct contact with the ethylene glycol. The desiccator was placed into an oven at $60^{o}C$ for a minimum of eight hours.

Samples were analysed using the PANalytical X'Pert Pro Multipurpose Diffractometer in the MIT CMSE XRD laboratory. The generator was operated at 45 mV and 40 mA with a Cu diffraction tube. The powder samples were run between $3^{o}2\theta$ and $90^{o}2\theta$ in steps of $0.0167^{o}2\theta$ with a counting period of 210 seconds per step. The clay film samples were run between $3^{o}2\theta$ and $40^{o}2\theta$ in steps of $0.0167^{o}2\theta$ with a counting period of 210 seconds per step or between $3^{o}2\theta$ and $30^{o}2\theta$ in steps of $0.0167^{o}2\theta$ with a counting period of 100 seconds per step. An automatic divergence slit with an irradiated length of 5 mm was used for all samples. The 10 mm beam mask, 2 mm anti-scatter slit, and 0.02 mm soller slit were used for all samples.

The generated X-Ray diffraction patterns were analysed using HighScore Plus v3.0. The raw and processed X-Ray diffraction tracings are presented in Appendix C. Results show that all seven samples contain kaolinite and quartz. Most also contain illite or muscovite. The presence of several minerals within the soils is promising for brick production as it is documented that soils showing a mixture of clay minerals do not shrink as much when fired as those composed predominantly of one type of clay mineral (Bell, 2007).

Several diffraction patterns also show the presence of smectite clays, such as montmorillonite. Smectite clays are undesirable for brick production as they exhibit shrinking and swelling behavior due to their interaction with water. This can produce excessive shrinkage or deformation of bricks during drying and firing (Mueller, 2008). The smectites are observed in the soils of the brick factories as well as the soils of the PHW plots. Although quantitative X-Ray diffraction analyses were not completed, it is unlikely that the smectites are the major constituent of the soils as the liquid limit and plastic limit values are below the range of smectite-dominated materials. Also, the brick factories are successfully producing bricks with soils containing smectites, indicating that the presence of such clays in relatively small quantities does not impede brick production.

Table 6 below presents a summary of the analyses completed on the X-ray diffraction patterns for the seven samples.

TABLE 6 - SUMMARY OF RESULTS FROM X-RAY DIFFRACTION ANALYSES

	SITE	QUARTZ	KAOLINITE	ILLITE	MUSCOVITE	SMECTITE
PHW PLOTS	GBALAHI	YES	YES	YES	POSSIBLE	YES
	KPAUMO	YES	YES	YES	YES	YES
	WAYEMBA	YES	YES	LIKELY	YES	NO
BRICK FACTORIES	OSEI-BONSU	YES	YES	YES	POSSIBLE	POSSIBLE
	ADAMS	YES	YES	YES	POSSIBLE	POSSIBLE
	OBENG 1	YES	YES	LIKELY	YES	POSSIBLE
	OBENG 2	YES	YES	NO	NO	YES

6.2 Brick Testing

Brick samples were collected during visits to the brick factories in Ghana in January 2014. Good quality, properly-fired bricks were collected from the Osei-Bonsu, Adams, Obeng 1, and Obeng 2 factories and brought back to MIT. No samples were collected at the Tamakloe Factory.

Test bricks were also made at the PHW filter factory from soils collected from the PHW plots being investigated for brick making. Bulk samples were collected from the Kpaumo, Wayemba, and Gburma sites; soil from the Gbalahi site was available at the filter factory. Bricks were moulded using a hand mould available at the factory and allowed to dry for a week. Due to time limitations, the bricks could not be fired in Ghana and therefore a selection was brought back to MIT for firing. During transport, most of the unfired bricks broke and therefore bricks were remoulded and dried anew at MIT. The bricks were fired in an electric kiln at MIT's Department of Materials Science and Engineering. The firing schedule used mimicked the firing conditions utilized at PHW's filter factory, as this would represent the firing conditions available presently at the factory (see Figure 44). A maximum firing temperature of 830°C was reached after 11 hours. The samples were removed after 42 hours and it was observed that several of the bricks exploded during firing. This is thought to have been caused by the uneven heat distribution in the kiln, where the heat is provided by side metal coils and from a base plate. The bricks that were closest to the bottom of the kiln exploded; these were from the Gbalahi and Kpaumo plots. Five bricks were successfully fired, including two Gburma Plot bricks, one Wayemba Plot clay soil brick, one Wayemba Plot silty clay soil brick, and one Kpaumo Plot brick.

Prior to the January 2014 field visit, staff at the PHW filter factory had made bricks from Gbalahi soil with varying amounts of rice husk within the bricks. These bricks were also transported to MIT for laboratory testing.

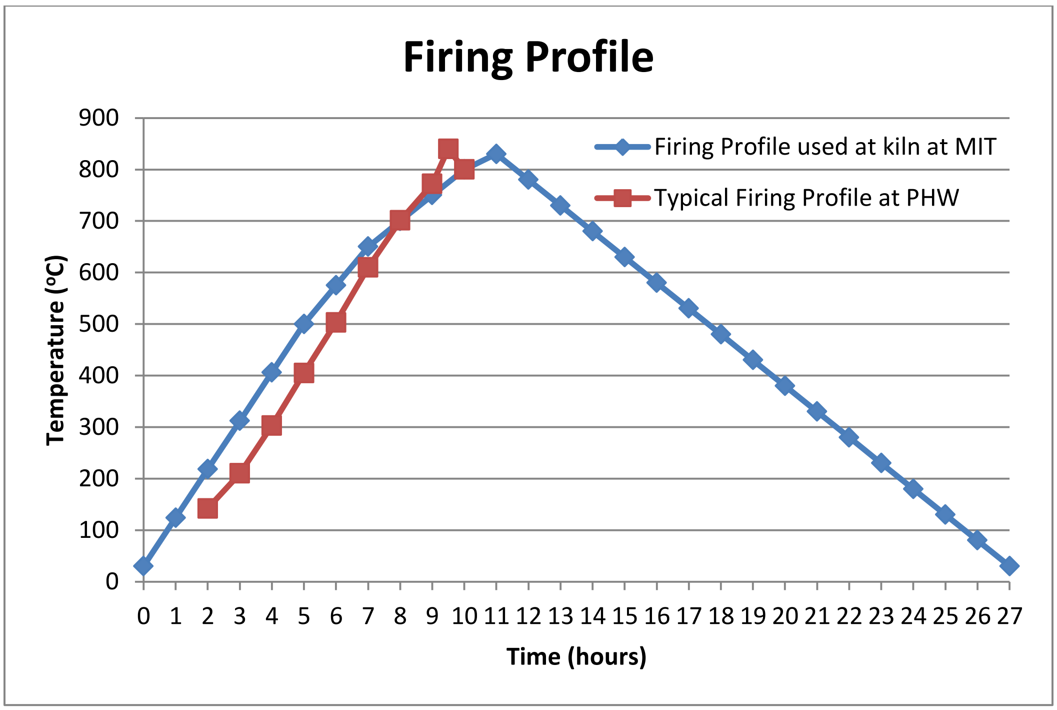

FIGURE 44 - BRICK FIRING SCHEDULE

6.2.1 Unconfined Compressive Strength

The uniaxial compressive strength of a material is measured in a load cell. The sample is placed between two steel platens and the load is increased until failure. The peak load at failure divided by the area of loading gives the compressive strength. Units of MPa are typically used when discussing the compressive strength of bricks. Bricks vary in compressive strength with values ranging from 5 to 100 MPa; common house bricks typically show values between 20 MPa and 40 MPa (Gorse et al., 2012).

A total of 23 bricks from the factories in Ghana and those made from PHW soils were prepared for UCS testing. The bricks were capped with Plaster of Paris on the top and bottom sides to provide an even and smooth surface for testing. Plaster of Paris is used at MIT as a capping material as it is has a very high stiffness. All of the brick samples were tested in the 20 kip

Baldwin load cell in the MIT Structures, Materials, and Rock Mechanics Laboratory under load-controlled conditions. Specimens were loaded to failure at a rate of 25,000 N/minute or 50,000 N/minute. All bricks were loaded perpendicular to the long axis and samples failed within five and 29 minutes. No standard testing procedure was used.

Figure 45 below shows the results of the unconfined compressive strength testing for the various bricks. The compressive strength of the samples varied considerably from 4 MPa to 35 MPa. The results are difficult to interpret due to several inconsistencies between the samples. The bricks were made using different methods (some were hand moulded and some were mechanically extruded), a variety of kilns were used (clamp, downdraft, and electric), the bricks were dried under different conditions (some in Ghana and some at MIT), the brick geometries varied (some were solid, some had vertical holes, and some had horizontal holes), and the firing temperatures varied (ranging from approximately 830^oC to 1200^oC – 1300^oC). However, some potential conclusions can be drawn from the data.

It is well documented in the literature that a higher firing temperature will produce bricks with a higher strength (Karaman, 2005). This trend is possibly observed in the compressive strength testing as shown in the dark brown and orange boxes in Figure 45. Hand moulded bricks tend to be of lower quality than mechanically extruded bricks. This trend is possibly observed in the compressive strength testing as shown in the purple and green boxes in Figure 45. The geometry of the bricks in relation to the direction of loading appears to influence the compressive strength. The bricks tested were solid, hollow with horizontal holes, or hollow with vertical holes. The hollow bricks with horizontal holes are outlined in pink in Figure 45 and show dramatically lower compressive strengths. Although further testing is required to confirm the above observations, preliminary results show that mechanically extruded bricks, fired at temperatures of approximately 1200^oC to 1300^oC, that are solid or have vertically aligned holes have the highest compressive strength. Load versus time curves for all 23 tested bricks are provided in Appendix D.

It should be noted that 78% of bricks fired to a maximum temperature of approximately 830^oC show compressive strengths below the typical range for common house bricks of 20 MPa to 40 MPa. This is the typical maximum firing temperature for the kiln at the PHW filter factory. The process of vitrification, where the minerals are converted into glass, imparts significant strength to bricks and typically occurs at temperatures between 800^oC and 1300^oC. Should brick making be undertaken by PHW, firing at temperatures higher than 830^oC will likely produce stronger bricks due to increased vitrification. However, further testing is recommended to confirm the data provided in Figure 45.

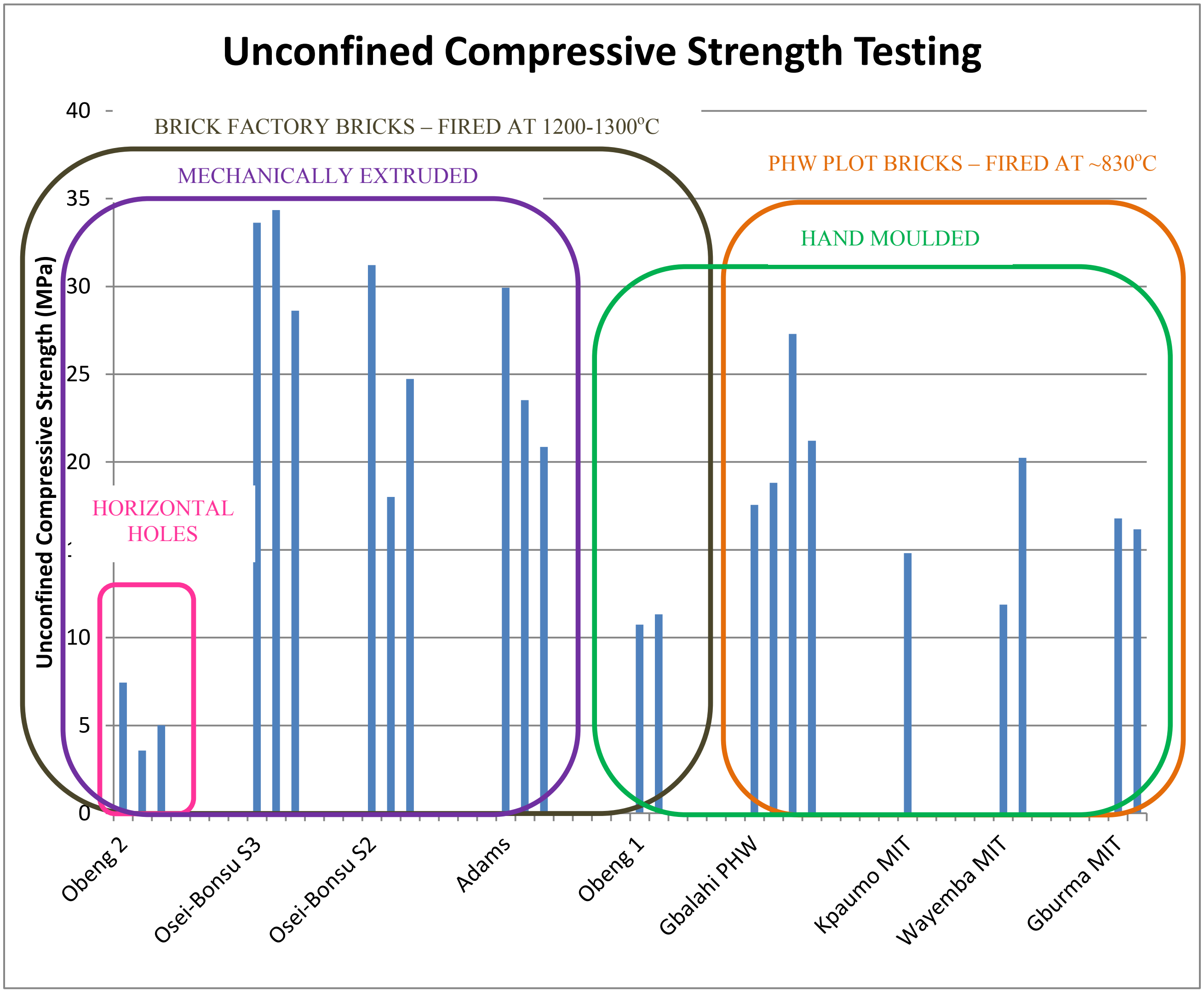

FIGURE 45 - RESULTS OF UCS TESTING

7.0 Clay Resource Evaluation

To determine which of the PHW plots has the greatest potential as a clay resource for brick making, several factors must be considered. The quality and the quantity of the source soils are important factors that come to mind immediately. However other factors will influence the feasibility of brick production, such as past land use and the reliability of the clay resource. The following sections outline important considerations in evaluating the potential for brick production at PHW.

7.1 Material Suitability

Section 6.0 documents the results of laboratory testing completed on the PHW plot soils. Index testing shows that the soils are relatively similar to those found in the southern part of the country.

The Gbalahi soils are low to high plastic clays with a clay content of 46%. The Atterberg limits plot within the range of values from the brick factories, suggesting that the material would be suitable for brick production. The X-Ray diffraction testing shows that kaolinite, quartz, illite, and possibly muscovite are present in the soil as well as montmorillonite. Based on these observations, it is predicted that the Gbalahi soils would be good source soils for brick production.

The Kpaumo soils are high plastic clays with a clay content of 48%. The Atterberg limits plot outside the range of values from the brick factories, suggesting that the material is more plastic than the soils currently used in Ghana for brick making. The X-Ray diffraction testing shows that kaolinite, quartz, muscovite, and illite are present in the soil as well as montmorillonite. Based on these observations, it is predicted that the Kpaumo soils would be marginal source soils for brick production due to their high plasticity.

The Wayemba soils are grouped into two categories. The first category comprises a high plastic clay with Atterberg limit values that plot within the range of values from the brick factories, suggesting that the material would be suitable for brick production. The X-Ray diffraction testing shows that kaolinite, quartz, muscovite, and illite are present in the soil; no montmorillonite was detected. The second category comprises a low plastic silty clay with Atterberg limit values that plot outside the range of values from the brick factories, suggesting that the material is less plastic than the soils currently used in Ghana for brick making. No X-Ray diffraction tests were completed on the second soil category. Based on these observations, it is predicted that the Wayemba high plastic clay would be a good source for brick production and that the Wayemba low plastic silty clay would be a poor source for brick production due to its low plasticity.

The Gburma soils are low plastic clays and based on field observations, they contain a higher percentage of sand. The Atterberg limits plot outside the range of values from the brick factories, suggesting that the material is less plastic than the soils currently used in Ghana for brick making. No X-Ray diffraction tests were completed on the Gburma soils. Based on these observations, it is predicted that the Gburma soils would be poor source soils for brick production due to their low plasticity.

The Taha soils are grouped into two categories. The first category comprises a high plastic clay with Atterberg limit values that plot just outside but very close to the range of values from the brick factories, suggesting that the material would be suitable for brick production. The second category comprises a low plastic silty clay with Atterberg limit values that plot outside the range of values from the brick factories, suggesting that the material is less plastic than the soils currently used in Ghana for brick making. No X-Ray diffraction tests were completed on either soil category. Based on these observations, it is predicted that the Taha high plastic clay would be a good source for brick production and that the Taha low plastic silty clay would be a poor source for brick production due to its low plasticity.

7.2 Observations from Pilot Brick Making

As outlined in Section 6.2, bulk samples from four PHW plots were collected for brick making. The soils were collected from the Gbalahi, Kpaumo, Wayemba, and Gburma plots.

In late January 2014, the soils were manually pounded and hand moulded into bricks by staff at the PHW factory (see Figure 46). They were dried for approximately one week on the filter drying racks under cover (see Figure 47), but due to time limitations they were never fired in Ghana. A selection of the green bricks was transported to MIT but many broke in transit. As a result, they were soaked in water and remoulded by hand into green bricks and then fired at MIT in March 2014. Some qualitative observations can be made from the brick making process in Ghana and at MIT to help evaluate the suitability of the various soils for brick making.

Five bulk samples were moulded into bricks:

1) Gbalahi clay (low to high plastic)
2) Kpaumo clay (high plastic)
3) Wayemba clay (low to high plastic)
4) Wayemba silty clay (low plastic)
5) Gburma clay (low plastic)

Table 7 below presents observations made during moulding and drying in Ghana. Observations show that the low plastic materials in general were more difficult to mould. In particular, the Wayemba silty clay was difficult to mould into green bricks. All of the green bricks cracked during drying. The cracking was least pronounced in the Gbalahi clay and the most pronounced in the Wayemba silty clay. The Gbalahi soil appears to have performed the best during green brick production; however it should be noted that the PHW staff that made the bricks are most accustomed to moulding Gbalahi soil as this is the main soil used at the filter factory. Therefore, there may be some bias in the observations due to the staff having a better feel for exactly how much water and kneading is required to optimize Gbalahi soils.

FIGURE 46 - HAND MOULDING BRICKS AT THE PHW FACTORY

FIGURE 47 - DRYING GREEN BRICKS AT THE PHW FACTORY

TABLE 7 - OBSERVATIONS FROM BRICK MAKING IN GHANA

Sample	Number Made	Moulding Observations	Drying Observations
Gbalahi clay (CL/CH)	5	Bricks moulded well	Minor to no cracking
Kpaumo clay (CH)	6	Bricks moulded well	Moderate cracking
Wayemba clay (CL/CH)	3	Bricks moulded well; minor remoulding required	Moderate cracking
Wayemba silty clay (CL)	2	Difficulty moulding bricks; soil lost shape easily	Extensive cracking
Gburma clay (CL)	3	Bricks moulded well	Minor cracking

Table 8 below presents observations made during moulding, drying, and firing at MIT. Observations show that the higher plastic materials were more difficult to mould. This is in direct contrast to the results from Ghana and is likely due to different personnel completing the moulding. In Ghana, the PHW staff moulded the bricks. They have worked extensively with clays and in particular the Gbalahi clay which is low to medium plastic. At MIT, the author completed the moulding with very limited experience working clays into bricks. This lack of skill by the author likely contributed to the moulding difficulties at MIT and is not a true reflection of the material behaviour. At MIT, the Gbalahi clay and Gburma clay produced the nicest brick shapes, however these were also the last bricks made by the author and therefore may reflect some skill improvement rather than a direct reflection of the material behaviour. Because of the inexperience of the author, the results from moulding at MIT are not considered as heavily in the pilot brick making evaluation.

A significant difference was also noted on the brick performance during drying. At MIT, the bricks were all dried indoors in a heat-controlled basement laboratory and overall, the bricks showed much less cracking at MIT than in Ghana. This can likely be explained by a difference in temperature and humidity. The bricks in Ghana were dried in the open air of a dry climate at temperatures between 30°C and 40°C. The bricks at MIT were dried in a building with relatively higher humidity and at temperatures between 20°C and 25°C. Therefore, the bricks dried at MIT likely dried slower than those in Ghana, which reduced cracking. This has important implications for brick making in Ghana, where most of the bricks cracked. Given the hot, dry climate in Tamale, it will be important to develop a good system for drying that minimizes cracking.

The bricks made from Gbalahi and Kpaumo clays both exploded during firing. This could be attributed to their placement at the bottom of the electric kiln on a layer of previously fired bricks. The kiln is heated from the sides by coils and by a plate at the bottom of the kiln. It is possible that the bricks nearest to the bottom were heated more quickly and therefore exploded (see Figure 48).

FIGURE 48 - BRICKS IN MIT KILN AFTER FIRING

TABLE 8 - OBSERVATIONS FROM BRICK MAKING AT MIT

Sample	Number Made	Moulding Observations	Drying Observations	Firing Observations
Gbalahi clay (CL/CH)	2	Moderately difficult to extract bricks from mould; good brick shape	No cracking	All bricks cracked/exploded
Kpaumo clay (CH)	3	Extremely difficult to extract bricks from mould; extra effort caused very deformed shape	No cracking	Most bricks cracked/exploded
Wayemba clay (CL/CH)	1	Moderately difficult to extract brick from mould; extra effort caused deformed brick shape	No cracking	No cracking
Wayemba silty clay (CL)	1	Brick moulded with relative ease and with decent shape	Minor cracking	No cracking
Gburma clay (CL)	2	Bricks moulded with relative ease and with good shape	Moderate cracking	No cracking

7.3 Quantity Estimate

The quantity of clay rich soil available for brick making is an essential consideration in evaluating the feasibility of brick production. Table 9 below summarizes the dimensions of the PHW plots and presents an estimate of the number of years of brick production that could be undertaken using the following assumptions:

- A production rate of 40,000 bricks per month operating 12 months per year (estimated full operating capacity);
- A solid brick with the following dimensions: 12 cm x 7 cm x 23 cm = 1932 cm^3 = 0.06823 cu. ft. (approximate dimensions of mould used at the Obeng factories); and
- A compaction factor of 0.2 (to account for compaction of the material during moulding) (Mueller, 2008).

The lateral extent of the deposits was considered in the “Assumed Coverage” category. If the test pits completed at the site showed the clay horizon, 100% coverage was assumed. In the case of the Wayemba Plot, two test pits were completed and only one showed the clay horizon; therefore the coverage was estimated at 50%. For the Taha Plot, existing PHW factory infrastructure is present over a significant portion of the plot; therefore the coverage was estimated at 50%. It should be noted that no wastage factor was included. However, in practice, some soil will be wasted during excavation, handling, and moulding. For these reasons, the numbers presented below are preliminary estimates with a low degree of accuracy as several assumptions were made. It is likely that the numbers presented are an overestimate of the actual quantity of material available.

TABLE 9 - CLAY RESOURCE QUANTITY ESTIMATE

	Surface Area	Clay Deposit Thickness	Assumed Coverage	Volume	Years of Brick Production
Gbalahi	30 acres	2 ft.	100%	1,960,000 cu. ft.	47.9 years
Kpaumo	1.5 acre	2 ft.	100%	130,000 cu. ft.	3.2 years
Wayemba	1 acre	2 ft.	50%	45,000 cu. ft.	1.1 years
Gburma	10 acres	3 ft.	100%	1,310,000 cu. ft.	32.0 years
Taha	2.5 acres	1.5 ft.	50%	80,000 cu. ft.	2.0 years

The values presented in Table 9 show that the Gbalahi and Gburma plots have the greatest amount of material available due to their larger surface area. They could support brick production for several decades based on the assumptions given above. The Kpaumo, Wayemba, and Taha plots are much smaller and therefore could support only a few years of full brick production.

7.4 Land Use

The establishment of a brick factory should be done with best practices principles in mind, including evaluating if it is appropriate to develop a clay borrow source on certain PHW plots. The PHW plots are all located within 11 kilometers of Tamale, but the history of development at the various sites varies considerably.

The Gbalahi Plot has been used as a gravel source for many years. Most of the surface gravel has been scraped away which has exposed the clay deposit over a substantial part of the plot. Therefore the site has already been disturbed and due to the removal of topsoil it is less likely to be used for agriculture. However, the site is located just to the north of the Gbalahi village and with recent road development near Gbalahi, it is likely that the village will expand. The plot, which is owned by the Gbalahi Chief, offers significant area for expansion. Overall, the current land use at the Gbalahi Plot seems highly compatible with further development as a clay borrow source.

The Kpaumo Plot has been used to a lesser extent for gravel also. Some areas of the plot have been cut down by up to four feet and while other areas appear to be untouched. The plot is located within sight of a small village and in close proximity to several plots of land with new house construction. It is likely that the area will be built up in the near future. This could have implications for the suitability of the plot for development as a clay borrow source, as neighbouring plots may dispute the stripping of the soil. PHW currently leases the property and is using it only as a minor source of clay for their filter production. Overall, the current land use at the Kpaumo Plot seems reasonably compatible with further development as a clay borrow source.

The Wayemba Plot is currently a vacant lot and is surrounded by other vacant lots. A large warehouse was under construction in January 2014 across the highway, but development is sparse in the vicinity. As the site is located adjacent to the Tamale-Navrongo Highway, a major thoroughfare in the Northern Region, it offers potential as a future sales office or building site. Therefore the potential land use at the Wayemba site is considered incompatible with development as a clay borrow source.

The Gburma Plot was leased by PHW as an experimental tree farm to support fuel requirements for its filter production. The plot is vegetated with a variety of tree species, including 300 seedlings planted by PHW and its partner organization in 2013 with an additional 1,500 seedlings to be planted in the 2014 wet season. The intention of tree culture at the Gburma site offers low compatibility with future development as a clay borrow source.

The Taha Plot is the site of the PHW filter production plant. There are several large structures/buildings on the site and it is located adjacent to the Taha Village. The current land use and proximity to the village make the Taha Plot poorly compatible with future development as a clay borrow source.

7.3 Resource Reliability

PHW has access to the various plots described in this thesis, but the level of control that PHW has over these plots varies. Understanding the limitations at each plot is essential to minimize the vulnerability of PHW's brick production through stoppages or interruptions.

The Gbalahi Plot is owned by the Gbalahi Village Chief and is currently being used as a clay source for PHW's filter production through an agreement made with the Chief in 2009. PHW is permitted to extract the Gbalahi clay for filter production in exchange for employing villagers from the Gbalahi Village at the filter factory. It is in essence a tribal agreement, with no official documentation or obligation. PHW is therefore vulnerable to the goodwill and word of the village Chief to maintain access to the plot. In the past, misunderstandings between PHW and the Chief have resulted in limited access to the Gbalahi Plot or uncommunicated changes to clay extraction location. The potential for future misunderstandings or changes in relations represents a significant risk to PHW. The Gbalahi site is the main source of clay for filter production and from the findings of this thesis, is favourable for brick production. It would be to PHW's advantage to secure access to the Gbalahi site.

The Kpaumo and Taha sites have been leased for 99 years by PHW. To date, PHW has maintained control over the development and land use of the sites. It is anticipated that future development will not be exposed to significant risk as PHW controls the leases and maintains good relations with the surrounding communities.

The Gburma Plot has been leased for 99 years by PHW. To date, PHW has maintained control over the development of the site but any work completed at the site has been done in consultation with the Gburma Village Chief. The Chief has been very supportive of the proposed tree farm and seems to be receptive to any endeavor that brings employment to his villagers, however, the proximity of the site to the village and the Chief's involvement poses a minor risk to future development as a clay source for brick production.

The Wayemba Plot has been leased for 99 years by PHW. However, in January 2014, PHW learned of possible lease issues and land use limitations on this plot. The uncertainty involved with development at the Wayemba site poses a major risk for use as a clay source for brick production. It is anticipated that as a result of this uncertainty an alternate clay site will be provided by the Wayemba Chief.

7.4 Evaluation Matrix

The factors discussed above have been compiled into an evaluation matrix to understand the suitability of each plot for brick production development. Table 10 below provides an assessment of each plot and assigns numerical values to the assessments. A score of three was assigned for a favourable assessment; a score of two was assigned for a somewhat favourable assessment; and a score of one was assigned for an unfavourable assessment.

TABLE 10 - EVALUATION MATRIX OF PHW PLOTS

SITE	SOIL SUITABILITY	EASE OF BRICK PRODUCTION	APPROPRIATE LAND USE	RESOURCE SIZE	RESOURCE RELIABILITY	TOTAL SCORE	RANK
GBALAHI	3	3	3	3	1	13	1
KPAUMO	2	2	2	1	3	10	2
WAYEMBA	3	2	2	1	1	9	3
GBURMA	1	2	1	3	2	9	3
TAHA	1	2?	1	1	3	8	4
KEY: (1) UNFAVOURABLE (2) SOMEWHAT FAVOURABLE (3) FAVOURABLE							

As shown in Table 10, the Gbalahi Plot scores considerably higher than the other plots and appears to be the most suitable plot for development as a clay borrow source to support brick production. It should be noted that all factors were weighed equally and the score was calculated using the arithmetic sum of the scores in each category. It could be argued that some factors are more important than others and that these should be assigned weightings, but this is difficult to judge. Should PHW consider certain factors more important than others, weightings could be applied and the plots could be reevaluated. In addition, no pilot bricks were made from the Taha soil and therefore a score was estimated from the soil characterization and behavior of the other soils during brick production.

8.0 Best Practices Evaluation of Brick Technology

Although there are many potential benefits to establishing a brick production capacity in the Northern Region of Ghana including job creation, industry development, and production of locally-sourced construction material, there are also significant environmental and social concerns associated with brick production.

The firing process that imparts strength and durability to bricks is energy intensive and contributes to global greenhouse gas emissions. Furthermore, small-scale brick production in low income countries tends to be very labour intensive with significant drudgery for workers. These two issues will be examined in detail in the following sections.

8.1 Possible Improvements to Existing Brick Technology in Ghana

8.1.1 Kiln Technology

The five brick plants visited in Ghana use intermittent kiln technology with either clamp or downdraught kilns for brick production. Intermittent kilns are generally less energy-efficient because the fire is allowed to die out and the brick are cooled down after they are fired (Maithel and Uma, 2012). Therefore the heat generated during firing is lost after each batch of bricks is fired. By contrast, in continuous kilns the fire is always burning with bricks at various stages of the firing process. Heat in the flue gas is used to heat green bricks in preparation for firing at higher temperatures and the heat in recently fired bricks is used to heat air for combustion (Maithel and Uma, 2012).

Table 11 below presents a comparison of the energy requirements for different types of kilns. The clamp and batch kilns used in Ghana show the highest energy consumption of all kiln technologies. The specific energy consumption of these intermittent kilns is shown to be between two and six times higher than the continuous kiln technologies. The high energy requirements of intermittent kilns indicate that long-term adoption of this technology is not sustainable for potential brick production by PHW in northern Ghana. From an economic perspective, higher energy requirements require more money to be spent on fuel and from an environmental perspective, more fuel translates to increased deforestation in a country struggling with deforestation and increasing greenhouse gas emissions.

TABLE 11 - ENERGY REQUIREMENTS OF DIFFERENT KILN TECHNOLOGIES (HEIERLI, 2008)

Type of kiln	Specific Energy Consumption (MJ/kg of fired brick)	Specific coal consumption (tons/100,000 bricks)
VSBK (India, Nepal, Vietnam)	0.7-1.0	11-16
Fixed chimney BTK (India)	1.1-1.5	17.5-24
Moveable chimney BTK (India)	1.2-1.75	19-28
Tunnel kiln (Nam Dinh, Vietnam)	1.4-1.6	22-25
Modern tunnel kiln (Germany)	1.1-2.5	17.5-40
Clamp and other batch kilns (Asia)	2.0-4.5	32-71

A brief discussion on alternative kiln technologies is required to understand what potential exists for PHW's potential foray into brick making. Tunnel kilns are most commonly found in industrialized countries as they are highly mechanized and require a substantial capital investment. Tunnel kiln technology is not suitable for small- to medium-scale production and is generally used for operations that produce in excess of 10 million bricks per year (Heierli, 2008). Employment opportunities are significantly reduced with tunnel kilns due to their high level of mechanization (Heierli, 2008). Given that PHW brick production would be a small-scale operation aiming to provide employment for community members, tunnel kilns are not an appropriate technology.

The Bull's Trench Kiln (BTK) is a technology used in India that is suitable for medium-scale production (Heierli, 2008). It requires a significant amount of manual labour and offers poor environmental performance due to heavy air pollution and fugitive dust emissions (Heierli, 2008). The BTK appears to offer no advantage over the existing intermittent kilns currently used in Ghana.

The Vertical Shaft Brick Kiln (VSBK) is the most energy-efficient kiln presented in Table 11. In a VSBK, the bricks are moved vertically through a firing zone; above the firing zone the flue gases heat green bricks and below the firing zone, the heat from the fired bricks pre-heats air for combustion in the firing zone (see Figure 49). It is suitable for small-scale brick production and can be automated to reduce drudgery for workers. The VSBK also shows high environmental performance due to its energy-efficient design and low carbon dioxide, suspended particulate matter, and hydrogen fluoride emissions (Heierli, 2008). For the above reasons, the VSBK appears to offer a promising alternative to the intermittent kiln technologies currently being used in Ghana.

There are however, some distinct limitations to VSBK's. The short firing period of 24 hours requires that the green bricks withstand quick heating and cooling conditions. To achieve this, the type of soil suitable for VSBK brick production is more prescribed and requires a higher sand content, as seen in Table 12. Figure 50 shows the required grain size distribution in the form of a ternary diagram and presents different zones of suitability for brick making. The soils from the PHW plots plot in the area circled in purple, which indicates medium suitability for VSBK brick production. This suggests that the soils from the PHW plots could be suitable for brick production using the energy-efficient VSBK technology if sand were added to the soil to reduce the clay content.

TABLE 12 - SUGGESTED GRAIN SIZE DISTRIBUTION FOR VSBK TECHNOLOGY (MODIFIED FROM MUELLER, 2008)

Soil Type	Particle Size (mm)	Recommended Value (%)	PHW Soil Values (%) (Gbalahi and Wayemba)
Sand*	2 – 0.063	20 - 45	15 - 20
Silt*	0.063 – 0.002	25 – 45	35 - 45
Clay	<0.002	20 - 35	45 - 50

*Note: the particle size ranges presented in this table for sand and silt are different from the ranges used in the United Soil Classification System (see Table 1).

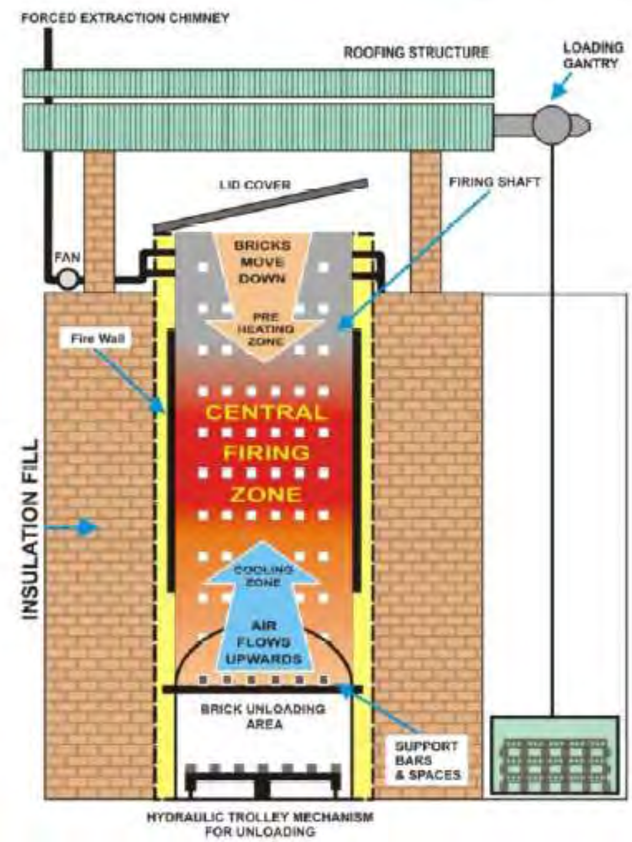

FIGURE 49 - SIDE VIEW OF THE VSBK (DE GIOVANETTI AND VOLDSTEEDT, 2013)

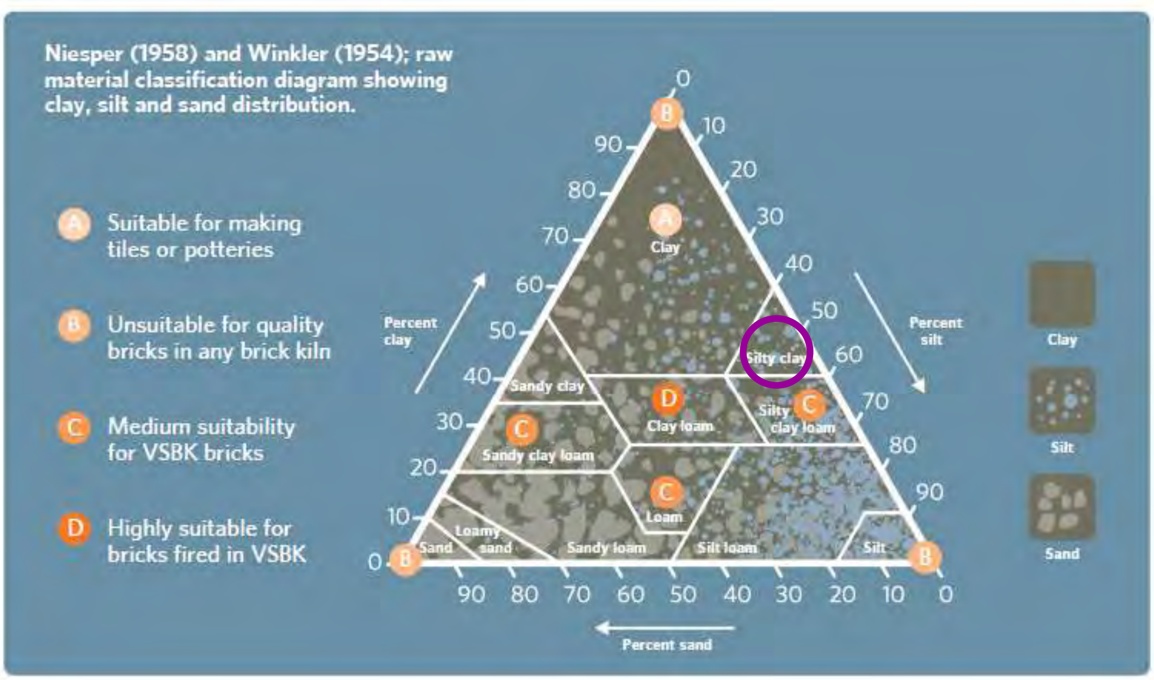

FIGURE 50 - TERNARY DIAGRAM SHOWING SUITABILITY OF SOILS FOR VSBK BRICK MAKING (MUELLER, 2008)

The VSBK also requires a higher level of commitment than intermittent kilns such as clamp kilns. A higher capital investment is required, land ownership or a long-term lease is imperative as the kiln cannot be moved easily, and 24-hour shifts are necessary due to continuous firing (Heierli, 2008). Furthermore, the VSBK tends to be less profitable than the less energy-efficient and more polluting intermittent kilns due to the higher level of commitment required (Heierli, 2008). Therefore, from the discussions above, VKSB technology may prove feasible in northern Ghana, but further investigation is recommended.

8.1.2 Fuel Source

A variety of fuel sources are used in brick production, including firewood, coal, natural gas, rice husk, or oil. In Ghana, the brick factories dominantly use firewood, with only one plant using a combination of firewood and residual oil. The burning of all of the fuel sources listed above will result in emissions of greenhouse gases; however some may be less environmentally harmful than others. It is recommended that an evaluation be conducted to determine the most appropriate fuel source for firing in Ghana.

The use of internal fuel within the bricks can improve brick quality, reduce particulate emissions, and decrease the amount of external fuel required (Heierli, 2008). Internal fuel sources such as powdered coal, boiler ash, rice husk, or saw dust can be used and are mixed in with the clay prior to moulding green bricks (Mueller, 2008). However, there are challenges associated with the use of internal fuel. The amount of internal fuel added must be appropriate, the internal fuel source and the clay soil must be mixed uniformly, and the firing process must be carefully controlled to ensure the quality of the produced bricks (Mueller, 2008).

8.1.3 Firing Temperature

The firing temperature has a marked effect on the quality and strength of produced bricks. As the bricks are fired to higher temperatures, the minerals within the soil undergo a series of physical and chemical reactions. As the firing temperature increases, the strength of bricks increases (Karaman et al., 2006). However due to concerns over greenhouse gas emissions and fossil fuel usage, there has been a recent wave of research examining the potential for lower temperature firing, including the use of additives or cementing agents. The effect of temperature was not the focus of this thesis but could be investigated further at PHW to reduce fuel requirements and emissions.

8.1.4 Brick Geometry

Hollow bricks offer another way to reduce the energy requirements of brick firing. Hollow bricks contain less clay material than solid bricks and therefore less energy is required to fire the bricks. They also offer increased shear resistance in buildings as mortar will partially fill the holes causing an interlocking effect to occur. Furthermore, hollow bricks increase the insulating properties of brick structures. For air conditioned structures, it is estimated that use of hollow bricks reduces energy requirements by 5% (Heierli, 2008). This may become more relevant in future decades as Ghana continues to develop and structures with air conditioning become more common. However, the orientation and percentage of voids should be considered as this can influence the compressive strength of the bricks. It is therefore recommended that PHW look into adopting hollow brick production to improve insulation against the heat while reducing fuel requirements during firing.

8.1.5 Occupational Health and Drudgery

In many low income countries, brick making is a labour-intensive industry which can expose workers to risk of injury. Several of the tasks are repetitive in nature and therefore repetitive strain injuries are possible. The clay-rich soil used for brick making is heavy and can be difficult to handle, exposing workers to the risk of back and other upper-body injuries. Respiratory health issues may also be a concern if dust is not controlled adequately. The situation is compounded by a scarcity of jobs in some communities which can result in workers accepting unsafe conditions to earn money for survival (Heierli, 2008).

The drudgery involved in brick making was observed first-hand at several of the existing brick factories in Ghana. At the borrow source, the clay-rich soil is extracted manually with shovels and pickaxes and loaded into trucks or wheelbarrows by hand. To prepare the soil for moulding, the soil is sometimes kneaded by foot to improve its consistency. At some factories the bricks are then hand moulded into green bricks using wooden moulds or if a mechanical extruder is used, the soil must be loaded by hand into the pug mill. Firemen can be exposed to heat, dust, and gases. Finally, the green bricks must be loaded into the kilns by hand and arranged carefully for firing and fired bricks must be unloaded.

Several of the tasks outlined in the above paragraph can be fully or partially mechanized to improve working conditions. The clay-rich soil can be extracted from the borrow source using an excavator or bulldozer; the soil can be mixed and kneaded using hammer mills and pug mills; the soil can be loaded into the mechanical extruder using a conveyor belt; mechanical extruders can be used instead of hand moulding; and certain kiln technologies use carts to load and unload bricks. However mechanization requires investment in equipment and facilities and would mean higher capital investment from PHW for brick production.

8.1.6 Community Considerations

The development of a brick production capability by PHW will have both positive and negative implications on the surrounding communities. Should the venture prove successful, there will be new and hopefully long-term jobs for community members and locally available construction materials. However there will also be increased traffic to the factory site and to the clay borrow source. Furthermore, the various communities may be affected in different ways. Certain communities closer to the factory may reap more benefits from spin-off business while others may feel slighted. Therefore it will be important for PHW to offer employment opportunities to all of the surrounding communities and to inform the communities as plans evolve to garner support.

9.0 Economic Assessment

The feasibility evaluation of brick production in northern Ghana requires examining the economics of brick production. The sections below present information gathered during the field visit in January 2014 through conversations with brick plant owners and other Ghanaians as well as personal observations from the field visit.

The scope of the feasibility evaluation originally included a detailed economic evaluation, but due to time limitations, the effort has been scaled back to a preliminary treatment of the subject.

9.1 Preliminary Cost Estimate

Table 13 below presents a preliminary cost breakdown for brick production. The estimate provides projected costs, revenue, and profit for average monthly production using existing infrastructure available at the PHW filter factory. All unit rates quoted are stated in Ghanaian Cedis and were obtained from conversations with the brick factory owners in southern Ghana.

Several assumptions were made with regards to the brick production:

- Clamp style intermittent kiln for initial production;
- Two firings a month with 20,000 bricks per firing (estimated full operating capacity);
- 80% of bricks fired can be sold (remaining 20% are under-fired, over-fired, or break);
- Semi-mechanical production (use of pug mill and mechanical extruder);
- Firewood used as fuel source (four truckloads of firewood per firing);
- Maintenance costs estimated at 10% of revenue;
- Monday to Friday operation with 20 workers (three foremen/kiln operators and 17 manual labourers);
- No seasonal variation (production is the same during dry and wet seasons); and
- Clay-rich soil is obtained at no cost.

TABLE 13 - MONTHLY CASH FLOW ESTIMATE

	Rate (Cedis)	Number of Days	Unit (Cedis/day)	Amount (Cedis)
Costs				
Labour - Foremen	15	22	3	990
Labour - General Workers	10	22	17	3,740
Food and Transportation	3	22	20	1,320
Kiln Fuel (Firewood)	--	--	--	4,000
Other Fuel	--	--	--	500
Water	--	--	--	100
Maintenance	--	--	--	1,920
Subtotal				12,570
Revenue				
Brick Sales	0.6	--	40,000	19,200
Profit				6,630

Table 13 shows that if full-scale brick production can be achieved, the venture will be profitable with an estimated 35% profit on generated monthly revenue at a production cost of 0.31 Cedis per brick. However, several of the provided assumptions are likely not realistic for brick production in northern Ghana. Firstly, the rainy season will likely affect brick production substantially. Access to the clay borrow pit will likely be much more difficult during the rainy season and the green bricks will take significantly longer to dry. Secondly, if a clamp kiln is used, firing will be affected as a clamp kiln is placed outdoors and is exposed to the elements. Thirdly, if full-scale brick production is achieved, the clay-rich soil will be required in large quantities and if the most promising source, the Gbalahi clay is used, it will likely no longer be available at no cost from the Gbalahi Village.

9.2 Capital Expenditures

The cost estimate presented above reflects a monthly operating budget utilizing the existing intermittent clamp kiln technology available in Ghana. However, as discussed in Section 8.0, mechanization can be added to the production system to reduce the drudgery involved with brick production and improve workings conditions. This requires capital investment which can be done in stages to ease the financial burden. Table 14 below presents a list of mechanical devices, an estimated cost (if available), a priority assessment, and comments on why the equipment is recommended.

TABLE 14 - POSSIBLE CAPITAL INVESTMENTS TO IMPROVE PRODUCTION AND WORKING CONDITIONS

Item	Estimated Cost (Cedis)	Priority Level	Comments
Tractor Motor (Used)	3,000	1	Used to power the pug mill/soil mixer
Mechanical Extruder	N/A	1	Used to form bricks and attached directly to the pug mill/soil mixer
Tractor Motor (Used)	3,000	1	Used to power the pug mill/soil mixer
Pug mill/soil mixer	N/A	1	Used to mix the soil before moulding
Hammer Mill	N/A	1	Used to break down the soil before mixing and moulding
Small Excavator	35,000	2	Used to excavate soil from the borrow source and load the soil into a truck for transportation
Downdraught Kiln	15,000	2	Intermittent kiln that offers improved brick quality over the clamp system
Conveyor System	N/A	2	Moves soil mechanically into the pugmill/hammer mill

9.3 Discussion

While visiting the brick factories, several anecdotal pieces of information were divulged that may affect the feasibility of brick production in northern Ghana. These comments and observations are presented below for consideration but the accuracy and validity of all the statements have not been verified.

Both Mr. Osei-Bonsu and Mr. Akwasosem stated that the brick business is a very challenging business. It is very difficult for them to produce bricks continuously due to cash flow limitations as money is required upfront to pay workers while the bricks can only be sold at the end of a multi-week production process. However, the demand for the product exceeds their capacity to produce bricks; this is particularly promising in Tamale, the fastest growing city in West Africa (McConnell, 2010).

The factory owners also mentioned the decline of the brick industry in Ghana. It appears that in recent years, the number of brick plants in the southern part of the country has been decreasing. The brick plant owners attribute the decline to a lack of support for small-business owners by financial institutions and by the government. They stated that it is extremely difficult to generate working capital in Ghana and that corruption permeates financial and government institutions. As outlined in Section 4.3, the difficulties small-business owners experience in generating working capital is partially related to the financing system set up in Ghana but also partially related to poor book-keeping and a lack of robust business planning by business owners (Omidyar Network, 2013). There is also a suspicion that the cement industry in Ghana is supported by the government. The main source of construction material currently in Ghana is concrete block (a mix of soil and cement) and the largest manufacturer of cement in Ghana was founded by the Government of Ghana in partnership with a Norwegian company (Ghacem, 2014). Therefore there may be some truth to the suspicion.

Daniel Osei-Bonsu and Obeng Akwasosem both also alluded to the fact that bricks are not the obvious choice for most Ghanaians, even in the southern part of the country where the factories exist. Mr. Osei-Bonsu has a plan to actively market his product and Mr. Akwasosem educates his customers regularly on the merits and advantages of bricks over concrete blocks. To establish a solid client-base in the north, marketing, public outreach, and consumer education will be extremely important and it could take some time for the business to become strongly established with a regular stream of customers.

Despite statements by Mr. Osei-Bonsu and Mr. Akwasosem that they employ between 20 and 25 people full-time, fewer workers were noted. Both plants were visited on a weekday in good weather. At the Osei-Bonsu Factory, approximately 15 people were working and at the Obeng 2 Factory, less than five people were working due to a mechanical breakdown of the main truck used for transporting soil. These observations suggest that work is not truly full-time for the employees, but is rather dependent on the status of the equipment, the weather, and production demands. This is important for PHW to be aware of so that employee expectations can be managed as well as staff resource planning.

9.4 Economic Evaluation Conclusions

Given the preliminary economic assessment presented above, it appears that brick production is profitable but may be influenced by a number of seasonal and cultural factors that add risk to the business. It is concluded that PHW should be cautiously optimistic about pursuing brick production as a means to support their goal of becoming financially self-sustaining. Further economic evaluation is recommended to determine how different rates of brick production will influence the profitability of the business and how the capital expenditures will affect cash flows. Lastly, some of the unit rate assumptions were taken from brick production in the southern part of the country; unit rates in the north should be verified.

10.0 Conclusions

10.1 Technical Recommendation

The work presented in this thesis concludes that in the short-term, brick production using the standard technologies currently available in Ghana is technically feasible and will likely provide revenue to support PHW's goal of becoming locally and financially self-sustaining.

In particular, the Gbalahi Plot appears to be most suitable as a clay borrow source given the properties of the soil and the amount of material available. It is recommended that PHW secure access to the Gbalahi clay deposit to reduce their level of risk should brick production be undertaken.

Given the existing infrastructure available at the PHW filter factory and the rapid growth of Tamale and environs, PHW is well-poised to commence brick production using standard intermittent kiln technology with only minimal capital investment. However, for long-term environmental sustainability and workplace safety, alternative continuous kiln technologies should be considered to minimize energy requirements, emissions, and worker drudgery. In particular, the VSBK technology should be evaluated as a promising alternative kiln technology; however there are limitations to the VSBK technology which should be examined further.

The preliminary economic assessment concludes that brick production is profitable but not extremely lucrative. Furthermore, substantial risks are inherent in the brick industry, including high working capital requirements, increased processing requirements of the source soil due to a lower moisture content than the soils in southern Ghana, substantially reduced production rates during the wet season, and a lack of local familiarity and demand for brick products.

10.1 Future Work Needed

Given the breadth of topics covered in this thesis, several areas of more detailed investigation are recommended. In particular, further work into best practices for brick production and a more thorough economic evaluation are required.

To establish sustainable long-term brick production, further research on energy-efficient kiln technologies and alternative fuels should be completed. Given PHW's involvement in sanitation work, possible synergies between both human and municipal waste treatment and fuel technology could be investigated. Work should also be undertaken to examine the effect of firing temperature on brick performance and strength to optimize firing conditions.

Additional economic analyses should be completed to evaluate the cash flow implications of seasonal variation in brick production, different fuel sources, alternate kiln technologies, and staged capital investment. Further research into the reported decline of the southern Ghana brick industry is also highly recommended to minimize the risks associated with undertaking brick production in northern Ghana.

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APPENDIX A

Summary of Descriptors Used in Test Pit Logs

Nomenclature Used to Separate Grain-Size Fractions [1]

Grain Size Diameter	Particle Name
<0.002 mm	Clay
0.002 – 0.075 mm	Silt
0.075 – 0.425 mm	Sand (fine)
0.425 – 2 mm	Sand (medium)
2 – 4.75 mm	Sand (coarse)
4.75 – 19 mm	Gravel (fine)
19 – 75 mm	Gravel (coarse)
75 – 300 mm	Cobbles
>300 mm	Boulders

Nomenclature Used to Classify Soil by Grain-Size Fractions [1]

Percent by Weight	Modifier	Example
>50% and main fraction	Noun	gravel, sand, silt, clay
35% – 50%	"and"	and gravel, and silt, etc.
20% – 35%	"y/ey"	gravelly, sandy, silty, clayey, etc.
10% – 20%	"some"	some sand, some silt, etc.
0% – 10%	"trace"	trace sand, trace silt, etc.

Nomenclature Used to Classify Degree of Plasticity as Determined by Limits Testing or Through Field Approximation [1,3]

Relative Value of W_L, Liquid Limit	Modifier
$W_L < 50\%$	Low Plastic
$W_L > 50\%$	High Plastic

Where W_L is the Liquid Limit

Relative Density of Cohesionless Soils [2,3]

Description	Field Identification
Very Loose	Easily penetrated with shovel handle.
Loose	Easily penetrated with 12 mm rebar pushed by hand. Easily excavated with hand shovel.
Compact	Easily penetrated with 12 mm rebar with 2.5 kg hammer. Difficult to excavate with hand shovel.
Dense	Penetrated 30 cm with driven rebar. Must be loosened with pick to excavate.
Very Dense	Penetrated only a few inches with driven rebar. Very difficult to excavate even with pick.

Consistency of Cohesive Soils [2,3.4]

Approximate Undrained Shear Strength (kPa)	Description	Field Identification
<12	Very Soft	Easily penetrated several centimeters by the fist.
12 – 25	Soft	Easily penetrated several centimeters by the thumb.
25 – 50	Firm	Can be penetrated by the thumb with moderate effort.
50 – 100	Stiff	Readily indented by the thumb but penetrated only with great effort.
100 – 200	Very Stiff	Readily indented by the thumbnail.
Over 200	Hard	Indented with difficulty by the thumbnail.

Hardness of Rocks [2,4]

Approximate Unconfined Compressive Strength (MPa)	Description	Field Identification
0.25 – 1	Extremely Weak	Indented by the thumbnail.
1 – 5	Very Weak	Crumbles under firm blows with point of geological hammer, can be peeled by pocket knife.
5 – 25	Weak	Can be peeled by a pocket knife with difficulty, shallow indentations made by firm blow with point of geological hammer.
25 – 50	Medium Strong	Cannot be scraped or peeled with a pocket knife, specimen can be fractured with single firm blow of geological hammer.
50 – 100	Strong	Specimen requires more than one blow of geological hammer to fracture it.
100 – 250	Very Strong	Specimen requires many blows of geological hammer to fracture it.
Over 250	Extremely Strong	Specimen can only be chipped with geological hammer.

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APPENDIX B

LOCATION: GBALAHI PLOT

COORDINATES: N: 9'26'23.82 W: 0'46'12.56

HOLE ID: TP-PHW14-001

LOGGED BY: CAROLINE BATES

DATE: JANUARY 9, 2014

GRAVEL (GW)
Fine to medium, sandy to some sand, trace to some silt, trace clay, well graded, hard, maximum particle size is 15 mm, equant, rounded to subangular, greyish brown clasts within an orangish brown matrix of fines, no odour, dry, strong cementation, very hard digging.
[GRAVEL DEPOSIT]

0.5 FT

CLAY (CL)
Silty to some silt, trace sand, low plastic, very stiff to hard, orangish brown and grey mottled, no odour, dry (trace moisture), no discernable structure, moderate to strong cementation, high dry strength, slow dilatancy, with hand pressure soil works to clumps, with work clumps work to clay.
[CLAY DEPOSIT]

From 2 ft; moist, very stiff, dark reddish brown, moderate cementation.

From 3.3 ft; clay appears to be foliated or bedded with undulating layers, muscovite mica present on some planes, material is harder to work, clumps are strongly cemented and do not break apart easily (would require pounding), zones of whitish/yellowish grey that are sandy silt (less weathered zones).

4.3 FT

END OF TEST HOLE AT 4.3 FT
POTENTIALLY USABLE ZONE: 0.5 – 2.0 FT

LOCATION: GBALAHI PLOT

COORDINATES: N: 9'26'24.99 W: 0'46'11.92

HOLE ID: TP-PHW14-002

LOGGED BY: CAROLINE BATES

DATE: JANUARY 9, 2014

0

GRAVEL (GW)

Fine to medium, sandy to some sand, trace to some silt, trace clay, well graded, very dense, maximum particle size is 15 mm, equant, rounded to subangular, greyish brown clasts within an orangish brown matrix of fines, no odour, dry, strong cementation.

[GRAVEL DEPOSIT]

0.25 FT

1

CLAY (CL)

Silty to some silt, trace sand, trace fine gravel, low plastic, very stiff to hard, orangish brown and grey mottled, no odour, dry (trace moisture), no discernable structure, moderate to strong cementation, high dry strength, slow dilatancy, lots of clumps in soil that are very difficult to break down with hand pressure.

[CLAY DEPOSIT]

1.5 FT

2

G1

GRAVEL (GP)

Coarse to fine, some clay, trace to some sand, trace silt, gap graded, very dense soil to very weak rock, maximum particle size is 100 mm, flat, elongated, subangular, orangish brown with layers of grey, no odour, dry, sub-horizontal laminations, strong cementation, material breaks down to clay with substantial effort, gravel present as corestones, extremely weak to very weak, yellowish grey, 40% rock, lenses of sandy material present.

[HIGHLY WEATHERED ROCK]

3

4

4.5 FT

END OF TEST HOLE AT 4.3 FT

POTENTIALLY USABLE ZONE: 0.25 – 1.5 FT

5

NOTES:

1) Hole ended due to difficult digging in unsuitable material.

2) Hole located approximately 150 ft northeast of TP-PHW14-001.

LOCATION: GBALAHI PLOT

COORDINATES: N: 9'26'24.85 W: 0'46'08.29

HOLE ID: TP-PHW14-003

LOGGED BY: CAROLINE BATES

DATE: JANUARY 10, 2014

0

GRAVEL (GW)

Fine to medium, sandy to some sand, trace to some silt, trace clay, well graded, very dense, maximum particle size is 15 mm, equant, rounded to subangular, greyish brown clasts within an orangish brown matrix of fines, no odour, dry, strong cementation.

[GRAVEL DEPOSIT]

0.8 FT

1 G1

CLAY (CH)

Some silt, trace sand, high plastic, very stiff to hard, grey with orangish brown mottling, no odour, moist to dry, no discernable structure, moderate to strong cementation, very high dry strength, slow dilatancy, medium effort required to work clay.

[CLAY DEPOSIT]

G2

2

At 1.75 ft; clay is darker brown with grey mottling, stiff to very stiff, moist, good clay for moulding, moderate cementation.

At 2.5 ft; clay is grey and brown mottled, slightly lumpier and takes more effort to work.

3

3.25 FT

GRAVEL (GP)

Coarse to fine, clayey, trace to some sand, trace silt, gap graded, hard soil to extremely weak rock, flat, elongated, subangular, orangish brown with layers of grey, no odour, dry to moist, mm-scale sub-horizontal laminations, strong cementation, some soil breaks down to clay with substantial effort, gravel present as corestones, extremely weak.

4

[HIGHLY WEATHERED ROCK]

5.0 FT

5

END OF TEST HOLE AT 5.0 FT

POTENTIALLY USABLE ZONE: 0.8 – 3.25 FT

NOTES:

1) Hole ended due to difficult digging in unsuitable material.

2) Hole located approximately 600 ft east of TP-PHW14-002 adjacent to a dug-out clay depression.

LOCATION: KPAUMO PLOT

COORDINATES: N: 9'26'39.50 W: 0'47'23.55

HOLE ID: TP-PHW14-004

LOGGED BY: CAROLINE BATES

DATE: JANUARY 10, 2014

0

GRAVEL (GW)
Fine to medium, sandy to some sand, trace to some silt, trace clay, well graded, very dense, maximum particle size is 15 mm, equant, rounded to subrounded, greyish brown clasts within an orangish brown matrix of fines, no odour, dry, strong cementation.
[GRAVEL DEPOSIT]

0.8 FT

1

CLAY (CH)

G1

Trace to some silt, trace to some sand, trace fine to medium gravel, high plastic, stiff to very stiff with hard soil to extremely weak gravel concretions, greenish grey with reddish brown and orangish brown mottles, no odour, moist, moderate cementation, very high dry strength, no dilatancy, significant effort required to work clumps and break down material for testing.
[CLAY DEPOSIT]

2

G2

From 1.5 ft; stiff, greenish grey soil with cm-scale, round, dark brown concretions present that are extremely weak rock to hard soil.

3.0 FT

3

G3

From 3.0 to 4.5 ft; cm-scale banding of greenish grey and dark redish brown material, hard soili to extremely weak rock with stiff grey clay zones, soil is difficult to work to soil, some rocky clumps up to 10 cm in length that do not break down (likely not suitable for clay brick making), material shows very thin laminations (possible foliation, bedding planes, or platy clay nature).

4

G4

4.5 FT

END OF TEST HOLE AT 4.5 FT

POTENTIALLY USABLE ZONE: 0.8 – 3.0 FT

5

NOTES:
1) Hole ended due to hard digging in unsuitable material.
2) Hole located in a previously used gravel borrow area. Natural grade is approximately 4 ft. above top of hole.

LOCATION: KPAUMO PLOT

COORDINATES: N: 9'26'40.22 W: 0'47'21.77

HOLE ID: TP-PHW14-005

LOGGED BY: CAROLINE BATES

DATE: JANUARY 12, 2014

0

GRAVEL (GW)

Fine to medium, some sand, some clay, trace silt, well graded, very dense, maximum particle size is 30 mm, flat and elongated to equant, subrounded to subangular, greyish brown clasts within an orangish brown matrix of fines, no odour, dry, no structure, weak to moderate cementation, subrounded gravel from 0 to 0.8 ft, more angular from 0.8 to 1.5 ft.

[GRAVEL DEPOSIT]

1

1.5 FT

G1

CLAY (CH)

2

Some silt, trace sand, trace fine gravel, high plastic, stiff to very stiff, greenish grey with orangish brown mottling, no odour, dry to moist (dries very quickly with exposure to air), no structure, weak to moderate cementation, very high dry strength, no dilatancy, soil works relatively easily.

[CLAY DEPOSIT]

From 3.0 to 3.5 ft; lenses of harder dark brown material (5-10% rock), can work to soil.

3

3.5 FT

From 3.5 to 4.0 ft; dark brown, extremely weak rock pieces/lenses present, material is more difficult to dig, more difficult to work (20-30% rock), mica present along planes, laminations present in dark brown rocky pieces, cm-scale layers of dark brown and greenish grey material.

G2

4

4.0 FT

END OF TEST HOLE AT 4.0 FT

POTENTIALLY USABLE ZONE: 1.5 – 3.25 FT

5

NOTES:

1) Hole ended due to hard digging in unsuitable material.

2) Hole located near access road.

3) Material from clay unit (1.5 to 3.5 ft) used for trial brick making.

LOCATION: WAYEMBA PLOT

COORDINATES: N: 9'30'24.48 W: 0'50'37.43

HOLE ID: TP-PHW14-006

LOGGED BY: CAROLINE BATES

DATE: JANUARY 13, 2014

0

SILT (ML)

Trace to some sand, trace clay, low plastic, hard, light orangish brown, no odour, dry, no structure but soil is porous with mm-scale voids (compressible?), moderate to strong cementation, slow dilatancy. [LOAM]

From 0.25 to 0.5 ft; in south-western part of test pit, seam of gravel (GW), fine to medium, some silt, some clay.

1

G1

1.25 FT

G2

CLAY (CL)

Some silt, trace sand, trace fine gravel, low plastic, hard, light reddish/orangish brown, no odour, dry, no structure, porous, strong cementation, very high dry strength, no dilatancy, material contains clumps that are extremely difficult to break down by hand (very dry and hard).

2

[CLAY DEPOSIT]

3.0 FT

3

From 3.0 ft; darker brown, gravelly to some gravel, fine to medium gravel, clasts are rounded to subangular, various colours, including red, orange, black, and orangish beige, likely an alluvial deposit, moist.

G3

4

At 4.0 ft; chunks of rock observed in south side of pit, dark pinkish/purplish red, sandstone, mica present, breaks along parallel planes, very weak to weak, faint laminations parallel to jointing, 5-10% rock, likely near bedrock surface.

G4

From 4.0 to 5.0 ft; material contains less gravel (trace gravel) and is easier to work (less clumps).

5.0 FT

5

END OF TEST HOLE AT 5.0 FT

NO USABLE MATERIAL

NOTES:

1) Hole ended due to hard digging in rocky material.
2) Hole located in northwest corner of PHW plot of land, 50-65 ft south and 10 ft east of NW stake.
3) Land has recently been burned with black grasses across plot. Burning may have caused soil to be excessively dry (beyond natural state).

LOCATION: WAYEMBA PLOT

COORDINATES: N: 9'30'22.63 W: 0'50'38.57

HOLE ID: TP-PHW14-007

LOGGED BY: CAROLINE BATES

DATE: JANUARY 13, 2014

0

CLAY (CL)
Silty, some to trace sand, low plastic, stiff to very stiff, light orangish brown, no odour, dry, no structure, moderate cementation, very high dry strength, slow dilatancy, trace rootlets present.
[TOPSOIL/LOAM]

0.5 FT

1

CLAY and SILT (CL/ML)
Some to trace fine sand, trace fine gravel (subrounded to rounded), low plastic, stiff to very stiff, light orangish/greyish brown, no odour, moist, no structure, weak cementation, very high dry strength, slow dilatancy, homogeneous material, very easy to work, rootlets present.
[SILTY DEPOSIT]

G1

2

2.5 FT

CLAY (CH)

G2

3

Some silt, trace fine to coarse sand, high plastic, mottled grey and brownish orange, no odour, moist, no structure, weak to moderate cementation, very high dry strength, no dilatancy, material forms clumps when wetted but are broken down with relative ease, promising brick material, trace rootlets present.
[CLAY DEPOSIT]

From 3.5 to 4.0 ft; gravel seam, some fine gravel to gravelly, some medium to coarse sand, poor material for bricks.

4

From 4.5 to 5.0 ft; material contains more gravel and rock pieces.

G3

END OF TEST HOLE AT 5.0 FT

POTENTIALLY USABLE ZONE FROM 2.5 – 3.5 FT and 4.0 – 4.5 FT

5.0 FT

5

NOTES:

1) Hole ended due to hard digging in rocky material (reddish pink sandstone).
2) Hole is located in southeast corner of PHW plot.
3) Land has recently been burned with black grasses across plot. Burning may have caused soil to be excessively dry (beyond natural state).
4) Two bulk samples taken for trial brick making: 1.0 to 2.0 ft and 2.5 to 3.5 ft.

LOCATION: GBURMA PLOT

COORDINATES: N: 9'28'40.51 W: 0'45'37.81

HOLE ID: TP-PHW14-008

LOGGED BY: CAROLINE BATES

DATE: JANUARY 14, 2014

0

SILT (ML)

Sandy, trace to some clay, low plastic, very stiff, brownish grey when dry, orangish brown when wet, slight organic odour, dry, no structure, moderated cementation, high dry strength, rapid dilatancy, mm to cm-scale voids (very porous), rootlets present.

[LOAM]

0.5 FT

1

G1

CLAY (CL)

Sandy, some silt to silty, trace fine gravel, low plastic, very stiff to hard, light orangish/greyish brown when dry, orangish brown when wet, slight organic odour, dry, no structure, moderate to strong cementation, very high dry strength, slow to no dilatancy, mm-scale voids (porous), rootlets present, material is relatively easy to work.

[CLAY DEPOSIT]

2

3

G2

3.75 FT

4

CLAY (CL)

And gravel, some sand, some silt, low plastic, hard, orangish brown when moist, no odour, moist (dries very quickly), no structure, strong cementation, very high dry strength, slow dilatancy, rootlets present, trace to no voids, material forms clumps that are extremely difficult to work and do not break down, material behaves like fine to coarse gravel when excavated and wetted (extremely hard to break down).

G3

5.0 FT

5

END OF TEST HOLE AT 5.0 FT

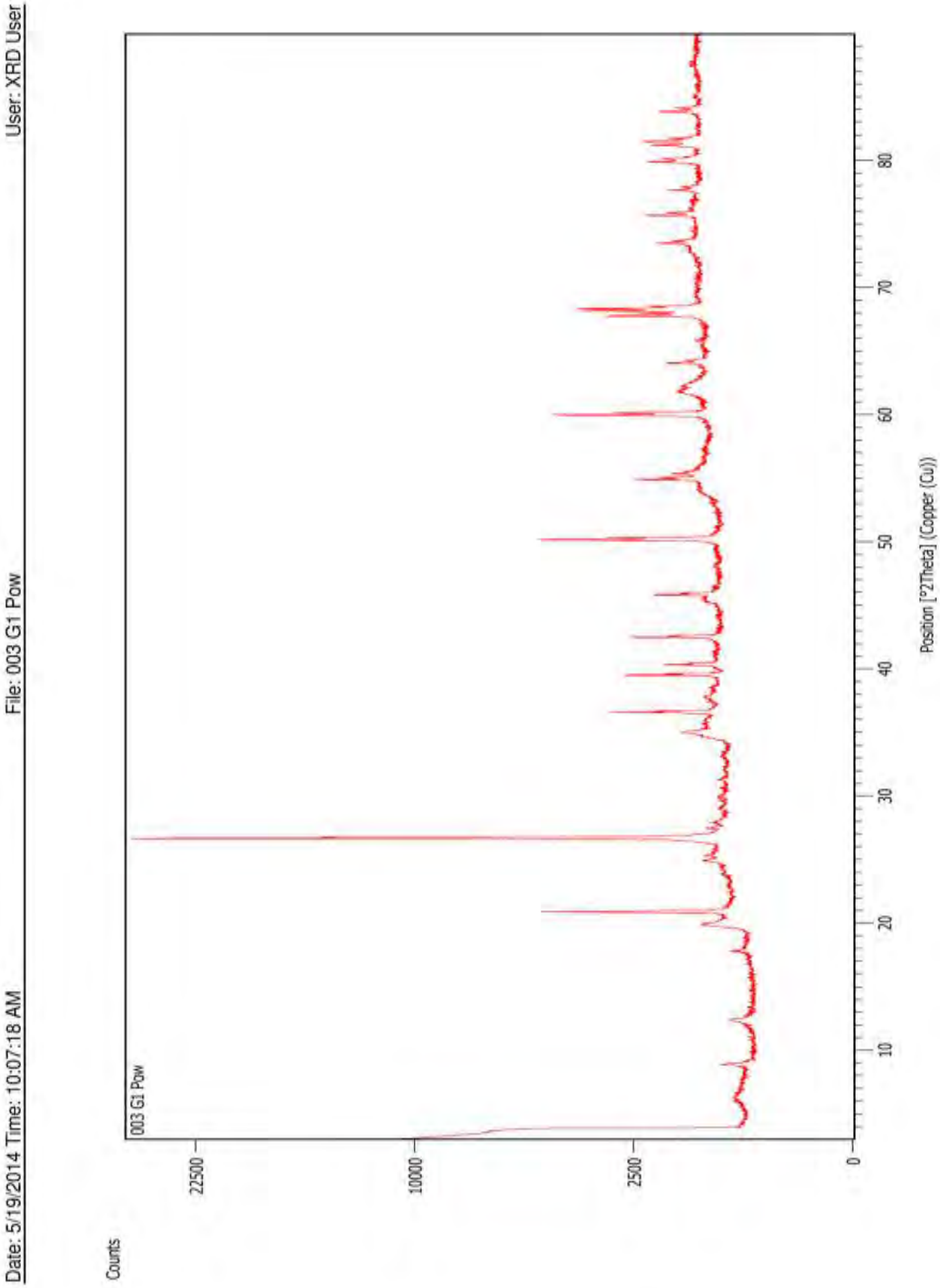
POTENTIALLY USABLE ZONE FROM 0.5 – 3.75 FT

NOTES:

1) Hole ended due to difficult digging in unsuitable material.
2) Hole is located within view of the road (close to the front of the property).
3) Bulk sample taken for trial brick making: 0.5 to 3.75 ft.

APPENDIX C

TP-PHW14-003 G1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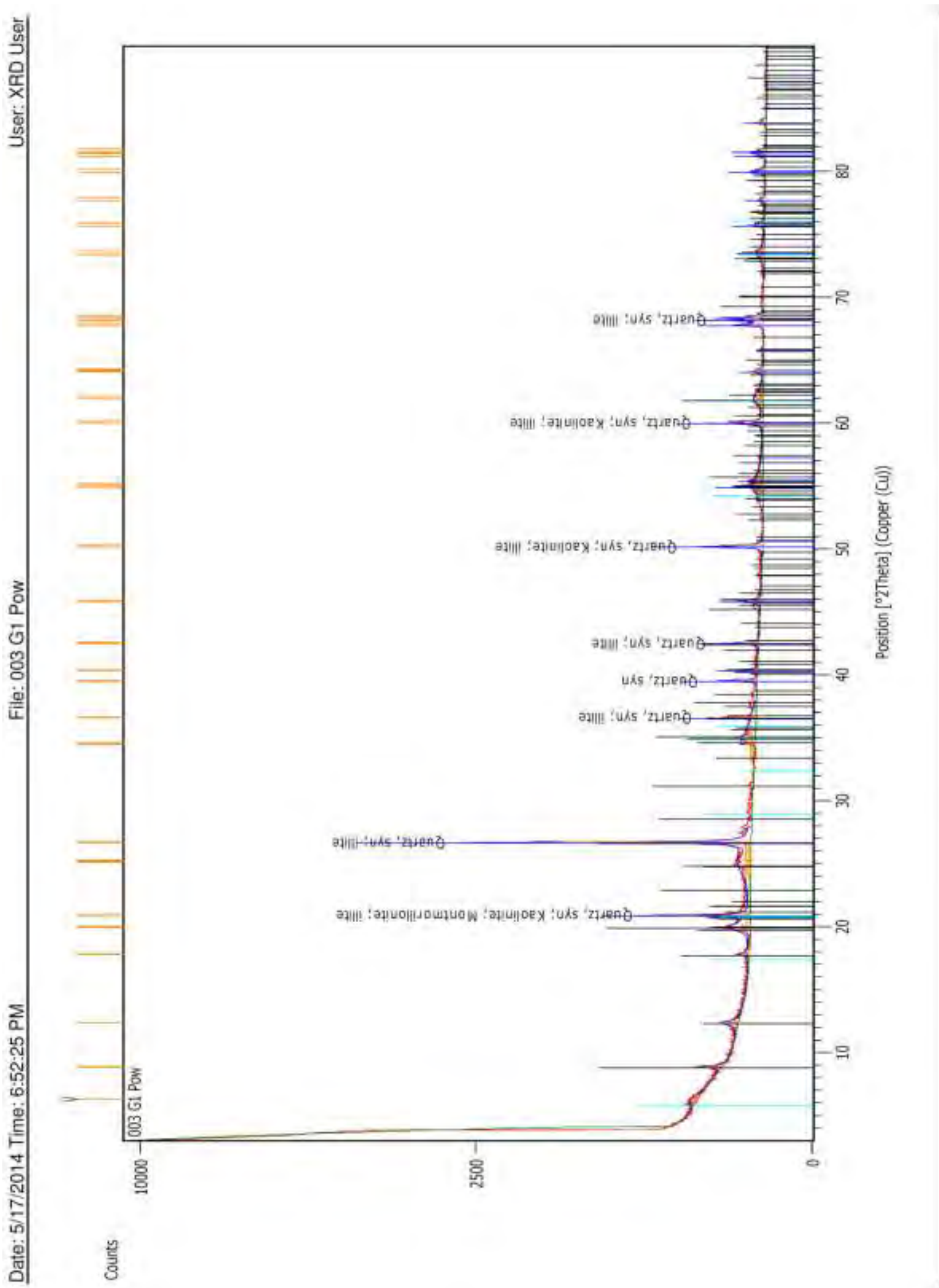
40
50
60
70
80
Position [°2Theta] (Copper (Cu))



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Quartz, syn; illite
Quartz, syn; illite
Quartz, syn
Quartz, syn; illite
Quartz, syn; Kaolinite; illite
Quartz, syn; Kaolinite; illite
Quartz, syn; illite
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30
40
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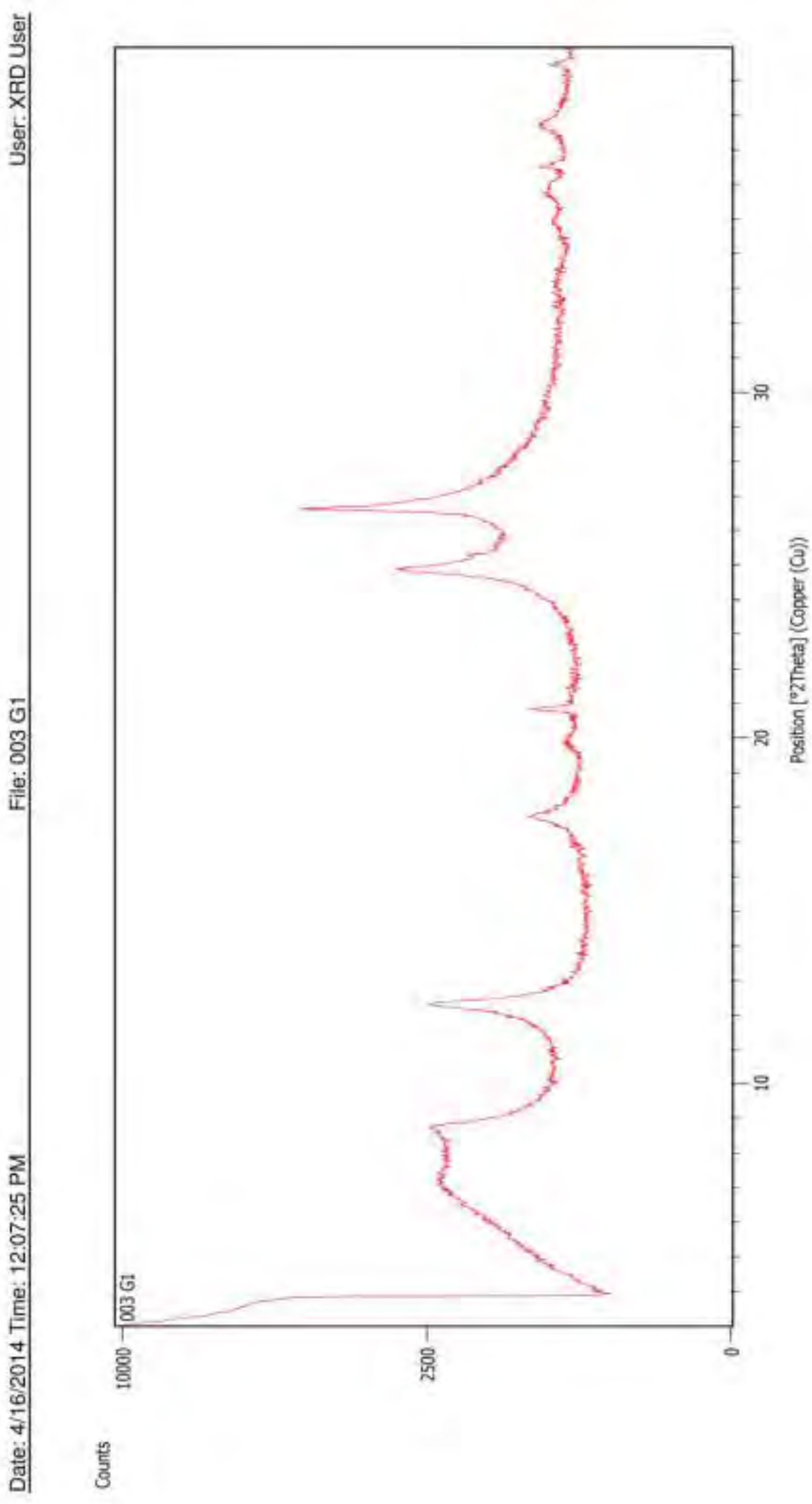
60
70
80
Position [°2Theta] (Copper (Cu))



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003 G1
10
20
30
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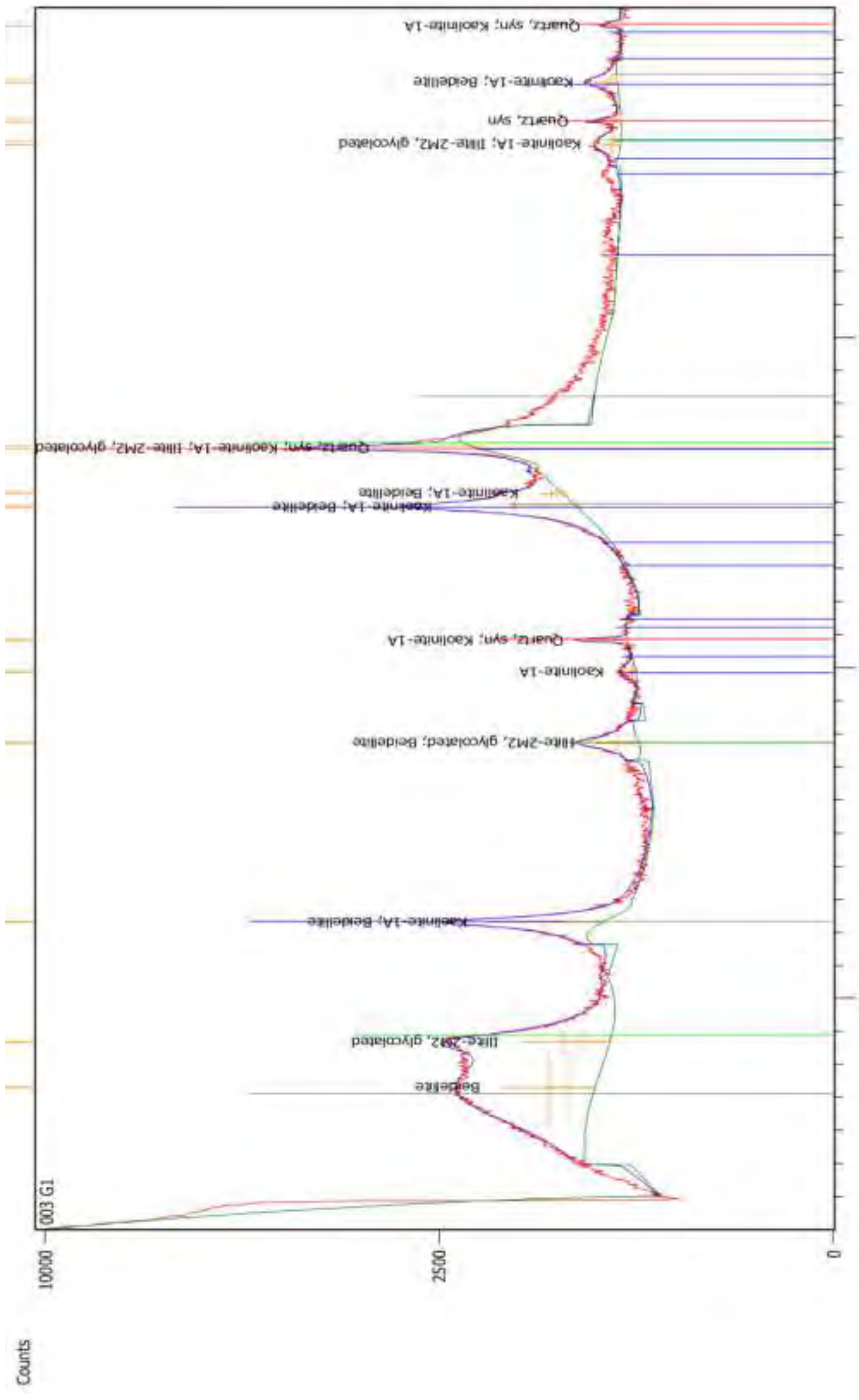
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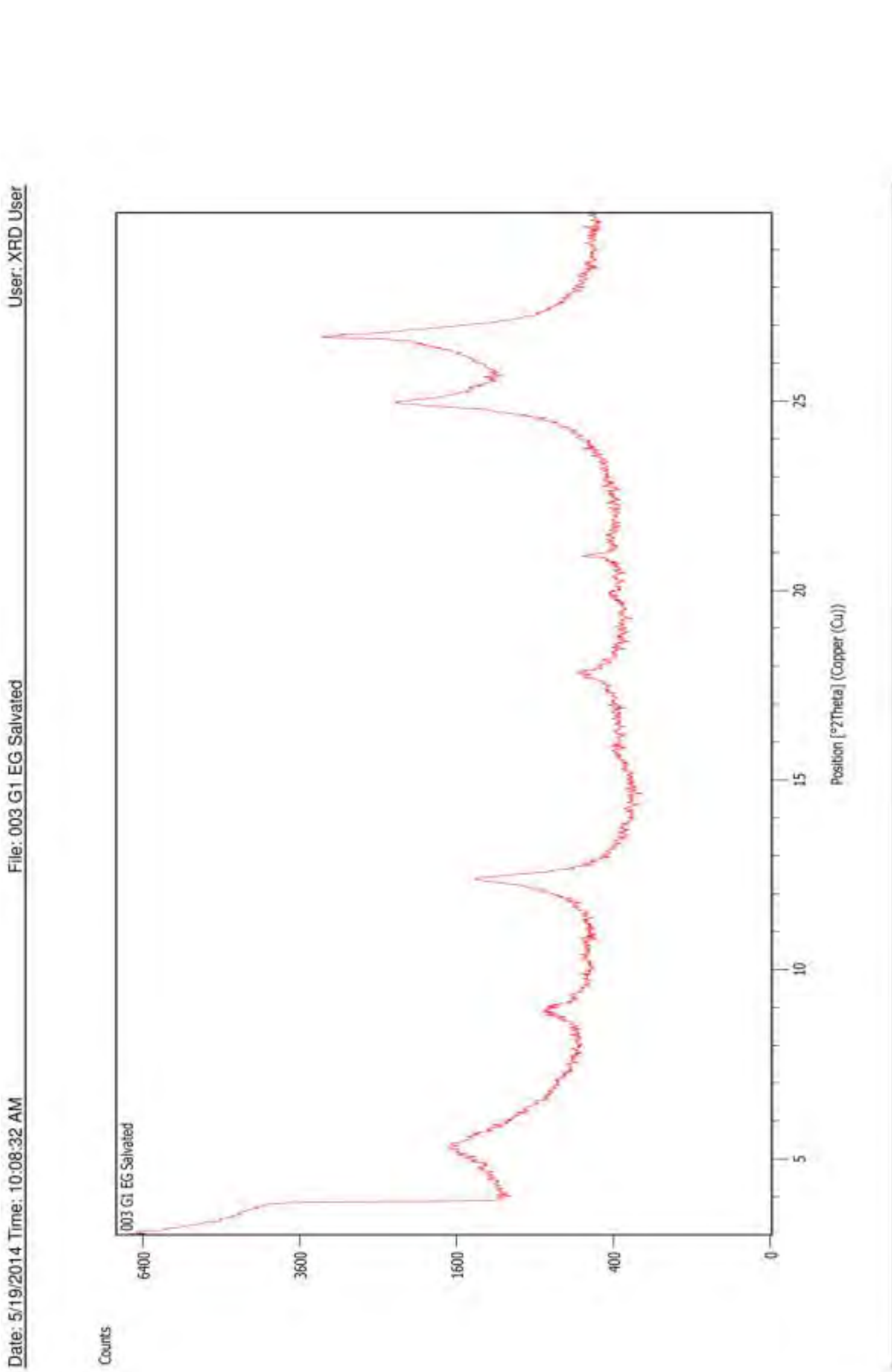
2500
0
10
20
30
003 G1
Beidellite
Illite-2M2, glycolated
Kaolinite-1A; Beidellite
Illite-2M2, glycolated; Beidellite
Kaolinite-1A
Quartz, syn; Kaolinite-1A
Kaolinite-1A; Beidellite
Kaolinite-1A; Beidellite
Quartz, syn; Kaolinite-1A; Illite-2M2, glycolated
Kaolinite-1A; Illite-2M2, glycolated
Quartz, syn
Kaolinite-1A; Beidellite
Quartz, syn; Kaolinite-1A



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25
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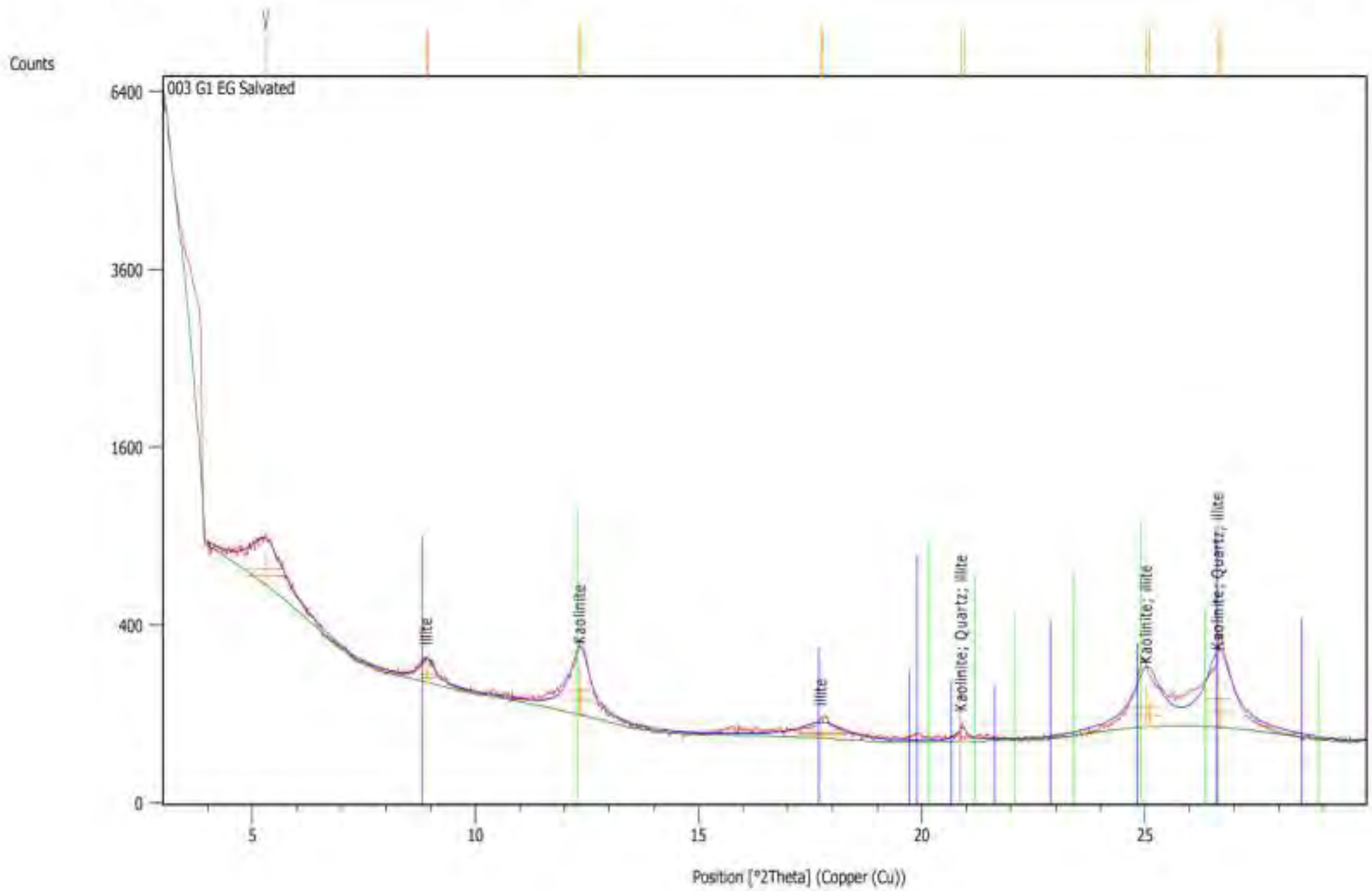
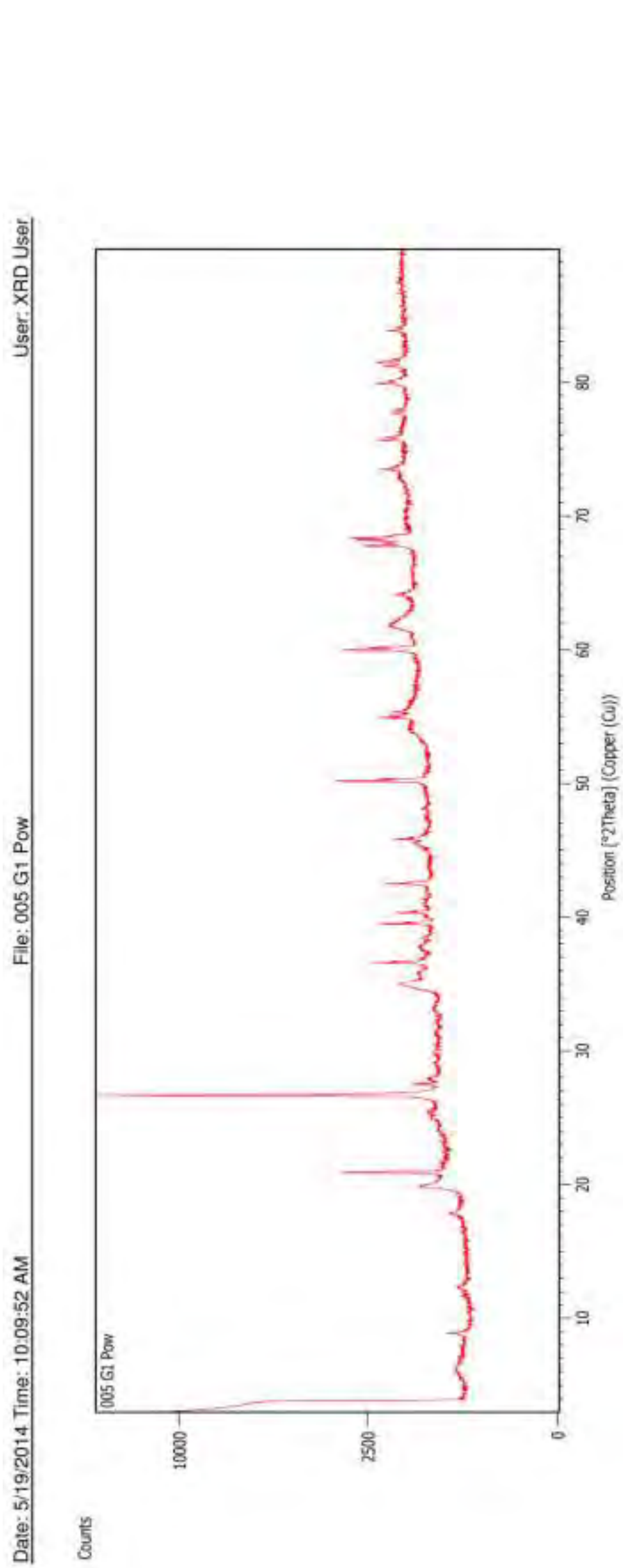


TP-PHW14-005 G2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005 G1 Pow
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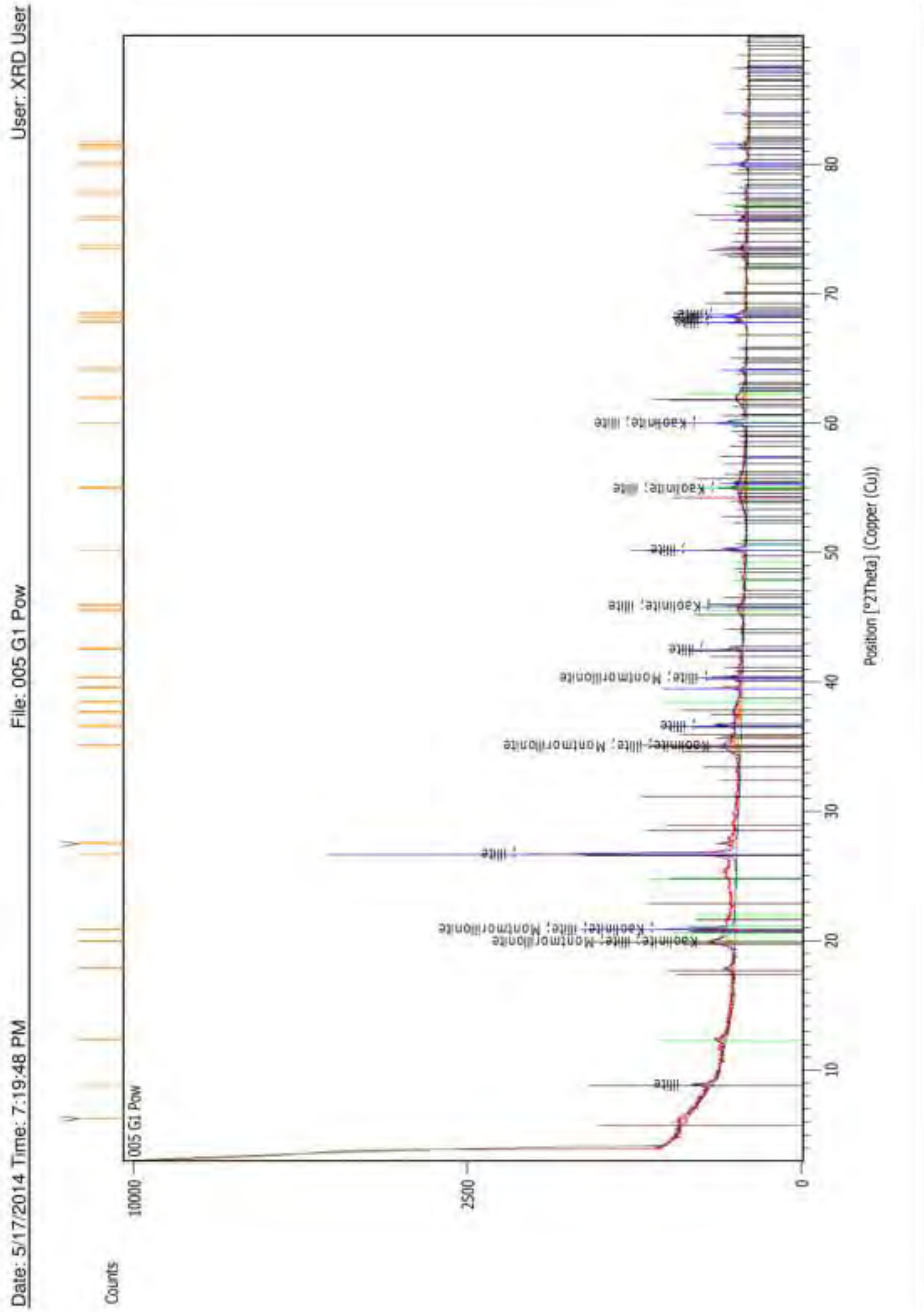
30
40
50
60
70
80
Position [°2Theta] (Copper (Cu))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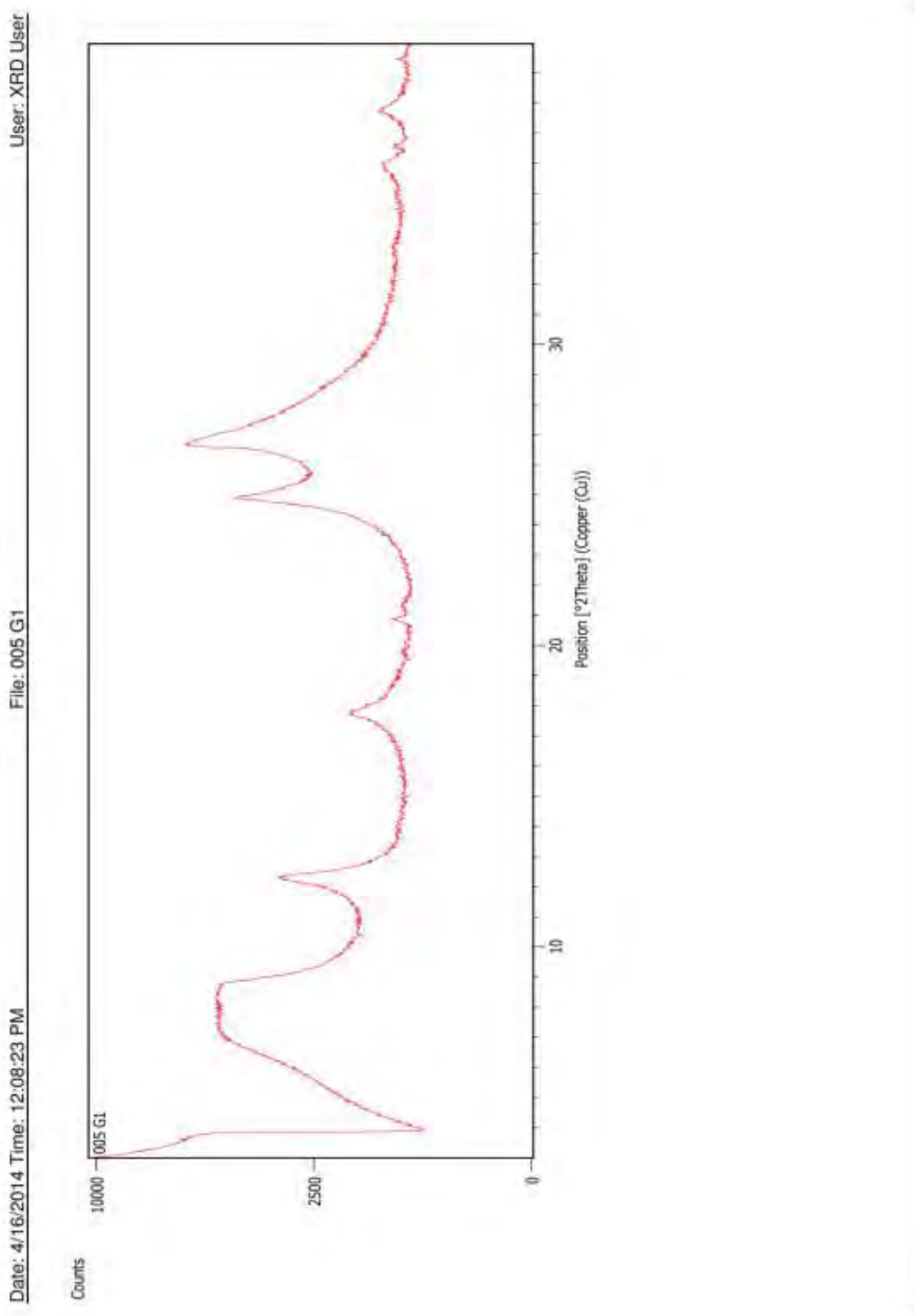
0
005 G1 Pow
Illite
Kaolinite; Illite; Montmorillonite
; Kaolinite; Illite; Montmorillonite
; Illite
Kaolinite; Illite; Montmorillonite
; Illite
; Illite; Montmorillonite
; Illite
; Kaolinite; Illite
; Illite
; Kaolinite; Illite
; Kaolinite; Illite
10
20
30
40
50
60
70
80
Position [°2Theta] (Copper (Cu))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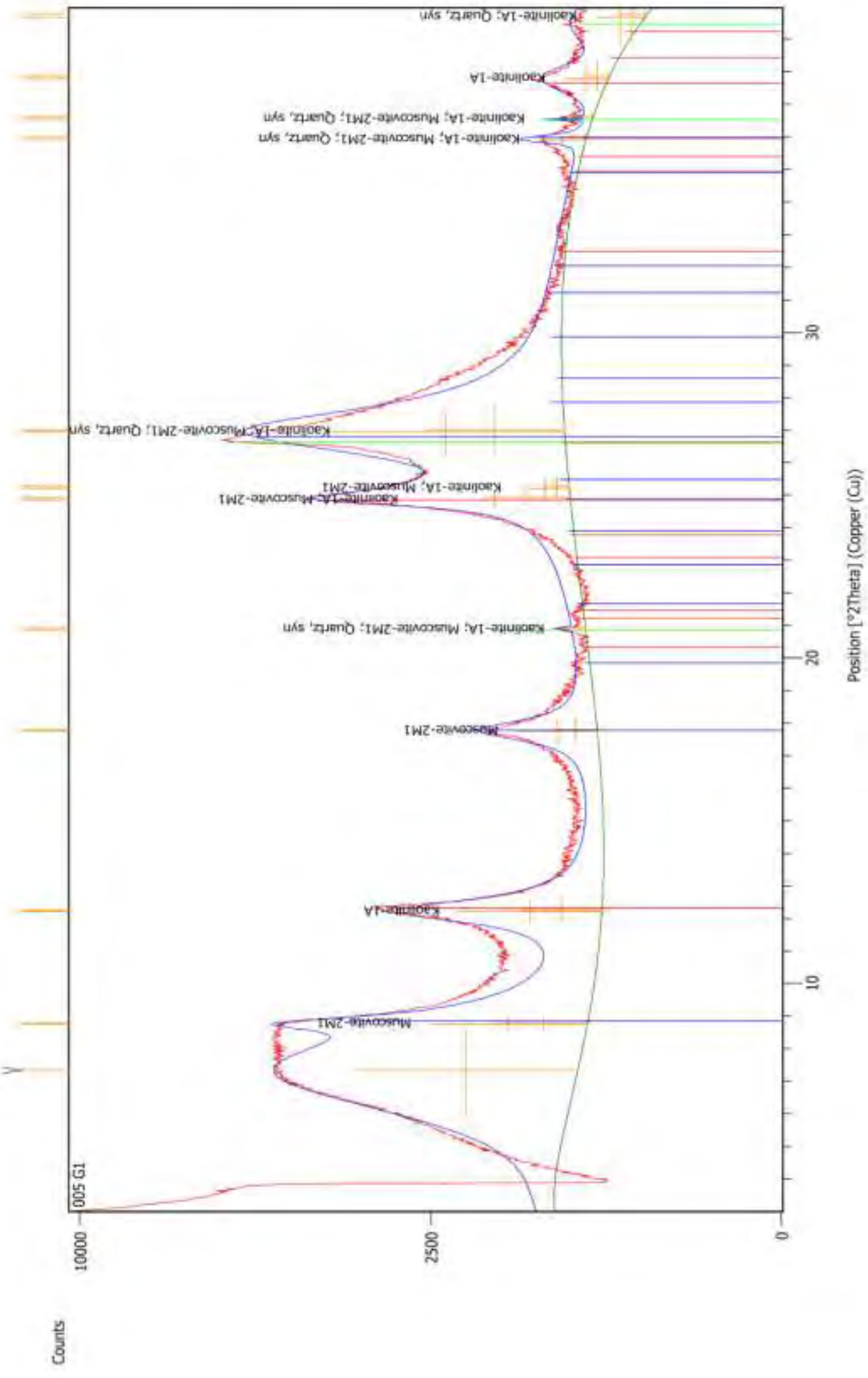
005 G1
10
20
30
Position [°2Theta] (Copper (Cu))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10000
2500
0
005 G1
Position [°2Theta] (Copper (Cu))
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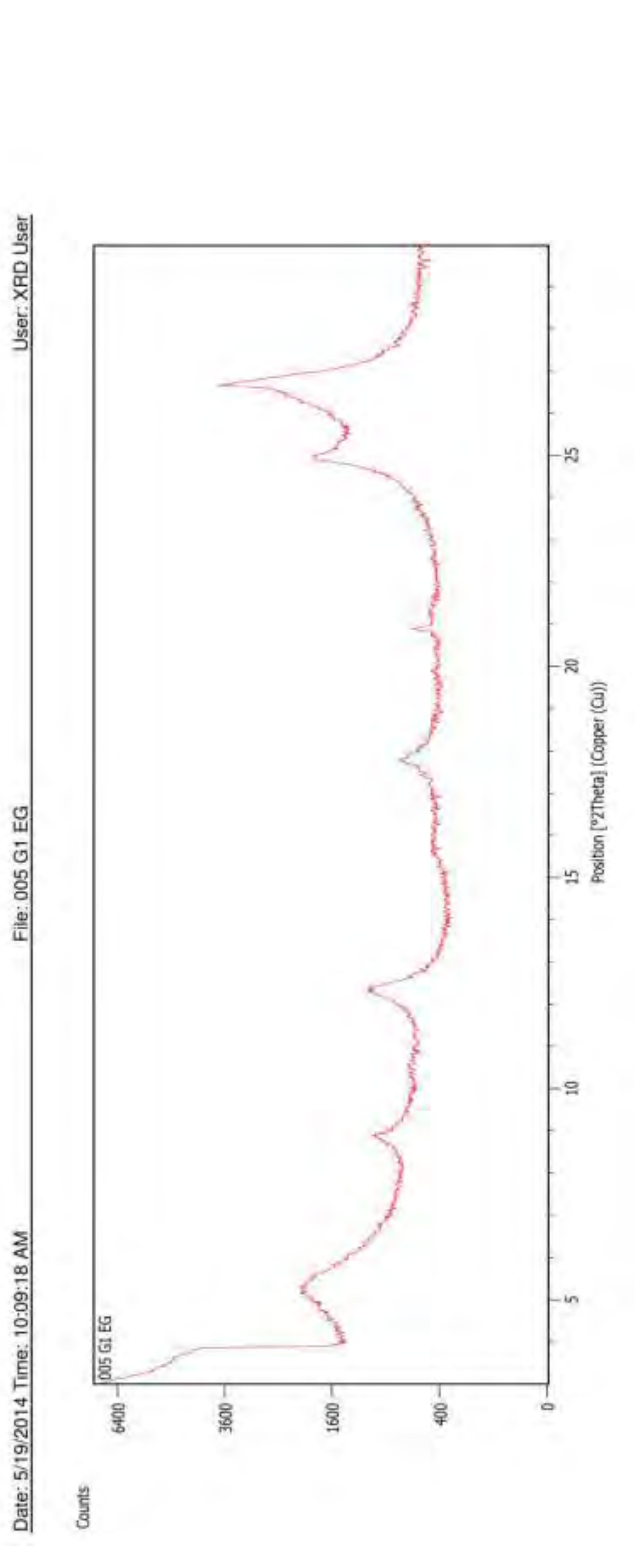
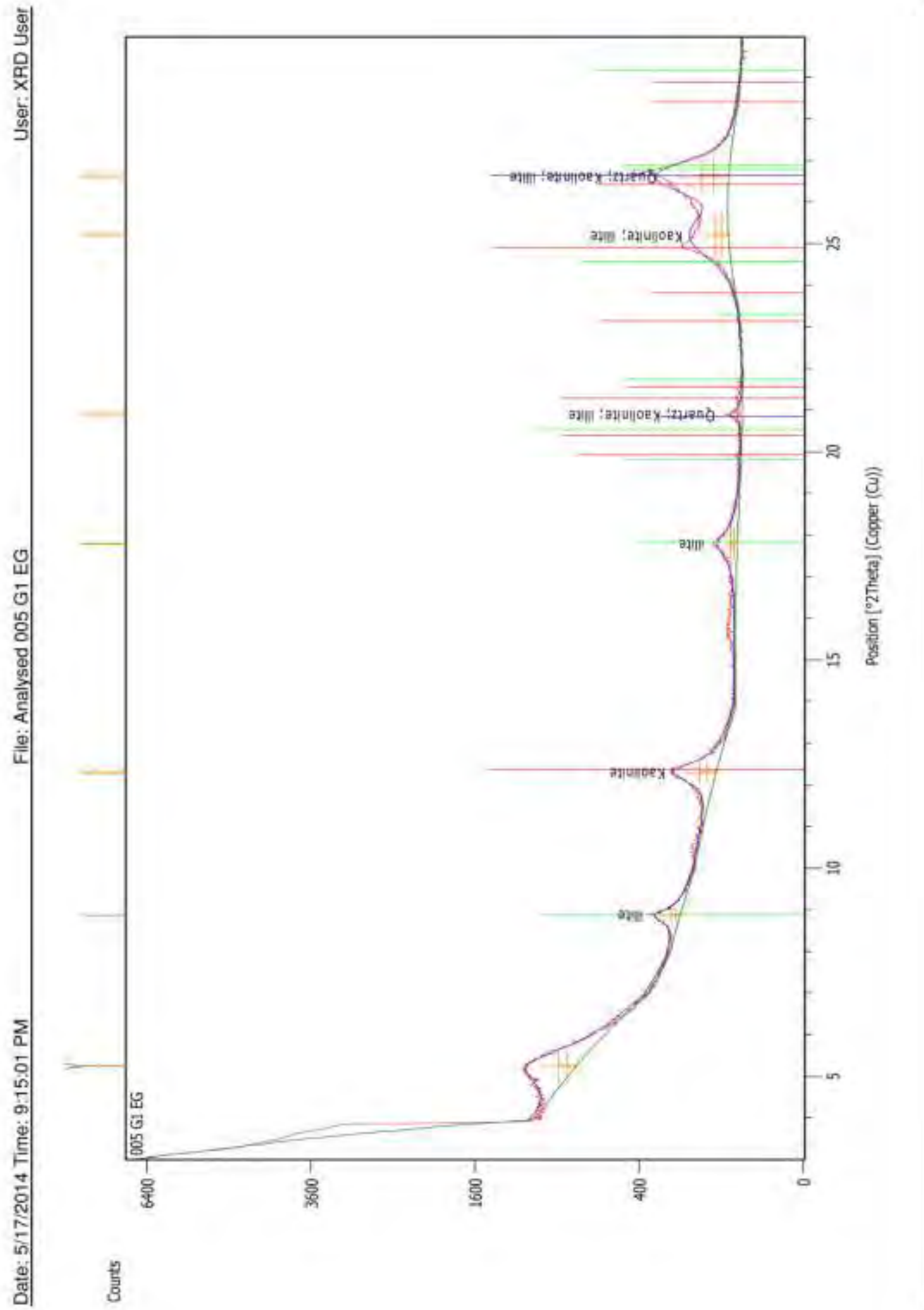
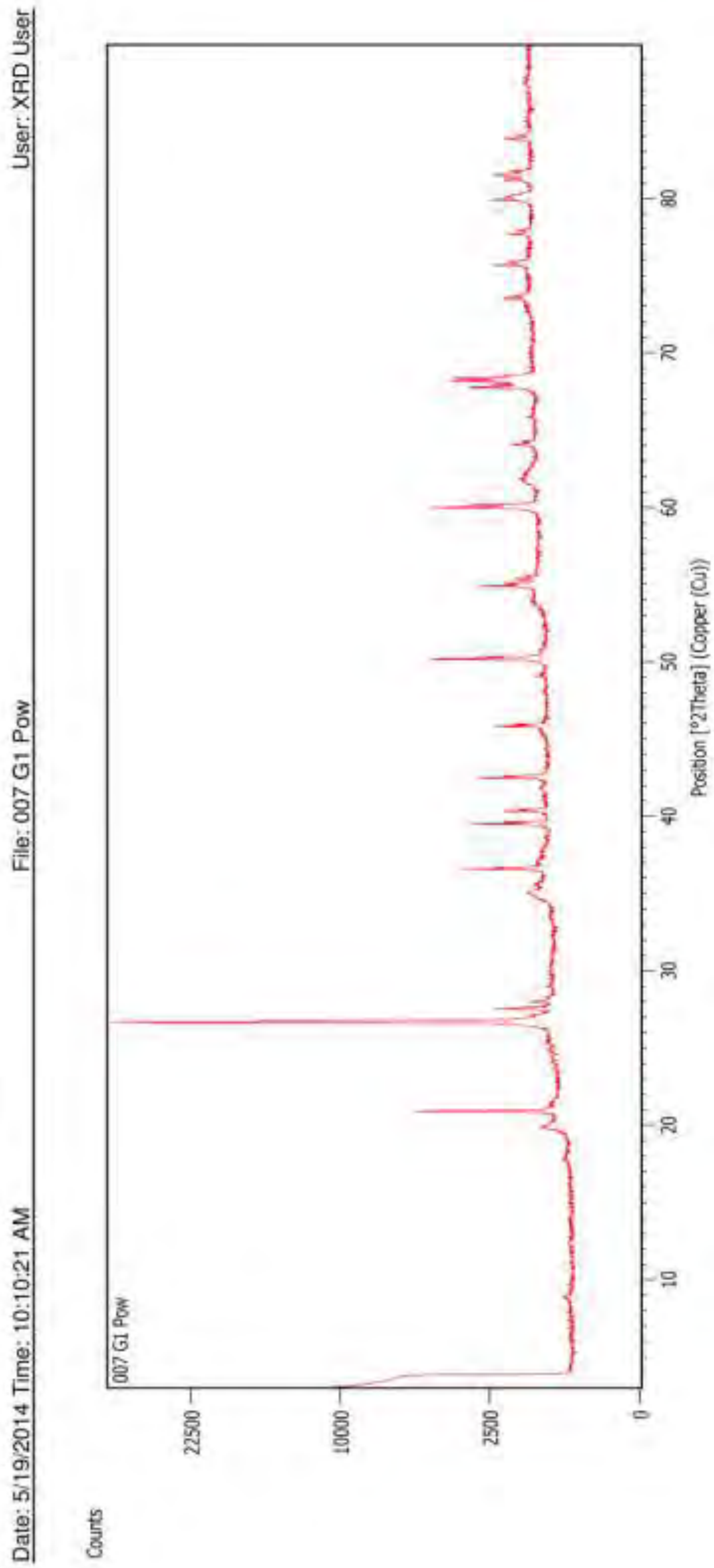
20
30
Muscovite-2M1
Kaolinite-1A
Kaolinite-1A; Muscovite-2M1; Quartz, syn
Kaolinite-1A; Muscovite-2M1
Kaolinite-1A; Quartz, syn



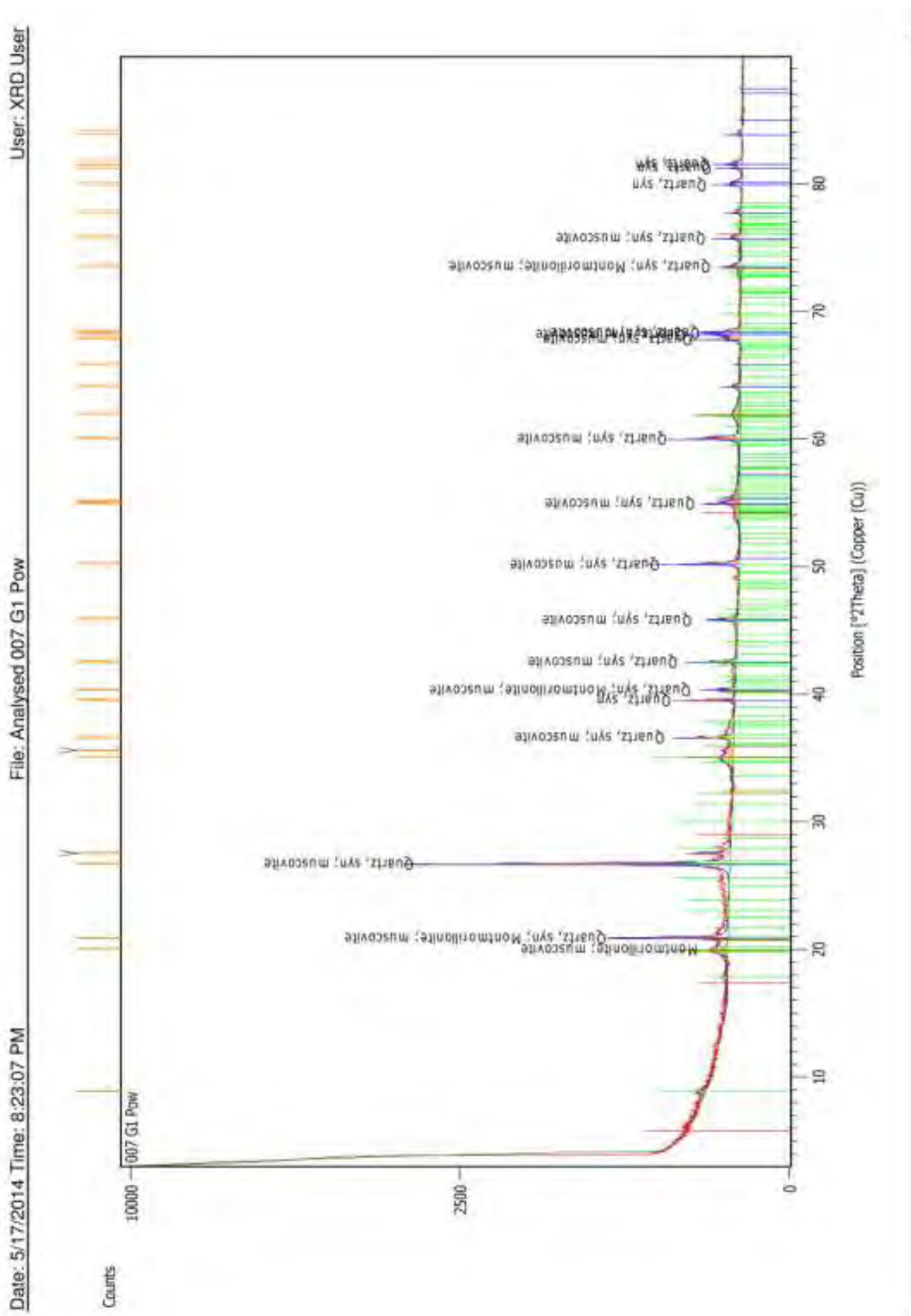
Date: 5/19/2014 Time: 10:09:18 AM
File: 005 G1 EG
User: XRD User
Counts
6400
3600
1600
400
0
005 G1 EG
5
10
15
20
25
Position [°2Theta] (Copper (Cu))


Date: 5/17/2014 Time: 9:15:01 PM
File: Analysed 005 G1 EG
User: XRD User
Counts
6400
3600
1600
400
0
005 G1 EG
Illite
Kaolinite
Illite
Quartz; Kaolinite; Illite
Kaolinite; Illite
Quartz; Kaolinite; Illite
5
10
15
20
25
Position [°2Theta] (Copper (Cu))

TP-PHW14-007 G2

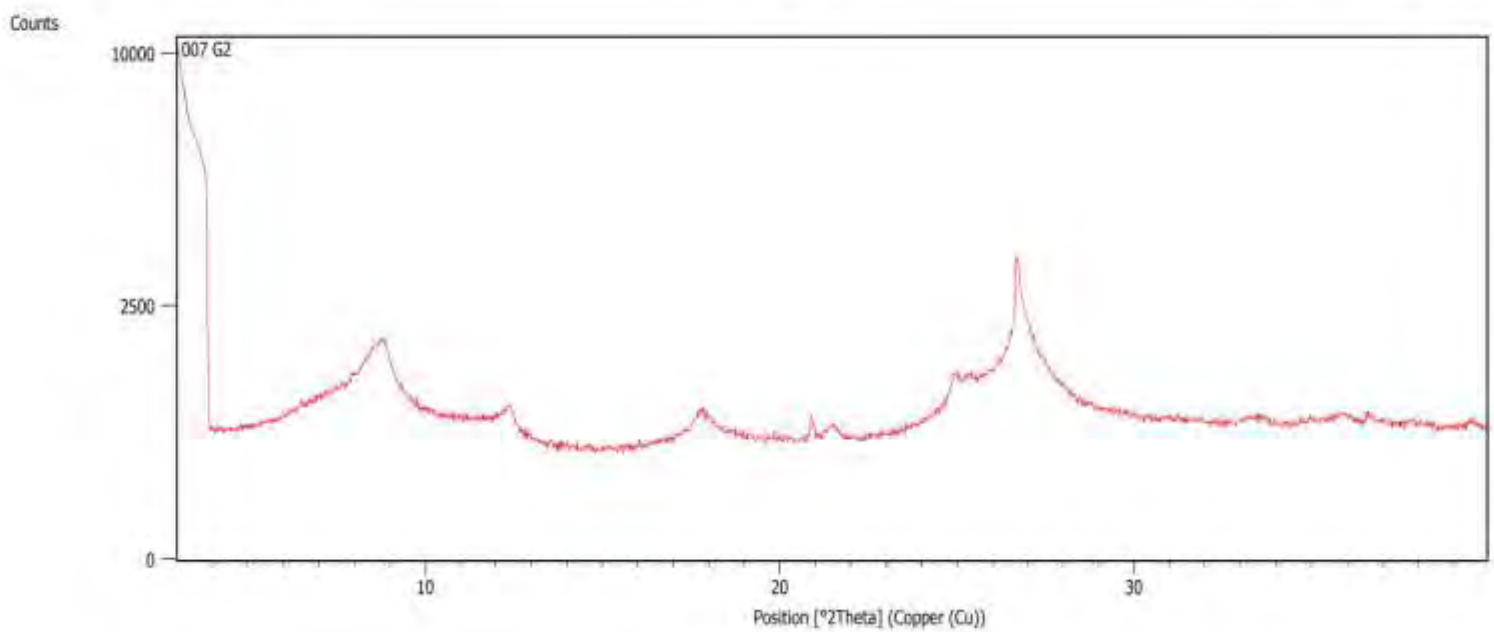


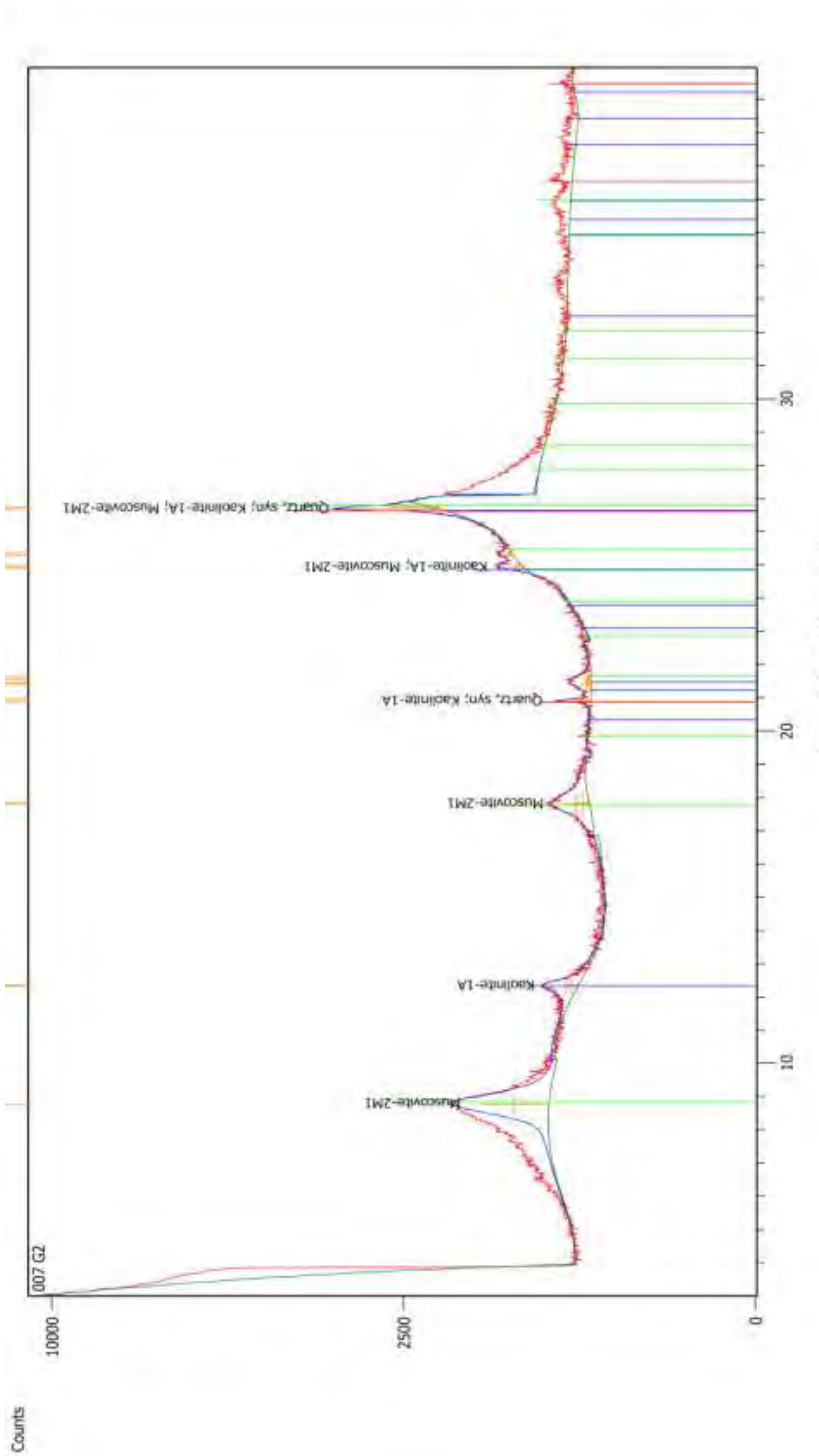
Date: 5/19/2014 Time: 10:10:21 AM
File: 007 G1 Pow
User: XRD User
Counts
22500
10000
2500
0
007 G1 Pow
10
20
30
40
50
60
70
80
Position [°2Theta] (Copper (Cu))

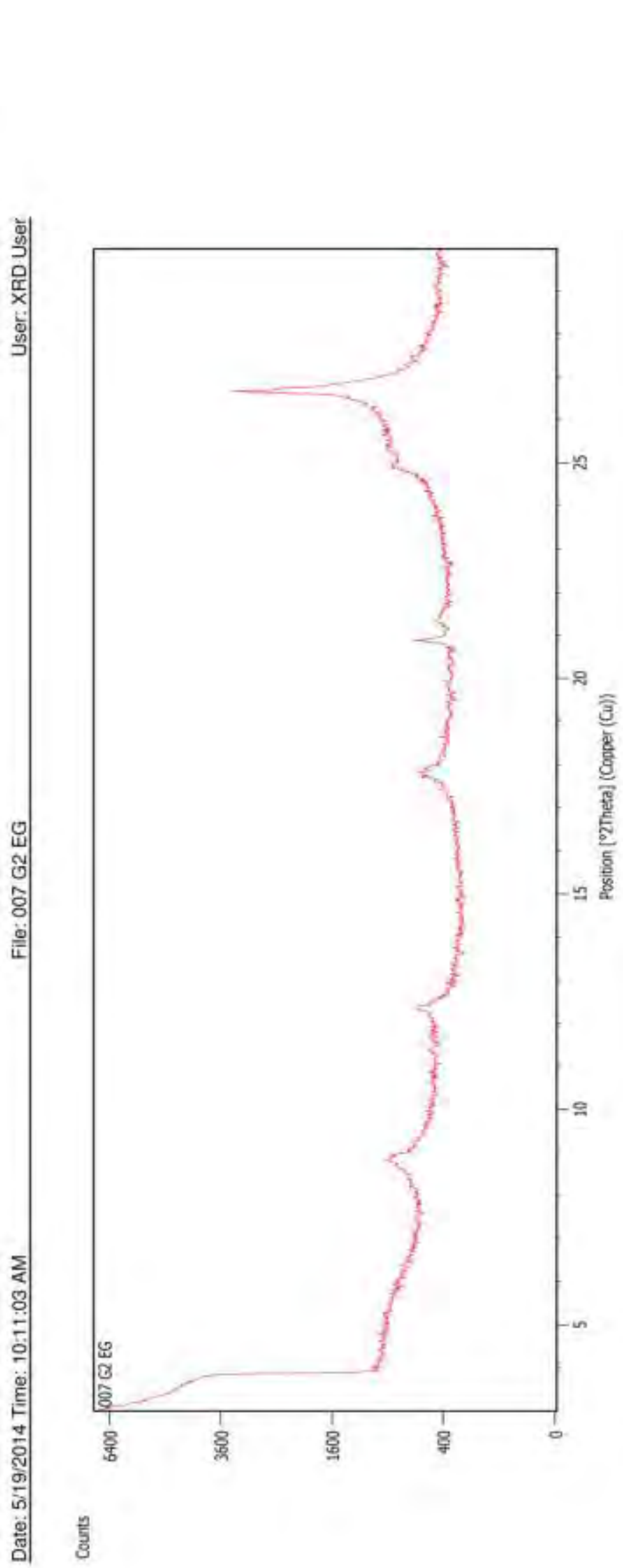


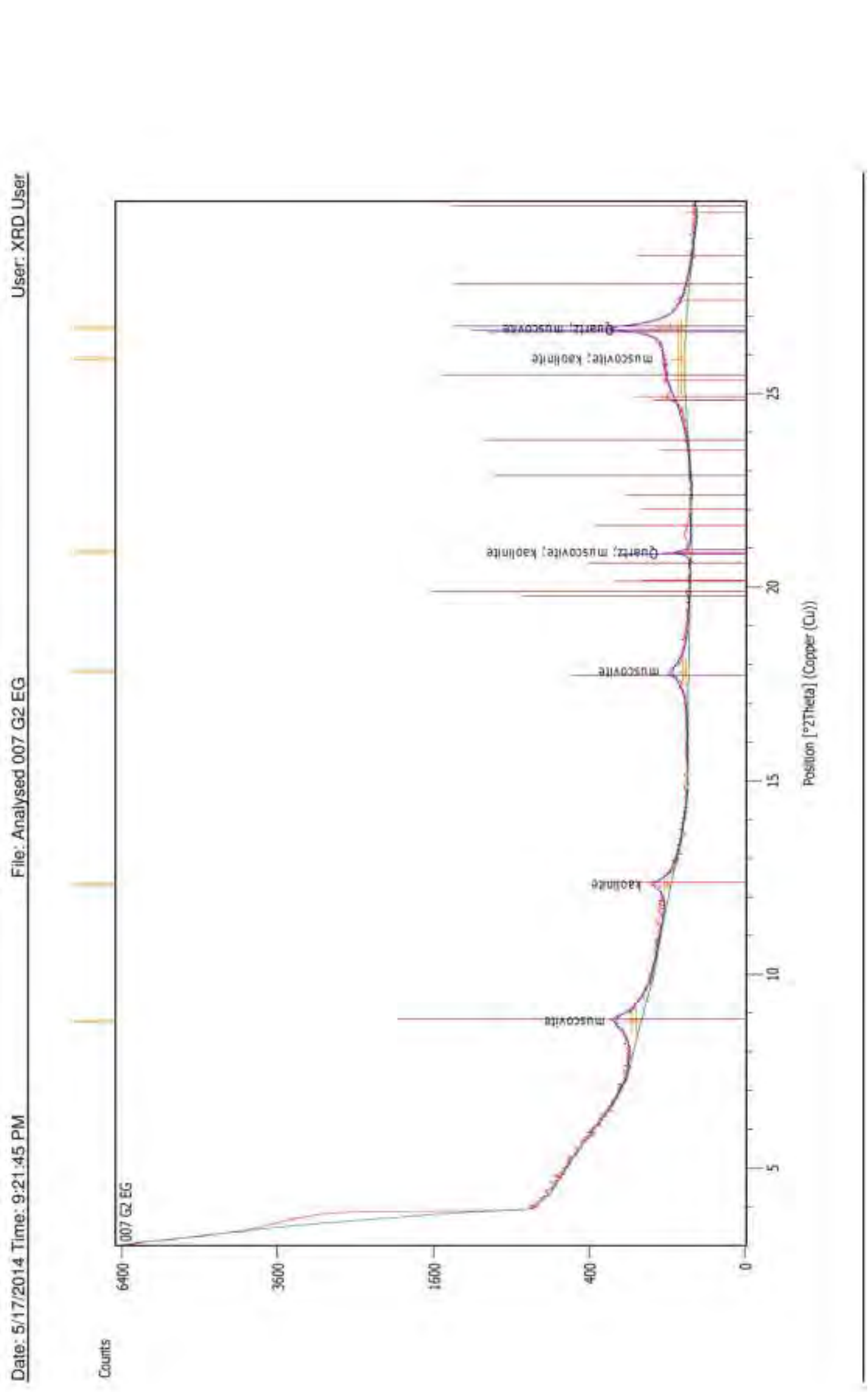
Date: 5/17/2014 Time: 8:23:07 PM
File: Analysed 007 G1 Pow
User: XRD User
Counts
10000
2500
0
007 G1 Pow
Montmorillonite; muscovite
Quartz, syn; Montmorillonite; muscovite
Quartz, syn; muscovite
Quartz, syn
Quartz, syn; muscovite
Montmorillonite; muscovite
Position [°2Theta] (Copper (Cu))

Date: 4/16/2014 Time: 12:08:49 PM File: 007 G2 User: XRD User

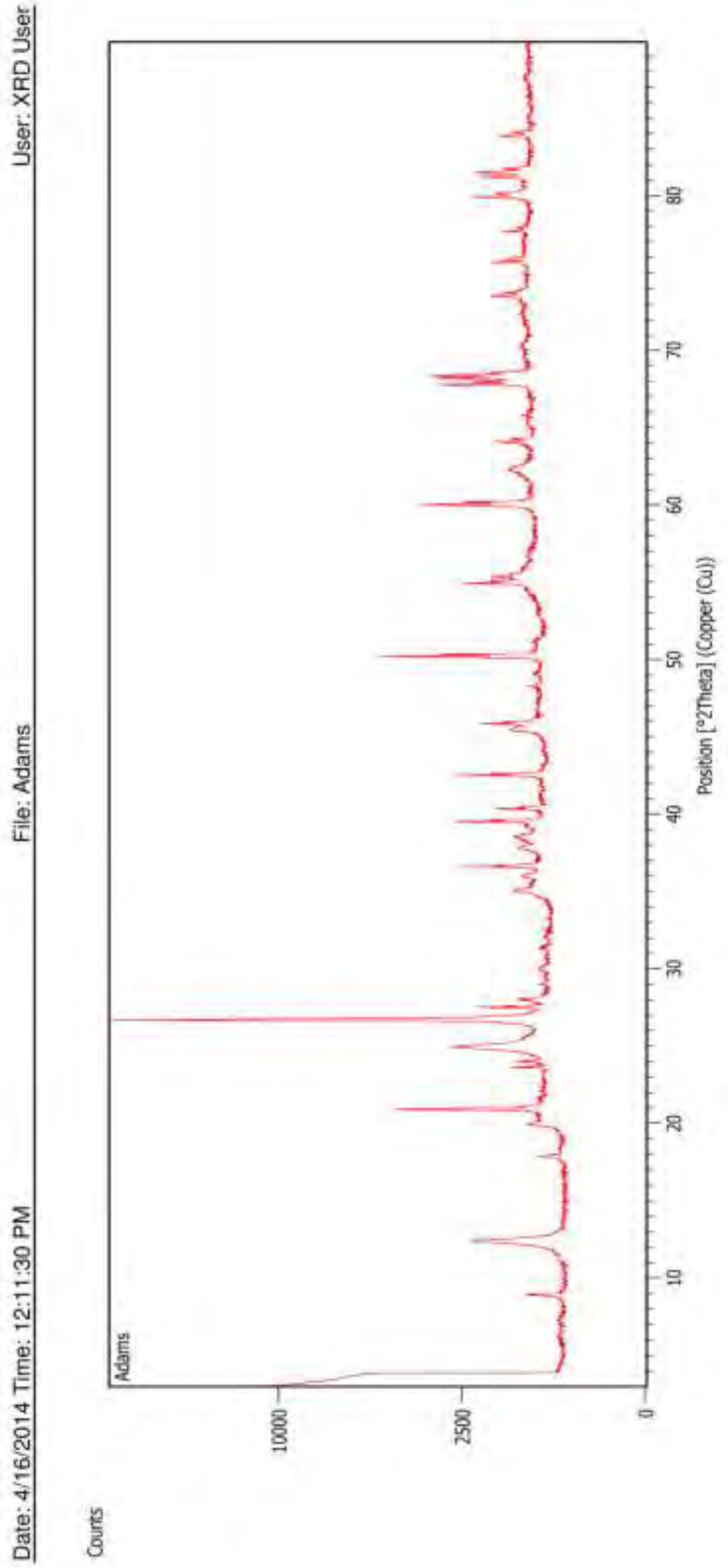


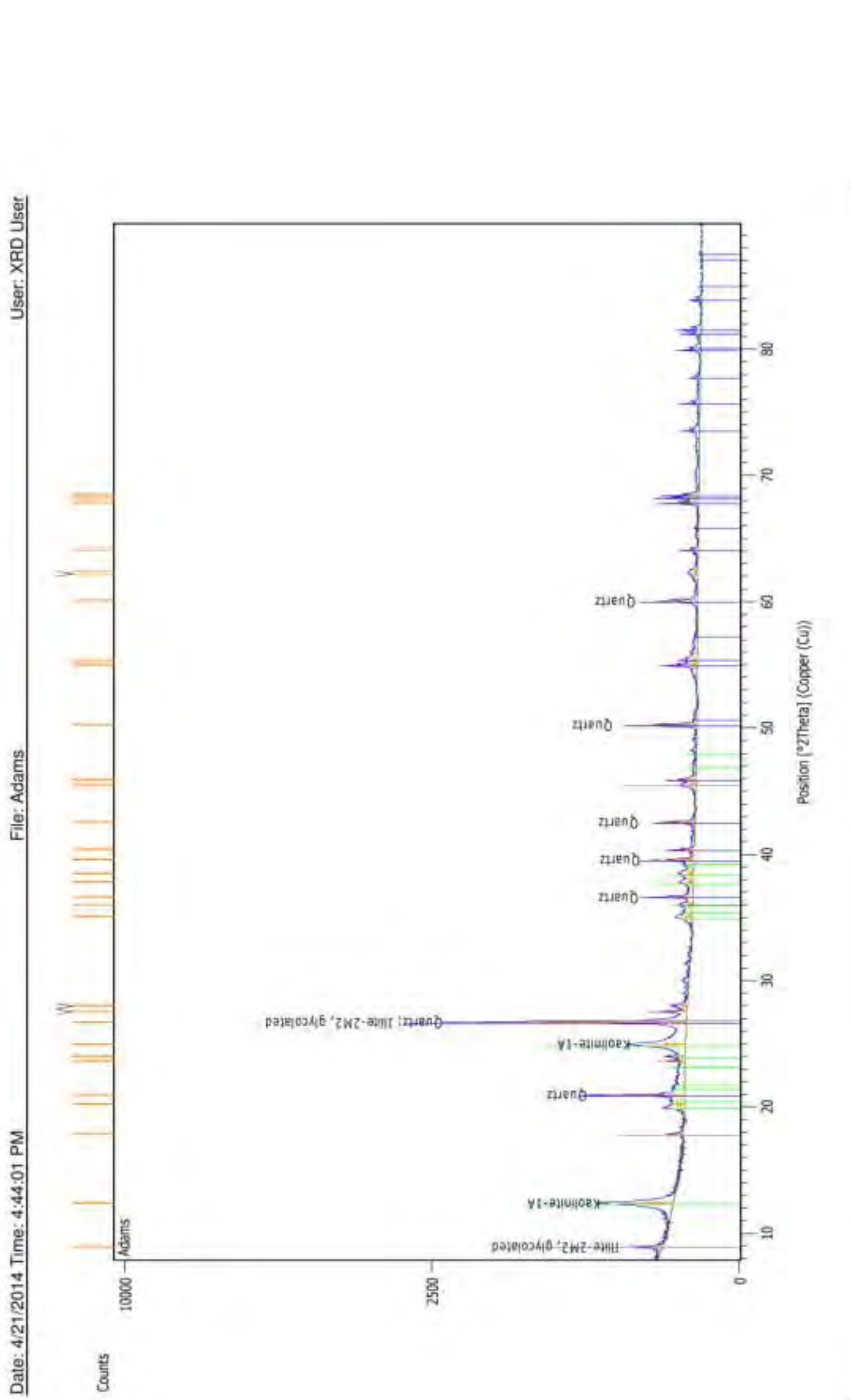

007 G2
Counts
10000
2500
0
Muscovite-2M1
Kaolinite-1A
Muscovite-2M1
Quartz, syn; Kaolinite-1A
Kaolinite-1A; Muscovite-2M1
Quartz, syn; Kaolinite-1A; Muscovite-2M1
10
20
30
Position [°2Theta] (Copper (Cu))

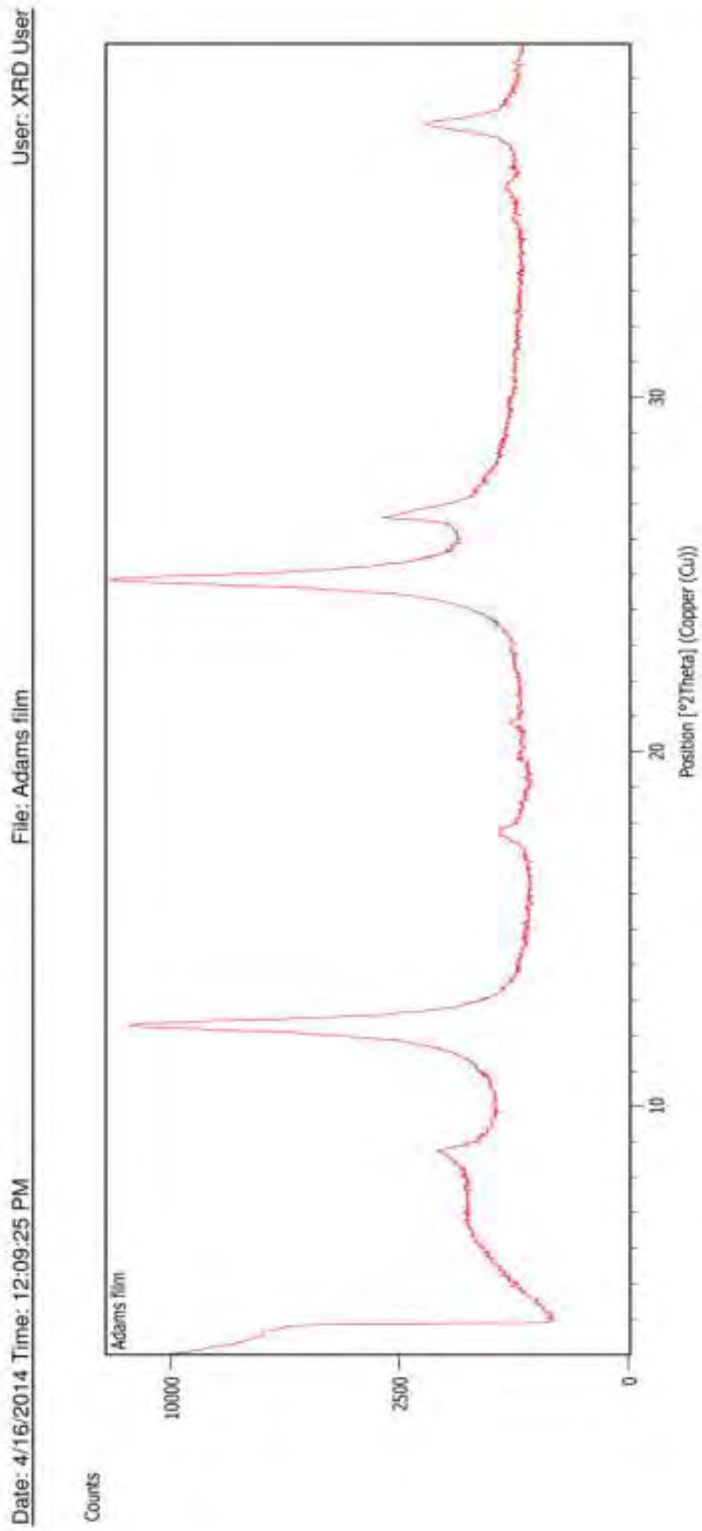

Date: 5/19/2014 Time: 10:11:03 AM
File: 007 G2 EG
User: XRD User
Counts
6400
3600
1600
400
0
007 G2 EG
5
10
15
20
25
Position [°2Theta] (Copper (Cu))


Date: 5/17/2014 Time: 9:21:45 PM
File: Analysed 007 G2 EG
User: XRD User
Counts
6400
3600
1600
400
0
007 G2 EG
muscovite
kaolinite
muscovite
Quartz; muscovite; kaolinite
muscovite; kaolinite
Quartz; muscovite
5
10
15
20
25
Position [°2Theta] (Copper (Cu))

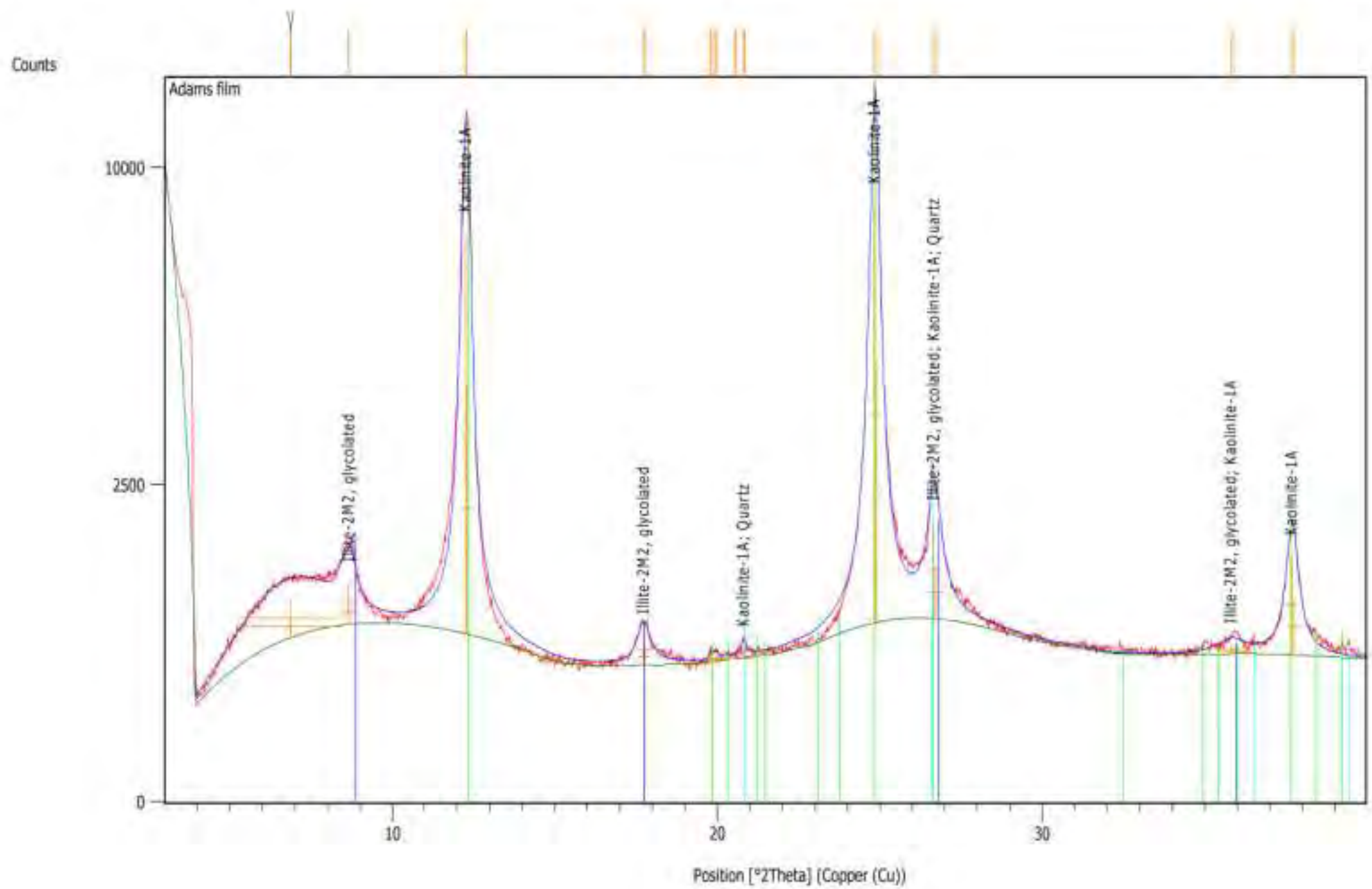
ADAMS BRICK FACTORY

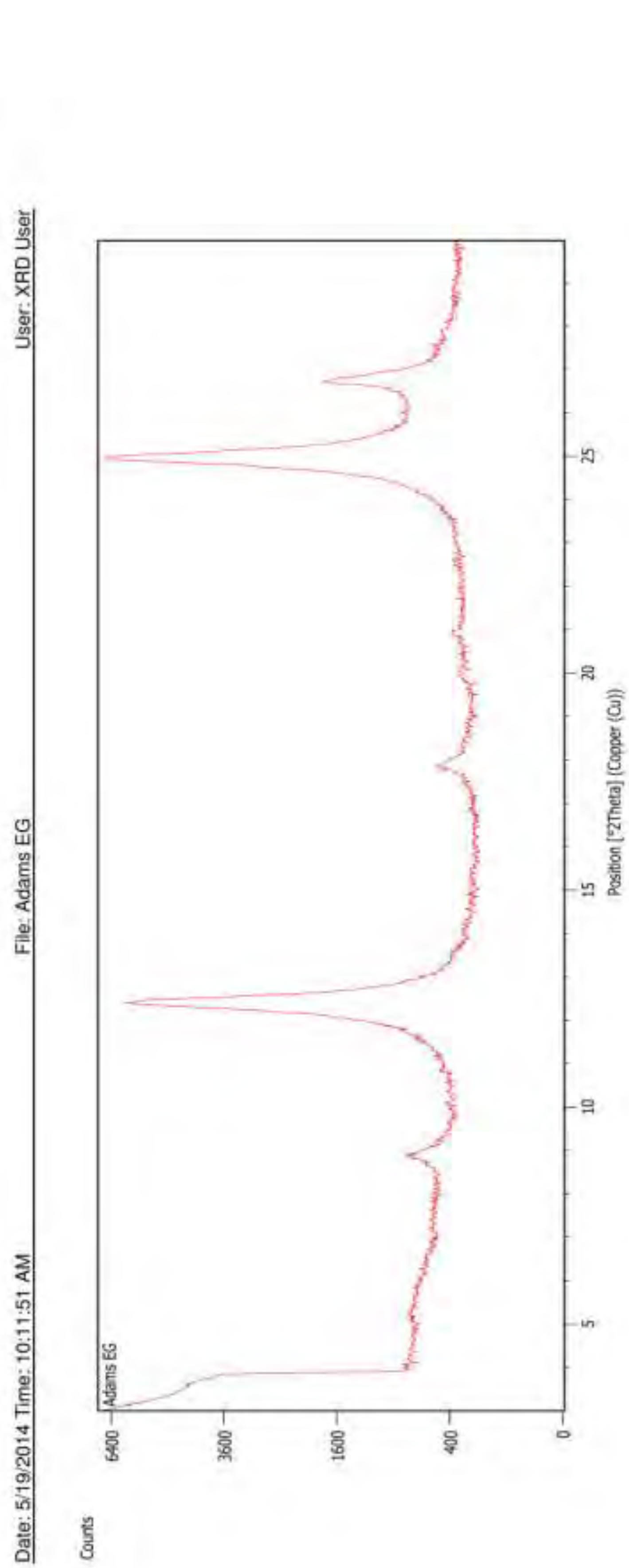

Date: 4/16/2014 Time: 12:11:30 PM
File: Adams
User: XRD User
Counts
10000
2500
0
Adams
10
20
30
40
50
60
70
80
Position [°2Theta] (Copper (Cu))


Date: 4/21/2014 Time: 4:44:01 PM
File: Adams
User: XRD User
Counts
10000
2500
0
Adams
Illite-2M2, glycolated
Kaolinite-1A
Quartz
Kaolinite-1A
Quartz; Illite-2M2, glycolated
Quartz
Quartz
Quartz
Quartz
Quartz
10
20
30
40
50
60
70
80
Position [°2Theta] (Copper (Cu))

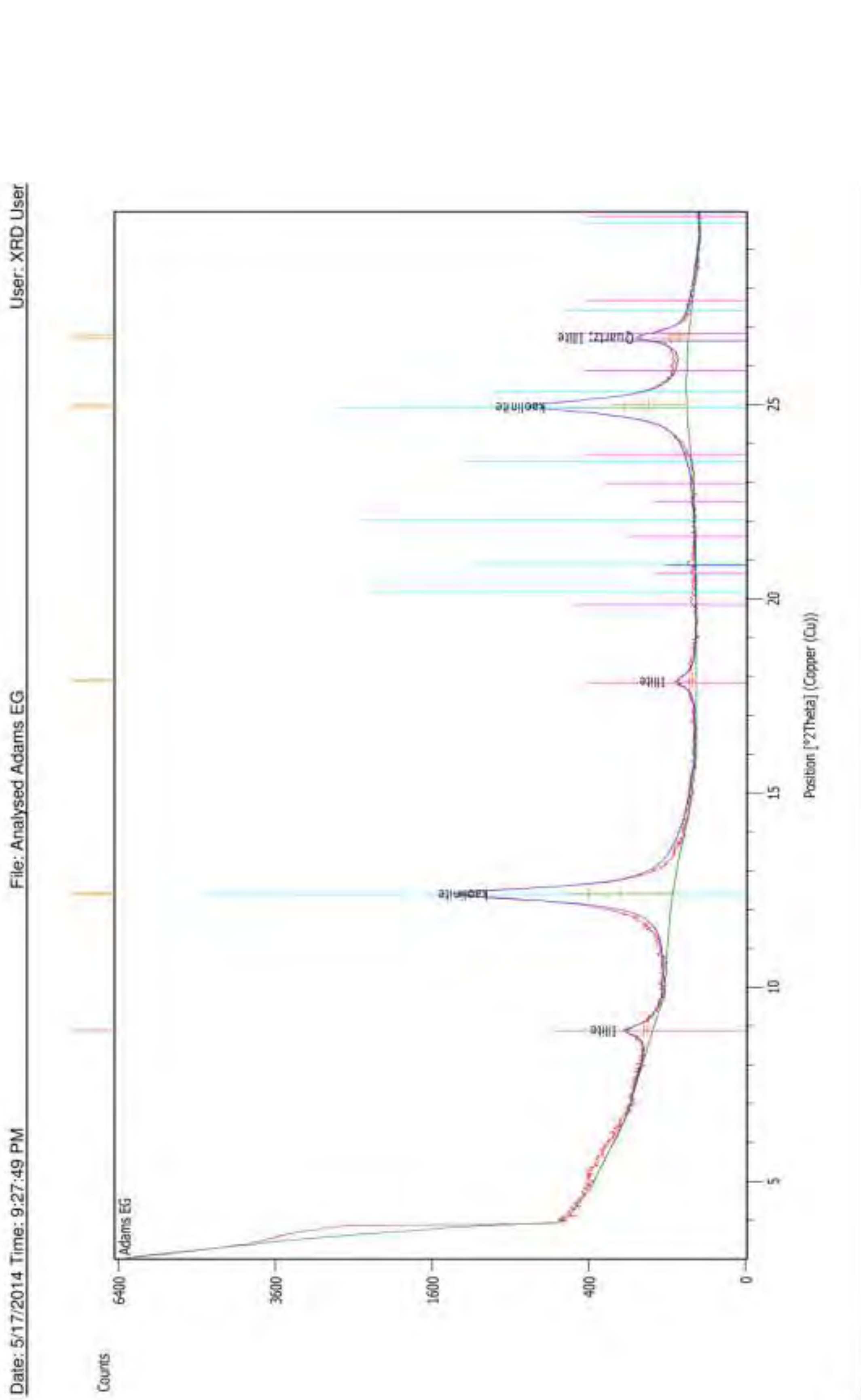

Date: 4/16/2014 Time: 12:09:25 PM
File: Adams film
User: XRD User
Counts
10000
2500
0
Adams film
10
20
30
Position [°2Theta] (Copper (Cu))

Date: 4/21/2014 Time: 5:12:18 PM File: Adams film_analysed1 User: XRD User



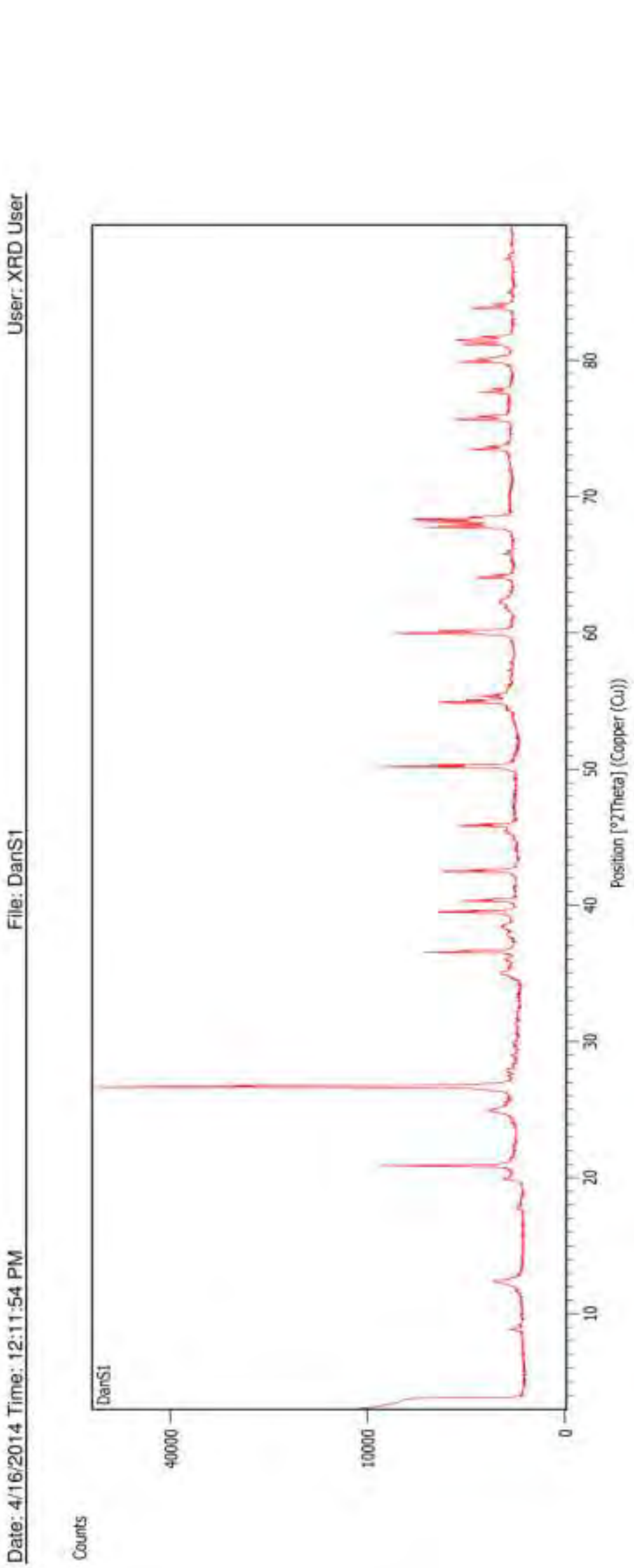


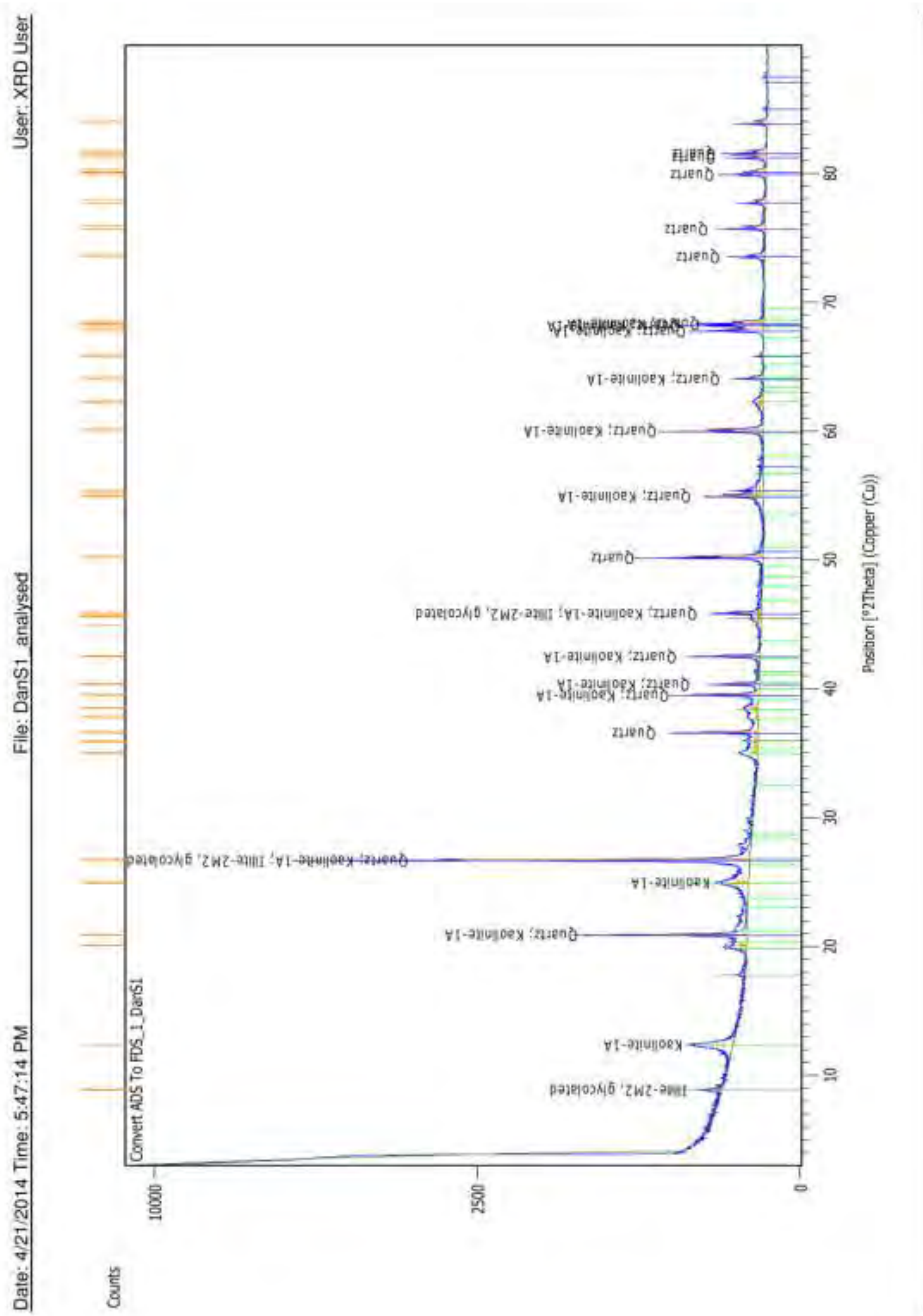
Date: 5/19/2014 Time: 10:11:51 AM
File: Adams EG
User: XRD User
Counts
Adams EG
6400
3600
1600
400
0
5
10
15
20
25
Position [°2Theta] (Copper (Cu))



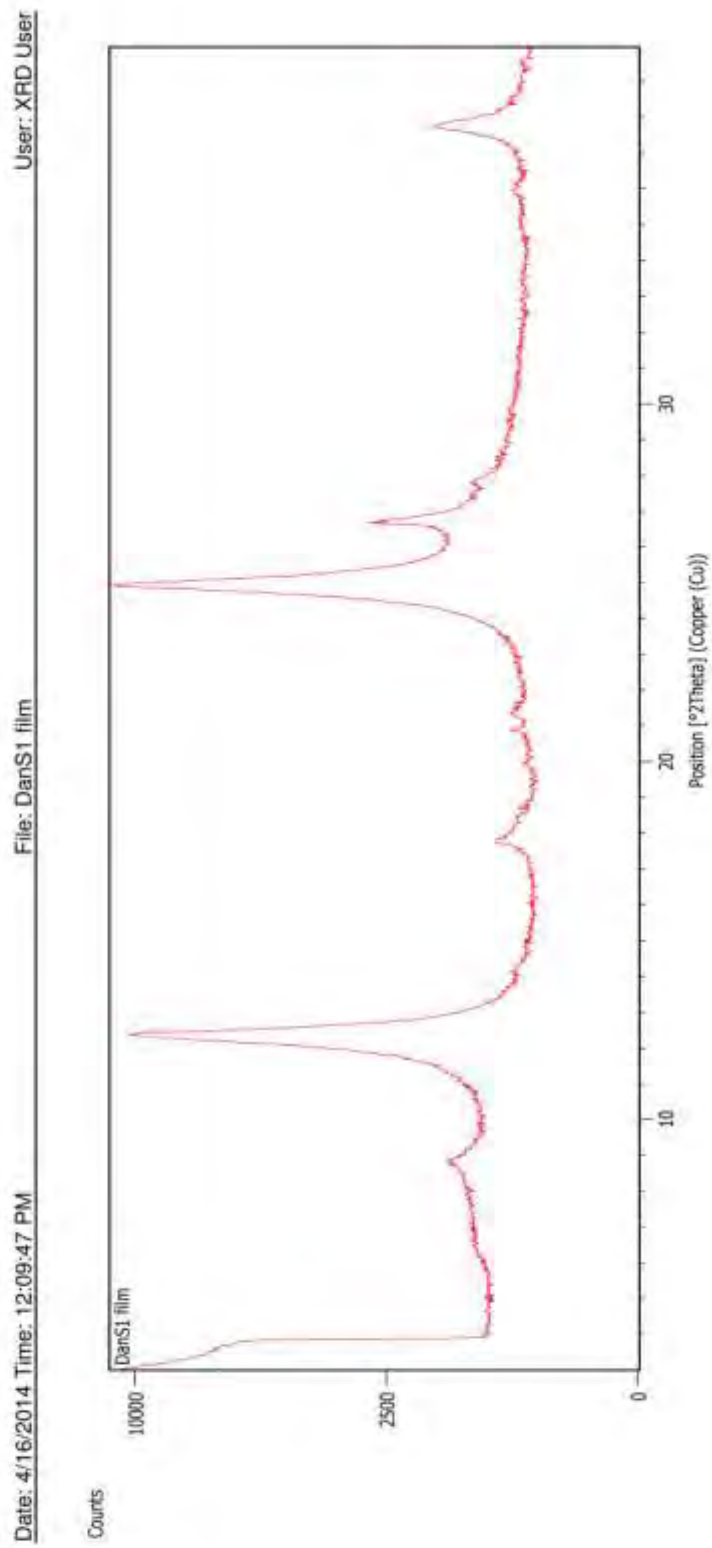
Date: 5/17/2014 Time: 9:27:49 PM
File: Analysed Adams EG
User: XRD User
Counts
6400
3600
1600
400
0
Adams EG
Illite
Kaolinite
Illite
Kaolinite
Quartz; Illite
5
10
15
20
25
Position [°2Theta] (Copper (Cu))

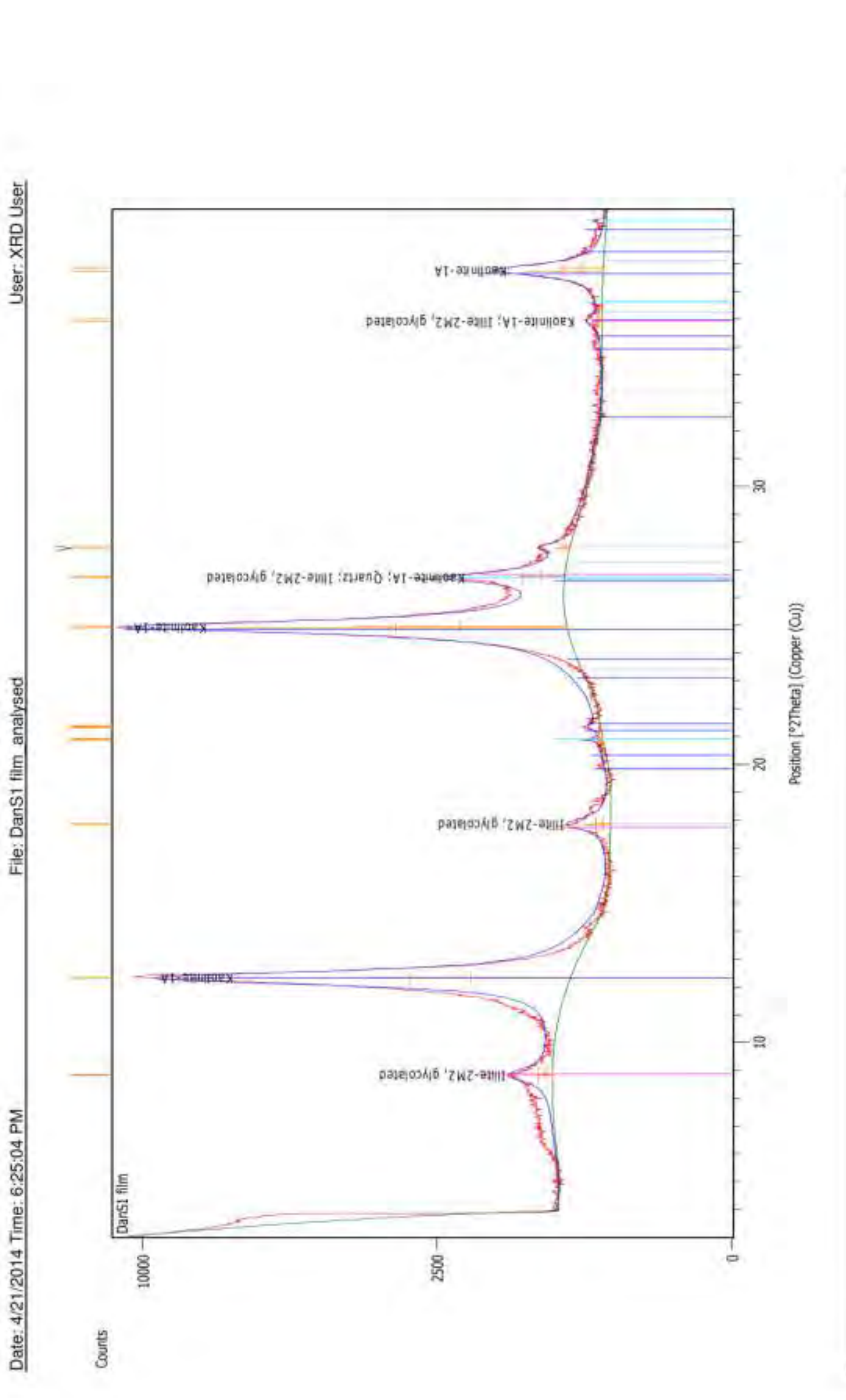
OSEI-BONSU BRICK FACTORY


Date: 4/16/2014 Time: 12:11:54 PM
File: DanS1
User: XRD User
Counts
40000
10000
0
DanS1
10
20
30
40
50
60
70
80
Position [°2Theta] (Copper (Cu))

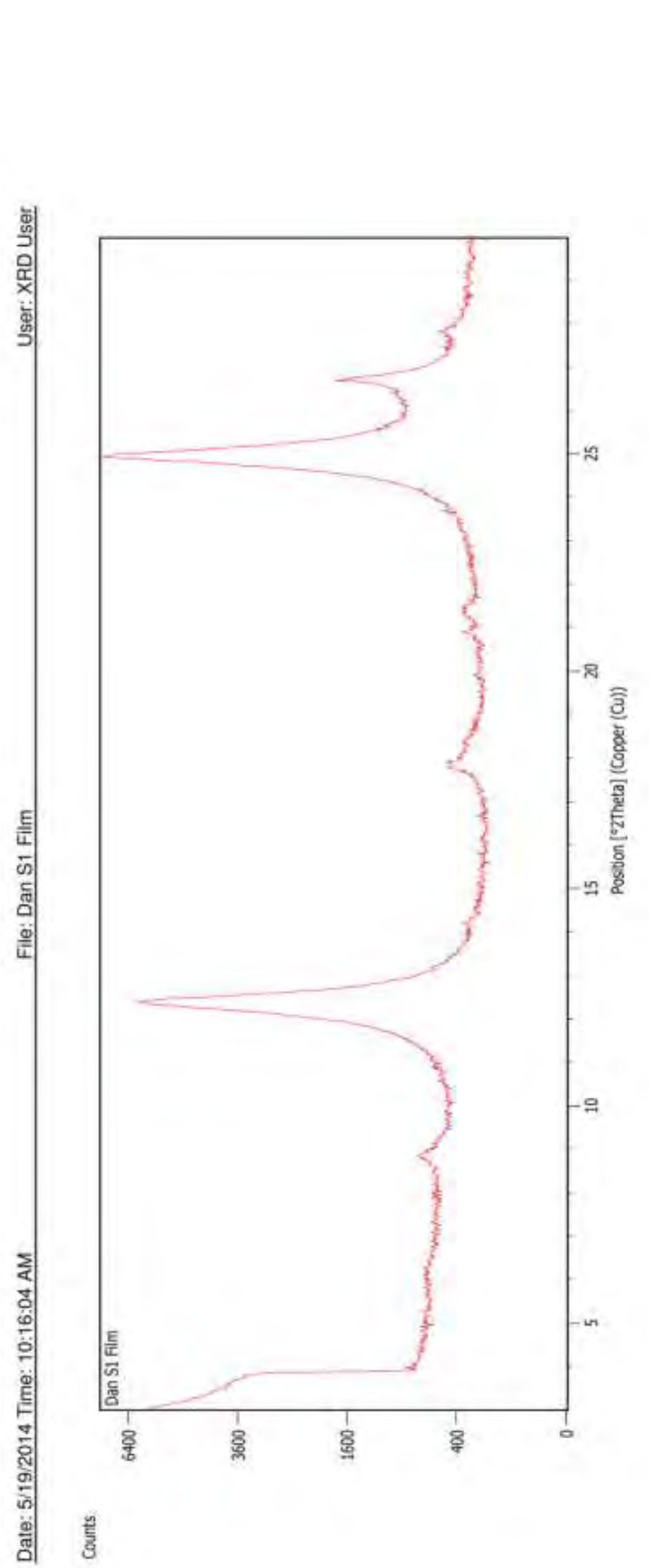


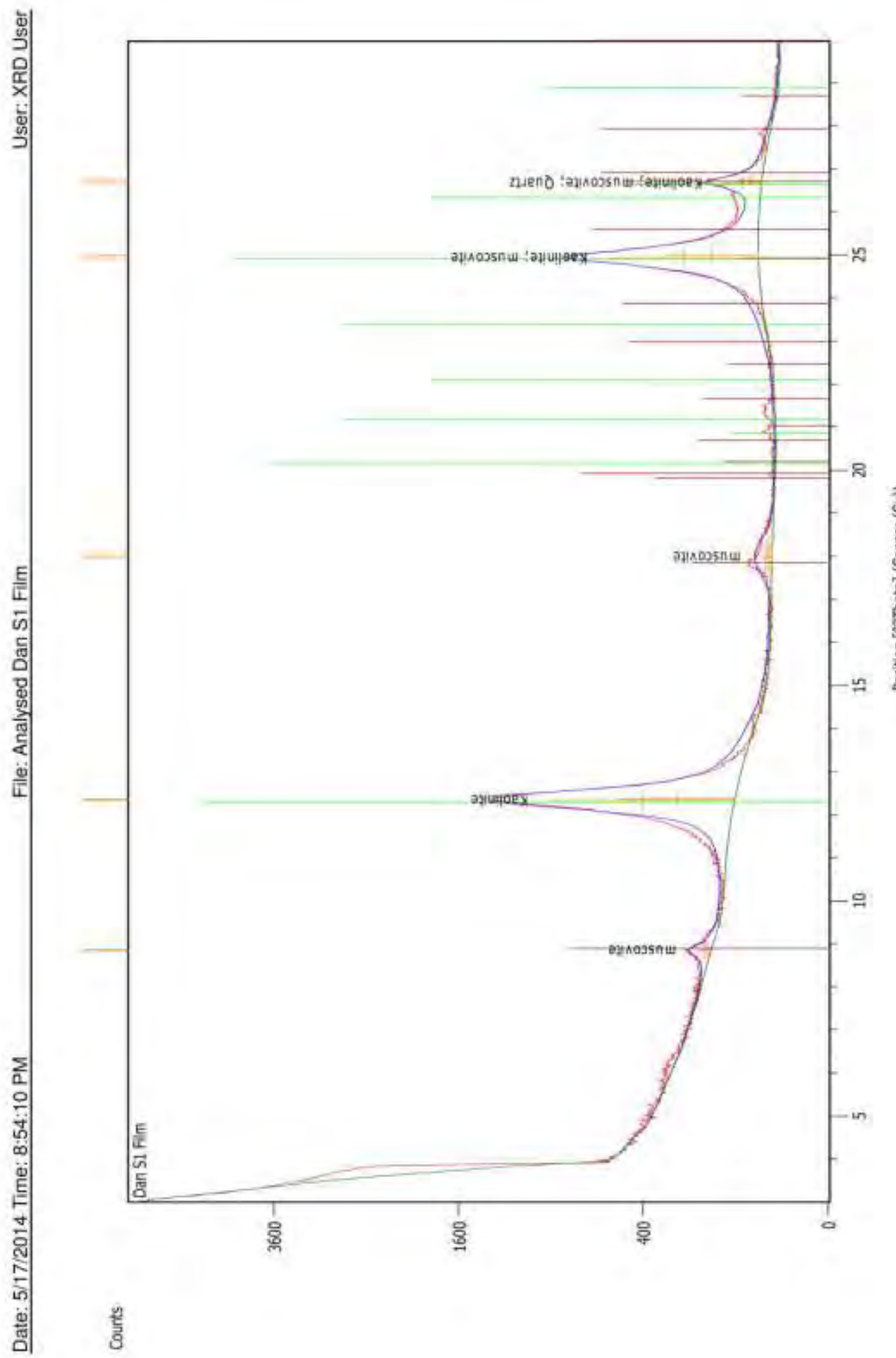
Date: 4/21/2014 Time: 5:47:14 PM
File: DanS1_analysed
User: XRD User
Counts
Convert ADS To FDS_1_DanS1
Position [°2Theta] (Copper (Cu))
Illite-2M2, glycolated
Kaolinite-1A
Quartz; Kaolinite-1A
Quartz; Kaolinite-1A; Illite-2M2, glycolated
Quartz


Date: 4/16/2014 Time: 12:09:47 PM
File: DanS1 film
User: XRD User
Counts
DanS1 film
10000
2500
0
10
20
30
Position [°2Theta] (Copper (Cu))

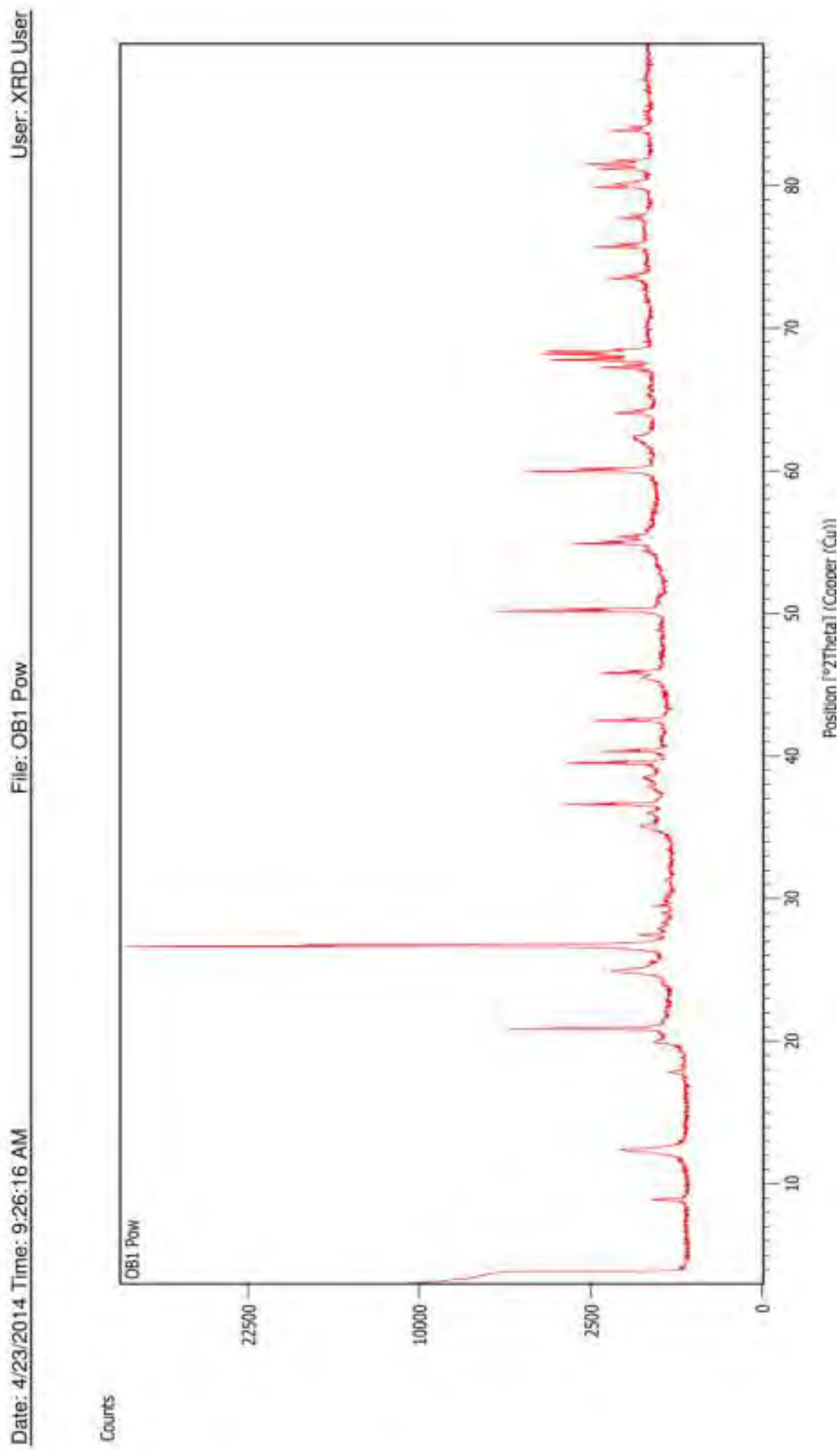


Date: 4/21/2014 Time: 6:25:04 PM
File: DanS1 film analysed
User: XRD User
Counts
10000
2500
0
DanS1 film
Illite-2M2, glycolated
Kaolinite-1A
Illite-2M2, glycolated
Kaolinite-1A
Kaolinite-1A; Quartz; Illite-2M2, glycolated
Kaolinite-1A; Illite-2M2, glycolated
Kaolinite-1A
10
20
30
Position [°2Theta] (Copper (Cu))

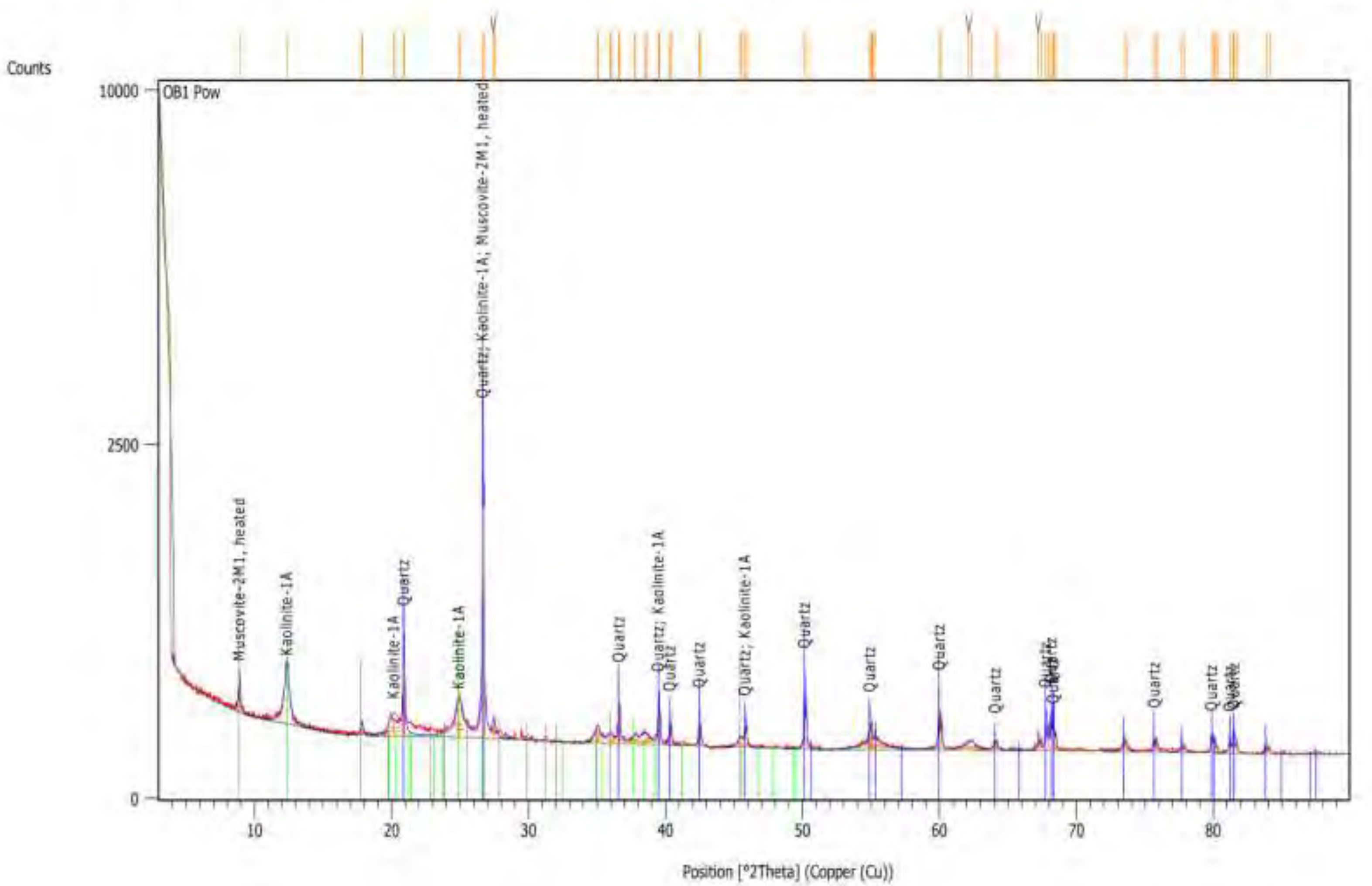

Date: 5/19/2014 Time: 10:16:04 AM
File: Dan S1 Film
User: XRD User
Counts
6400
3600
1600
400
0
Dan S1 Film
5
10
15
20
25
Position [°2Theta] (Copper (Cu))

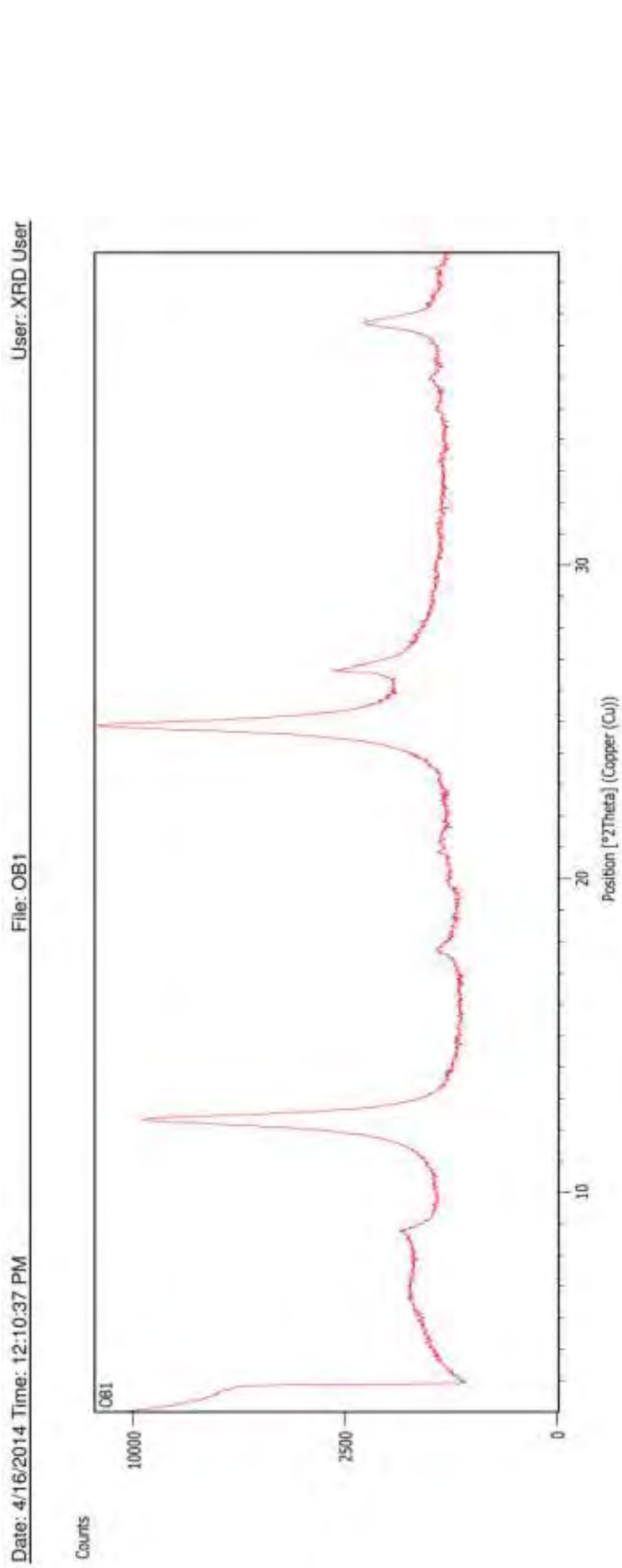

Date: 5/17/2014 Time: 8:54:10 PM
File: Analysed Dan S1 Film
User: XRD User
Counts
3600
1600
400
0
Dan S1 Film
muscovite
Kaolinite
muscovite
Kaolinite; muscovite
Kaolinite; muscovite; Quartz
5
10
15
20
25
Position [°2Theta] (Copper (Cu))

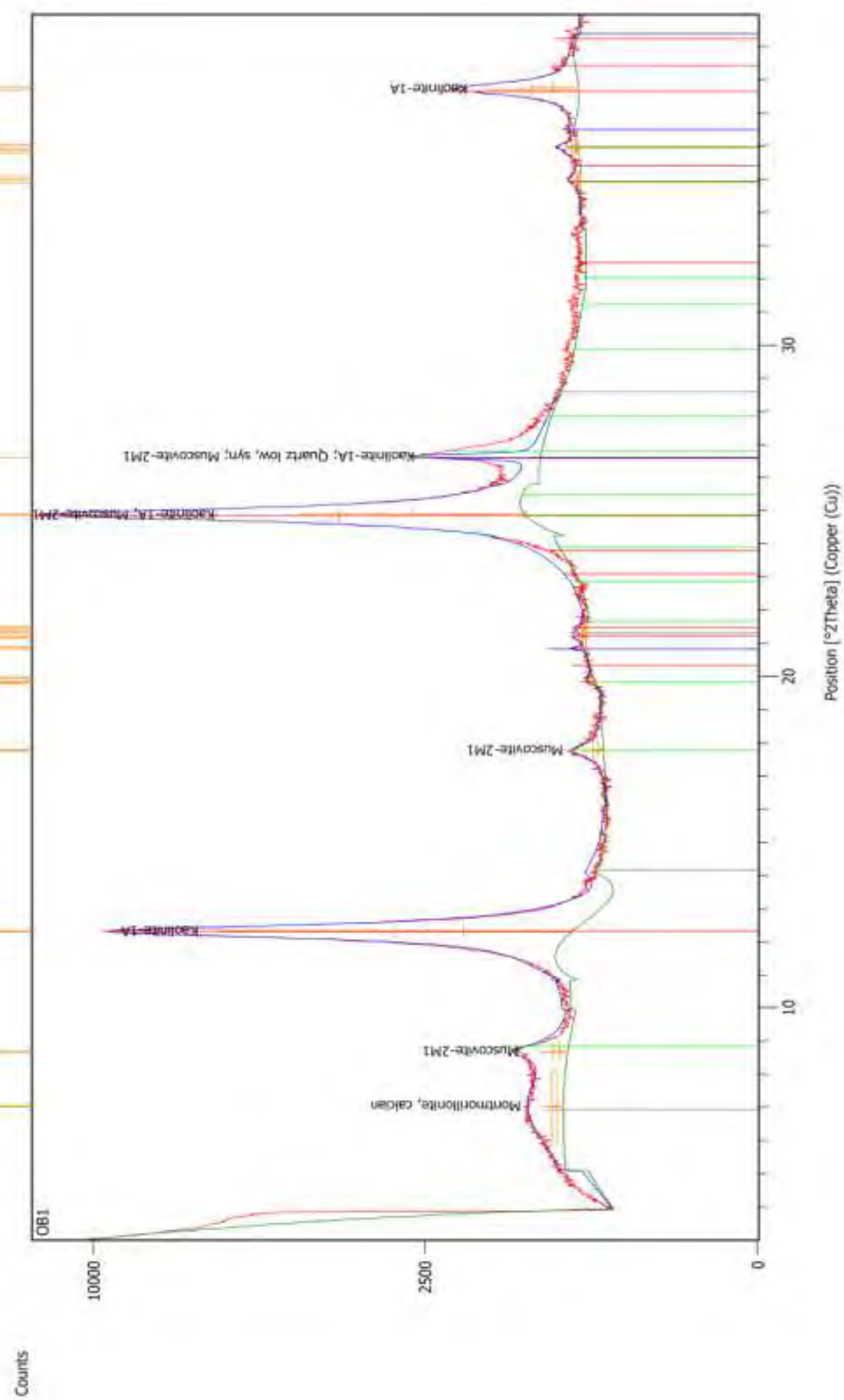
OBENG 1 BRICK FACTORY

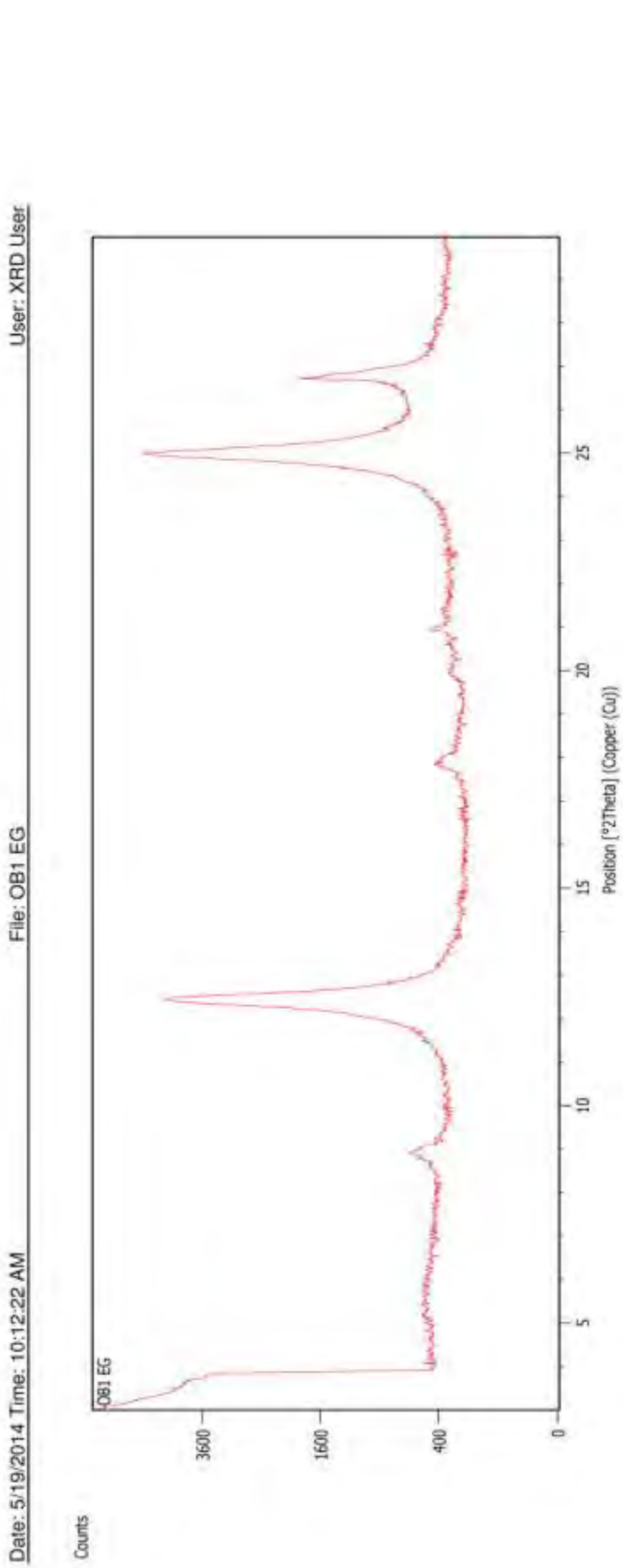

Date: 4/23/2014 Time: 9:26:16 AM
File: OB1 Pow
User: XRD User
Counts
OB1 Pow
22500
10000
2500
0
10
20
30
40
50
60
70
80
Position [°2Theta] (Copper (Cu))

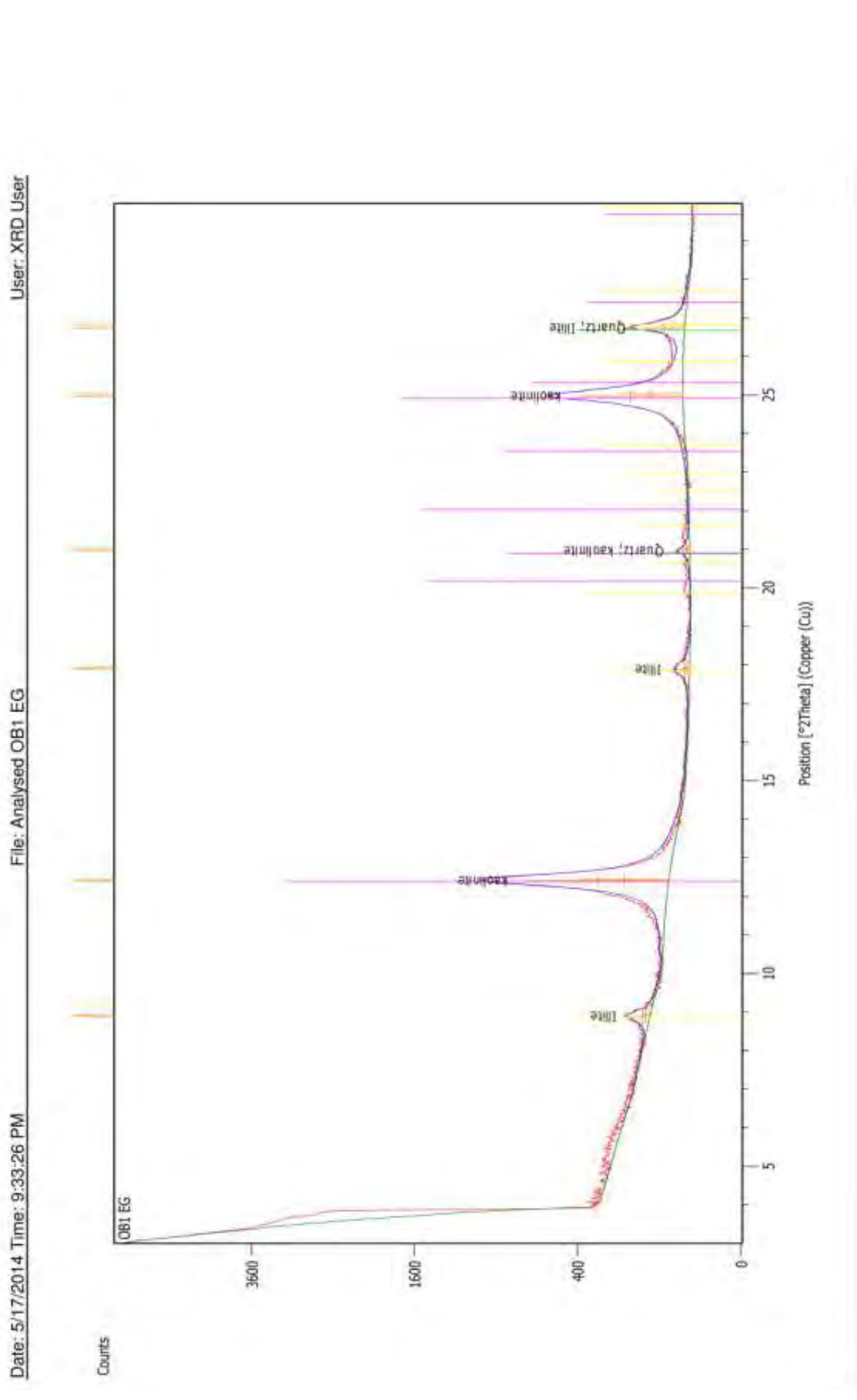
Date: 5/17/2014 Time: 8:19:46 PM File: Analysed OB1 Pow User: XRD User



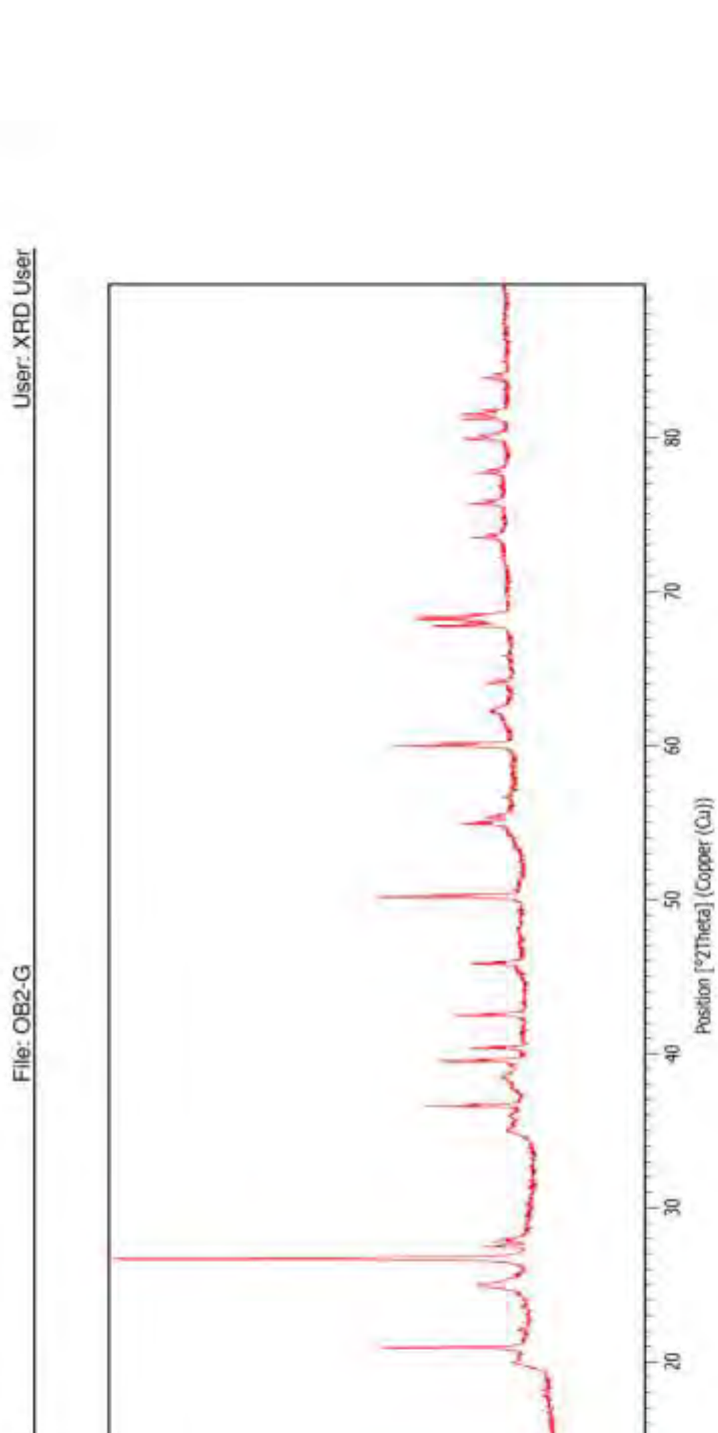

Date: 4/16/2014 Time: 12:10:37 PM
File: OB1
User: XRD User
Counts
10000
2500
0
OB1
10
20
30
Position [°2Theta] (Copper (Cu))


Counts
10000
2500
0
OB1
Montmorillonite, calcian
Muscovite-2M1
Kaolinite-1A
Muscovite-2M1
Kaolinite-1A; Muscovite-2M1
Kaolinite-1A; Quartz low, syn; Muscovite-2M1
Kaolinite-1A
10
20
30
Position [°2Theta] (Copper (Cu))

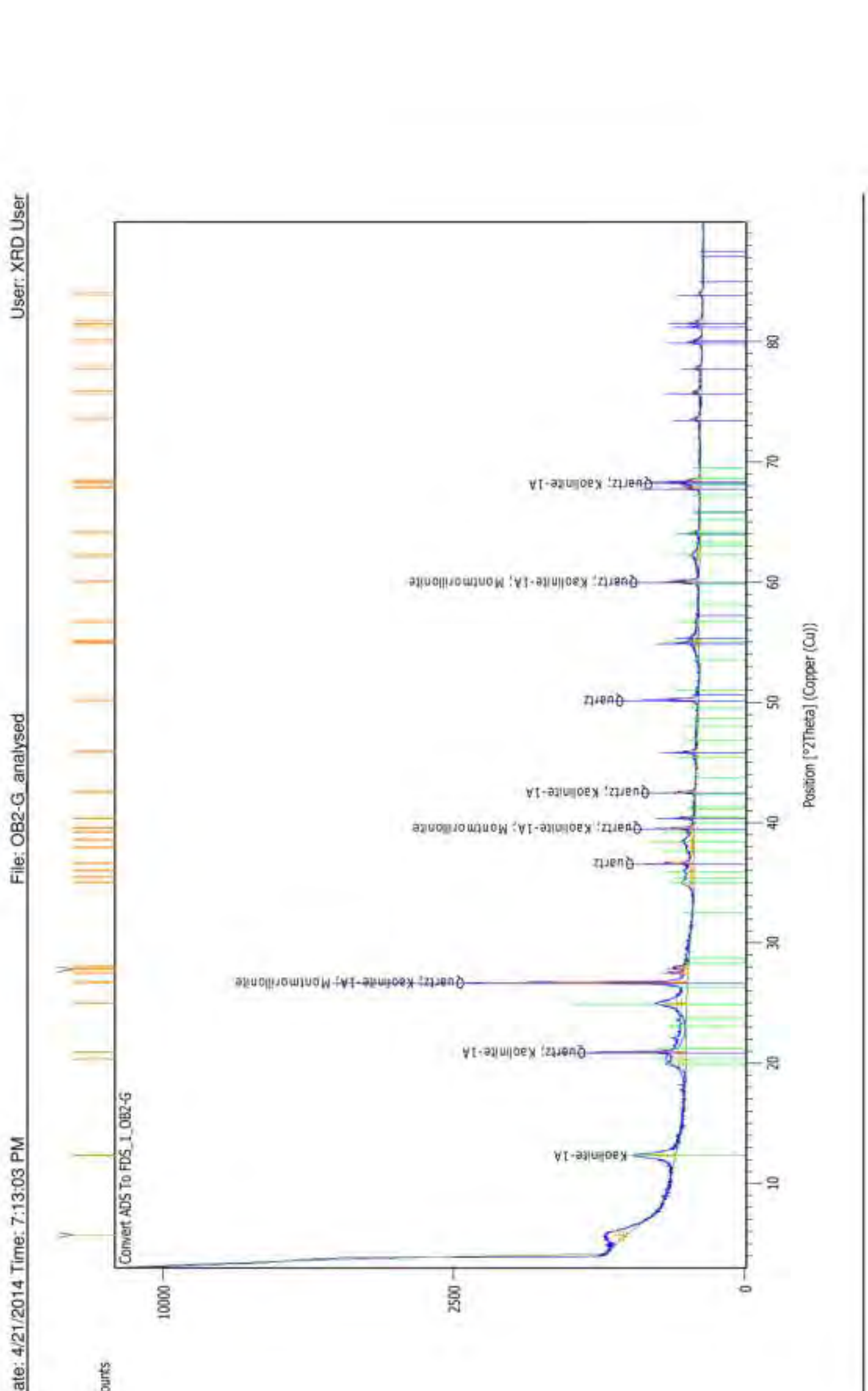

Date: 5/19/2014 Time: 10:12:22 AM
File: OB1 EG
User: XRD User
Counts
OB1 EG
3600
1600
400
0
5
10
15
20
25
Position [°2Theta] (Copper (Cu))

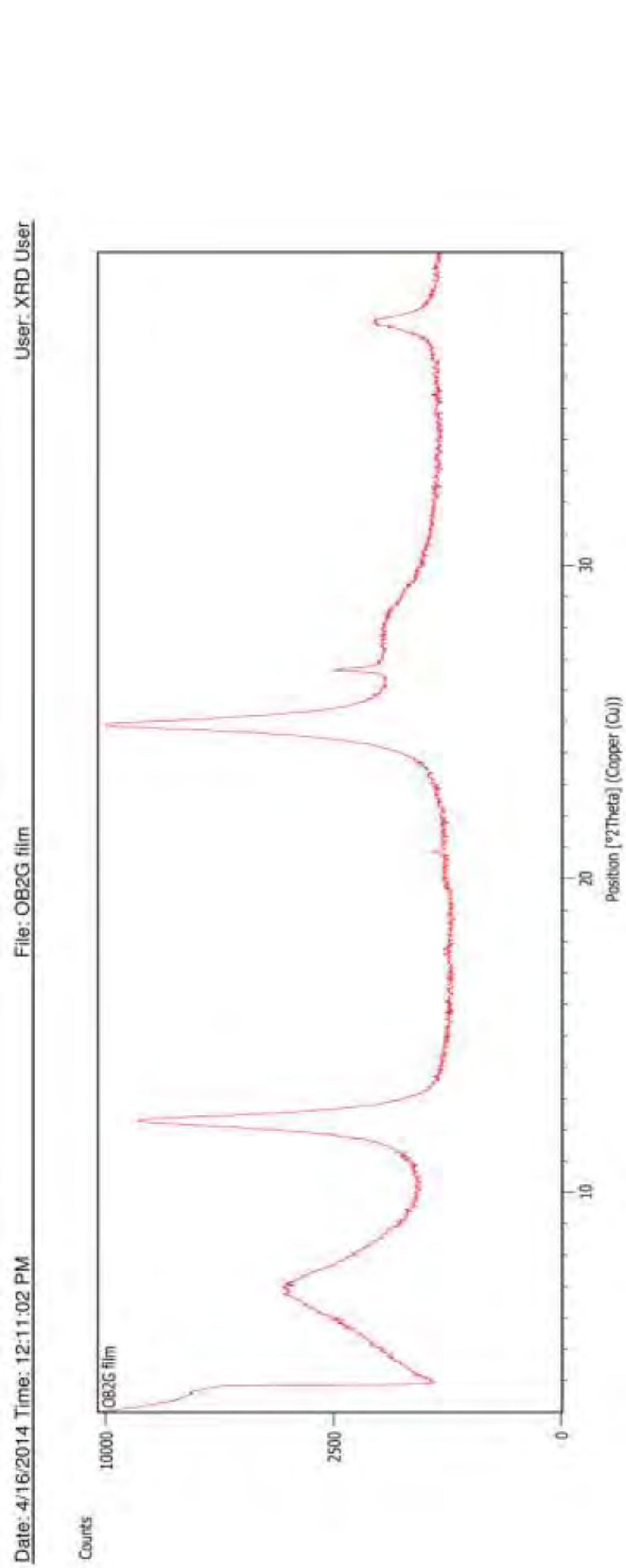

Date: 5/17/2014 Time: 9:33:26 PM
File: Analysed OB1 EG
User: XRD User
Counts
OB1 EG
3600
1600
400
0
Illite
Kaolinite
Illite
Quartz; kaolinite
Kaolinite
Quartz; Illite
5
10
15
20
25
Position [°2Theta] (Copper (Cu))

OBENG 2 BRICK FACTORY

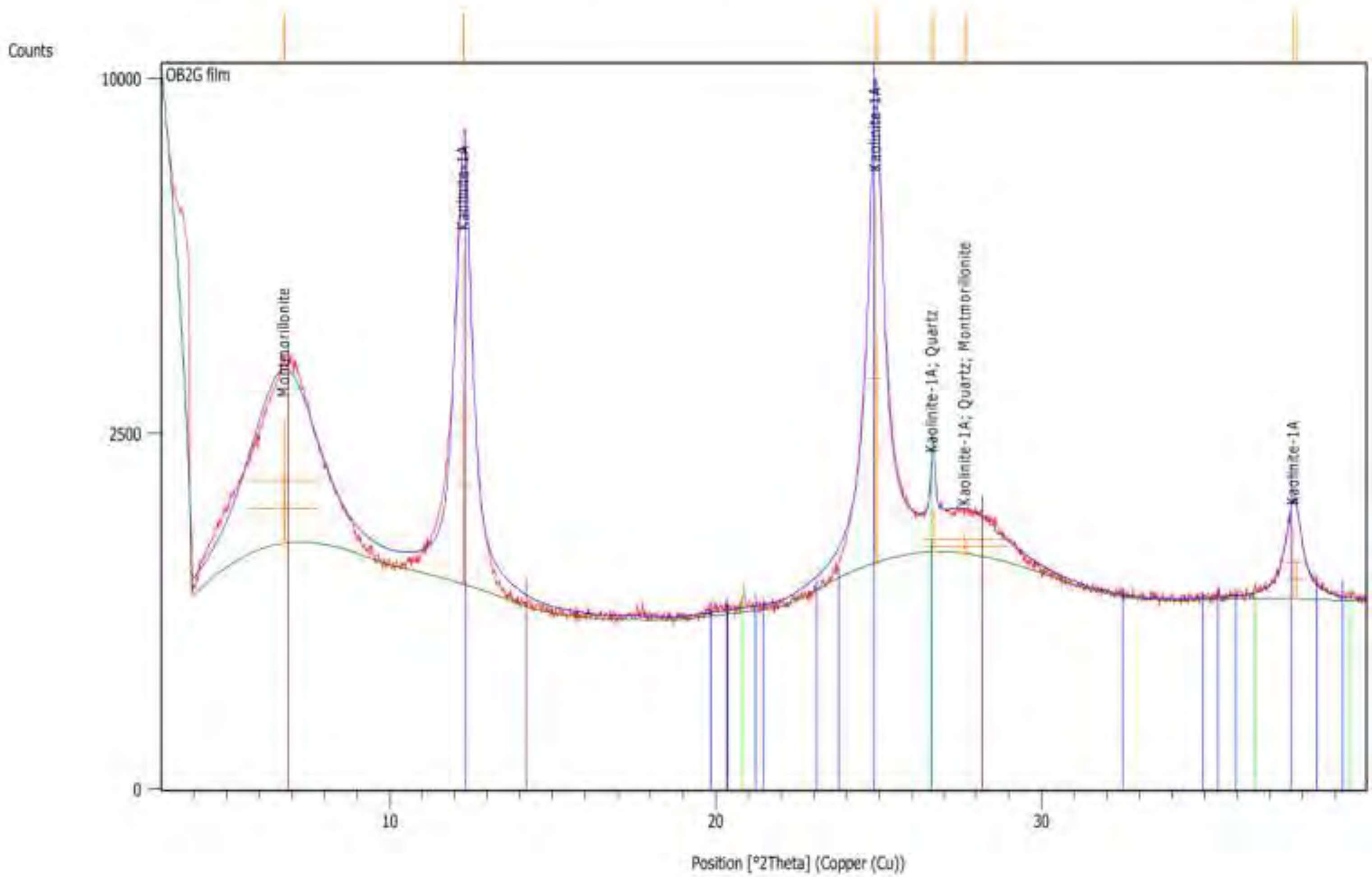


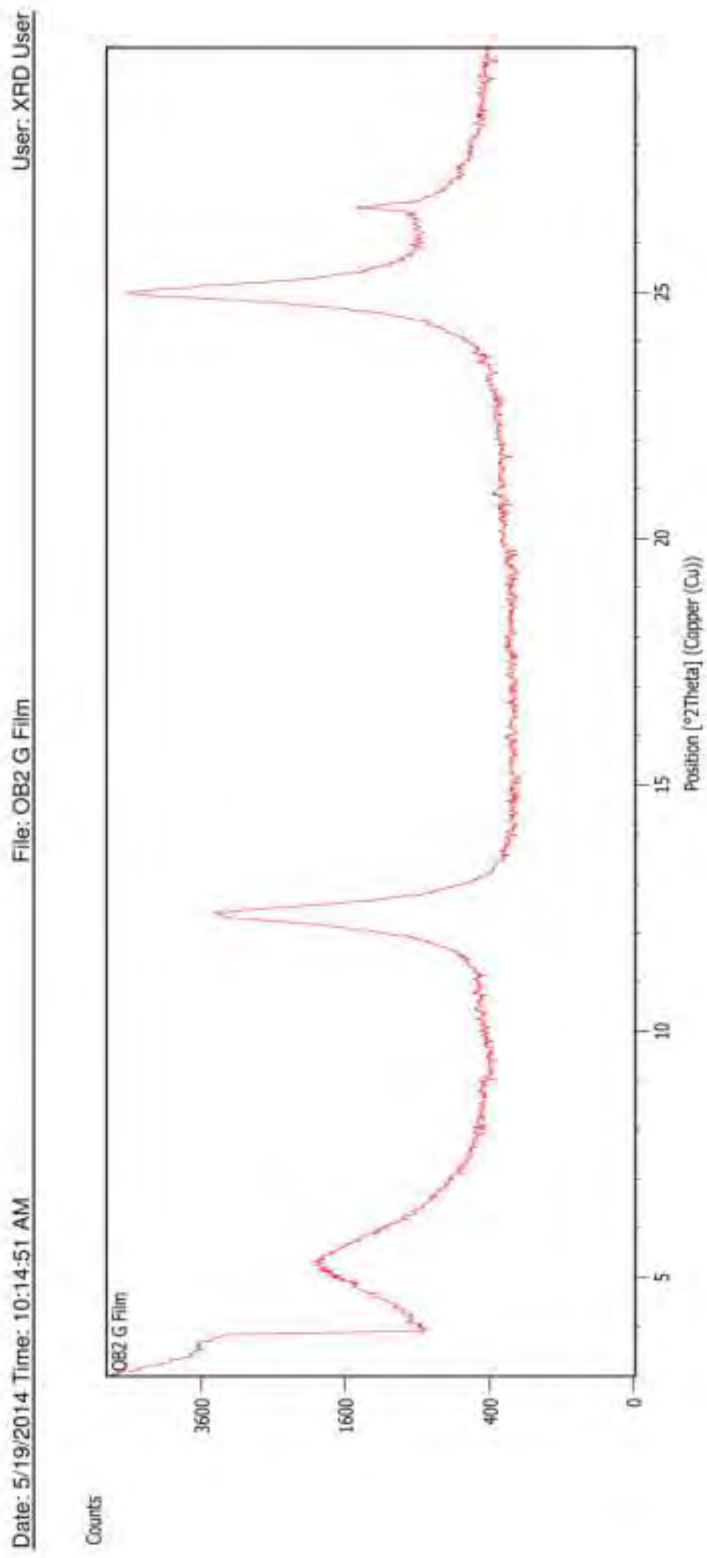
Date: 4/16/2014 Time: 12:12:20 PM
File: OB2-G
User: XRD User
Counts
10000
2500
0
OB2-G
10
20
30
40
50
60
70
80
Position [°2Theta] (Copper (Cu))

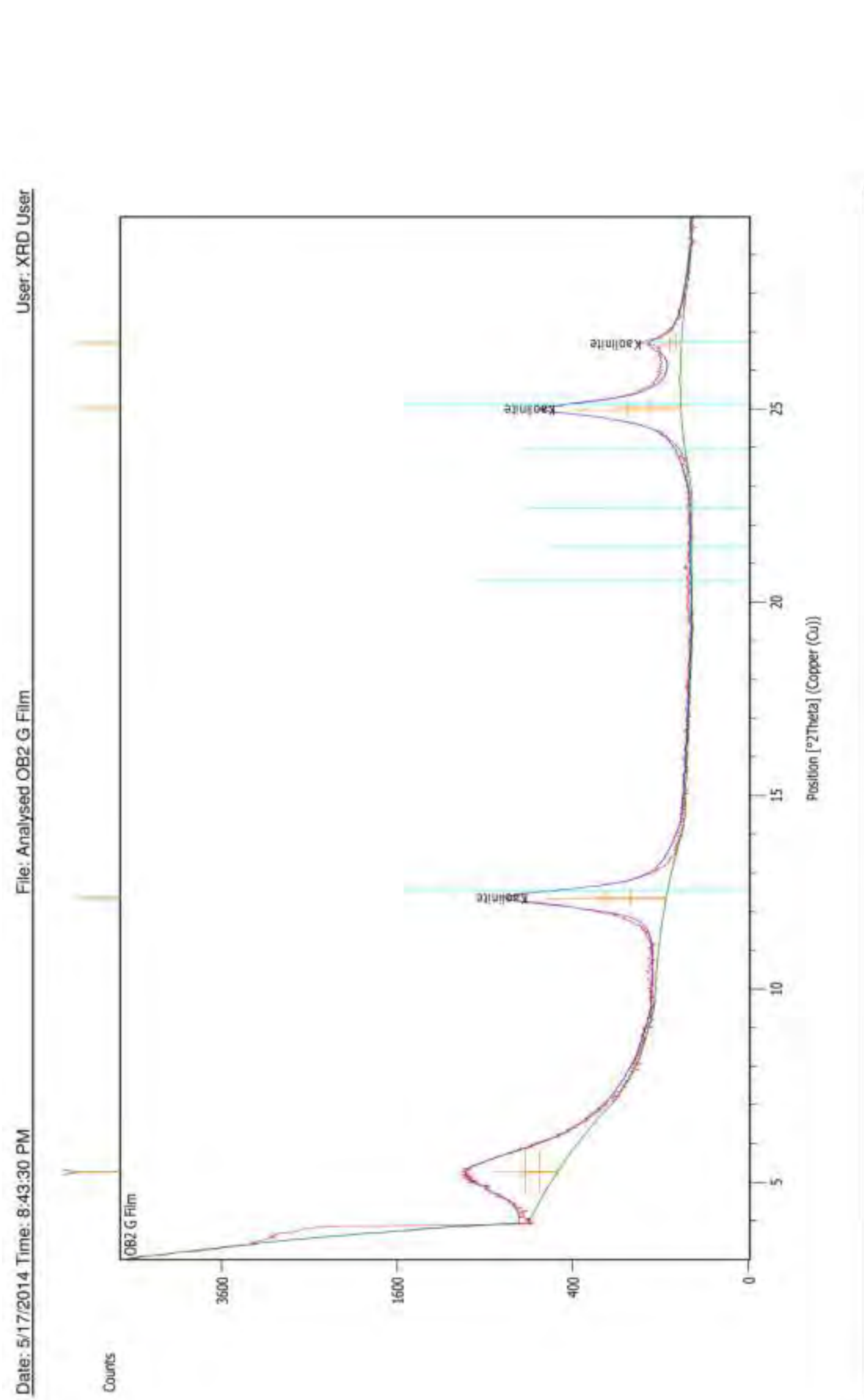

Date: 4/21/2014 Time: 7:13:03 PM
File: OB2-G_analysed
User: XRD User
Counts
10000
2500
0
Convert ADS To FDS_1_OB2-G
Kaolinite-1A
Quartz; Kaolinite-1A
Quartz; Kaolinite-1A; Montmorillonite
Quartz
Quartz; Kaolinite-1A; Montmorillonite
Quartz; Kaolinite-1A
Quartz
Quartz; Kaolinite-1A; Montmorillonite
Quartz; Kaolinite-1A
10
20
30
40
50
60
70
80
Position [°2Theta] (Copper (Cu))


Date: 4/16/2014 Time: 12:11:02 PM
File: OB2G film
User: XRD User
Counts
10000
2500
0
OB2G film
10
20
30
Position [°2Theta] (Copper (Cu))

Date: 4/21/2014 Time: 7:27:38 PM File: OB2G film_analysed User: XRD User

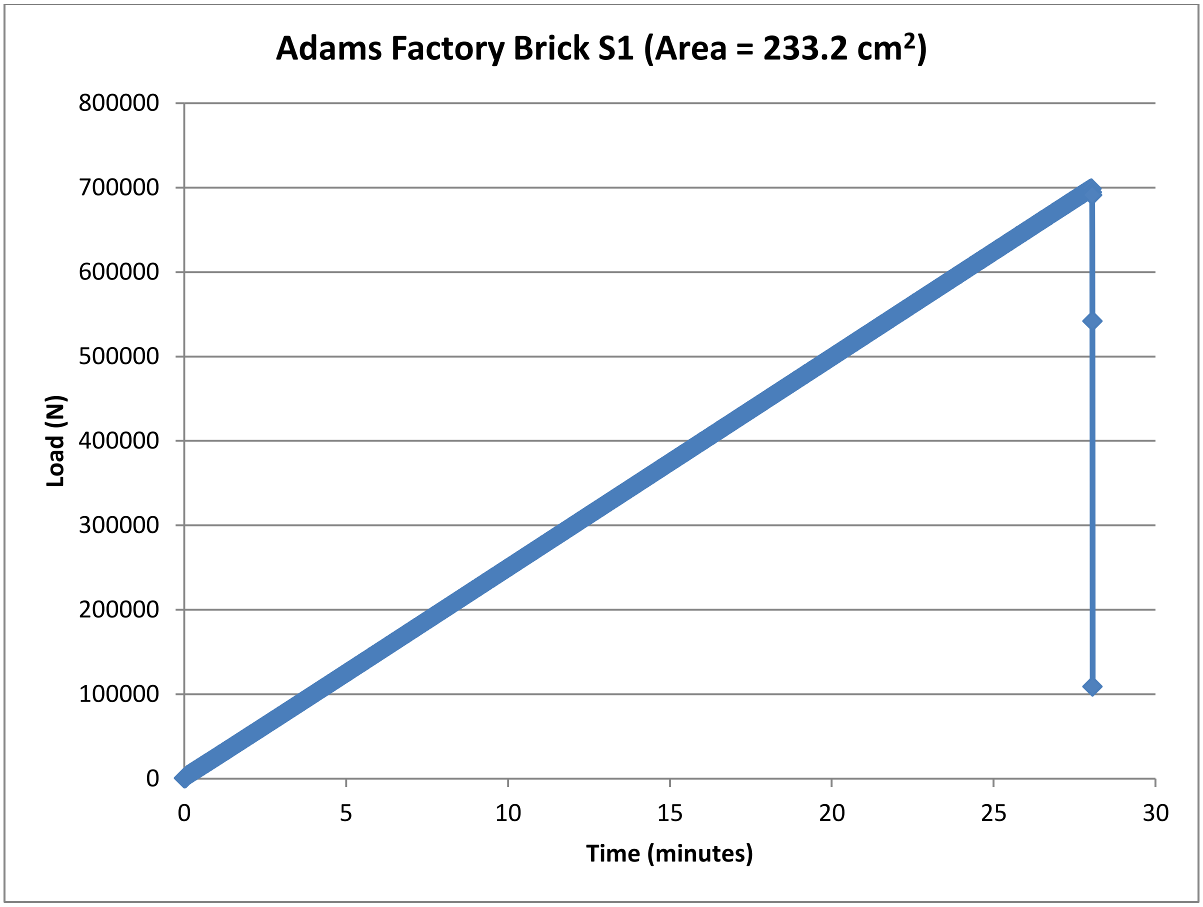


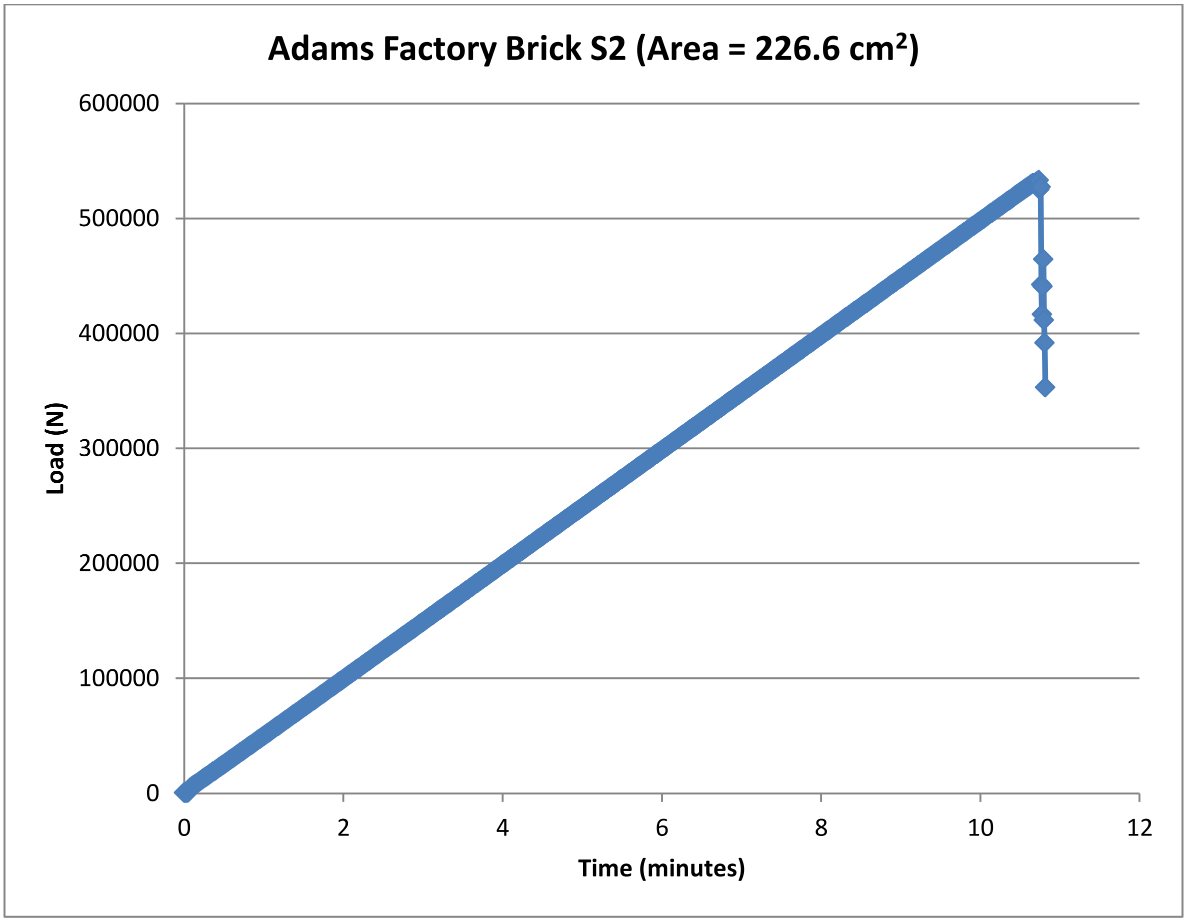

Date: 5/19/2014 Time: 10:14:51 AM
File: OB2 G Film
User: XRD User
Counts
3600
1600
400
0
OB2 G Film
5
10
15
20
25
Position [°2Theta] (Copper (Cu))



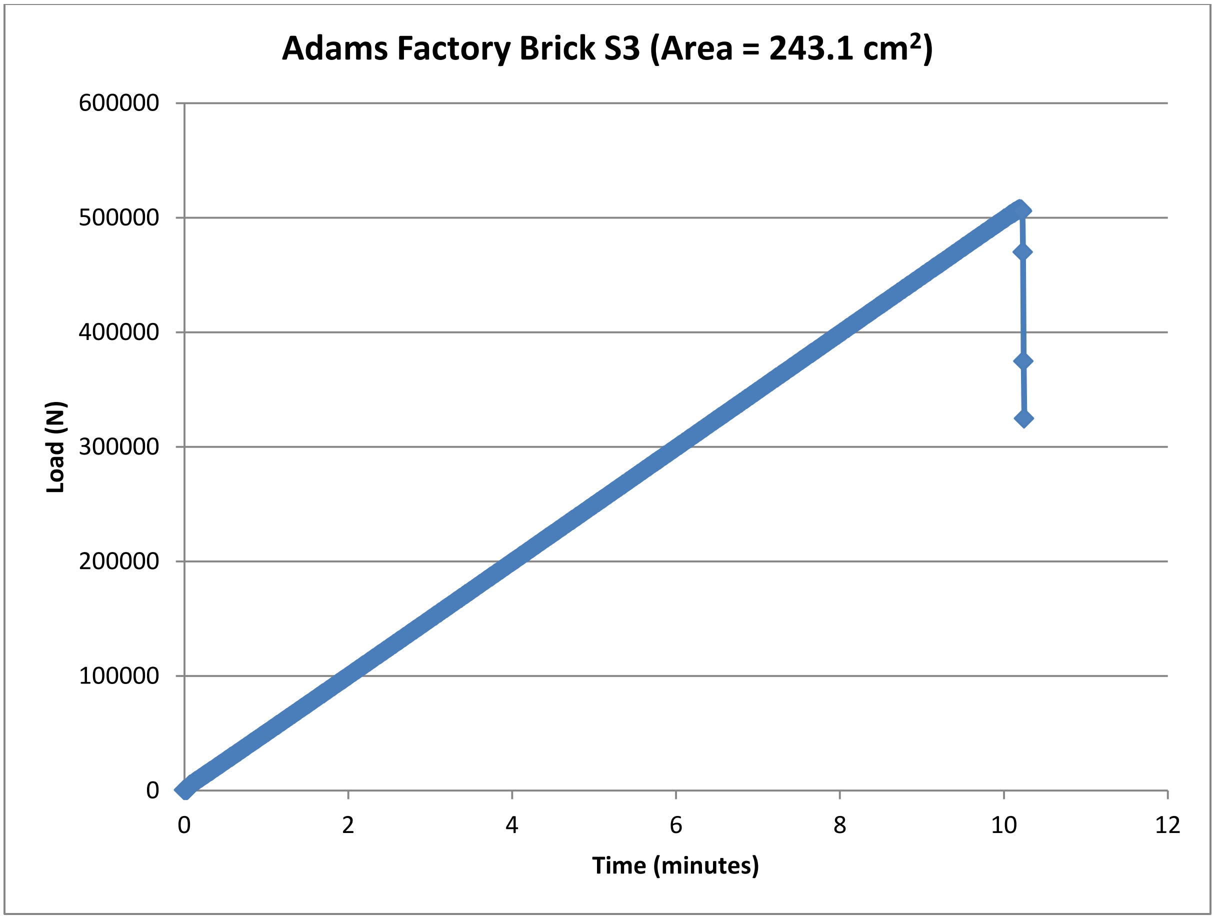
Date: 5/17/2014 Time: 8:43:30 PM
File: Analysed OB2 G Film
User: XRD User
Counts
3600
1600
400
0
OB2 G Film
Kaolinite
Kaolinite
Kaolinite
5
10
15
20
25
Position [°2Theta] (Copper (Cu))

APPENDIX D

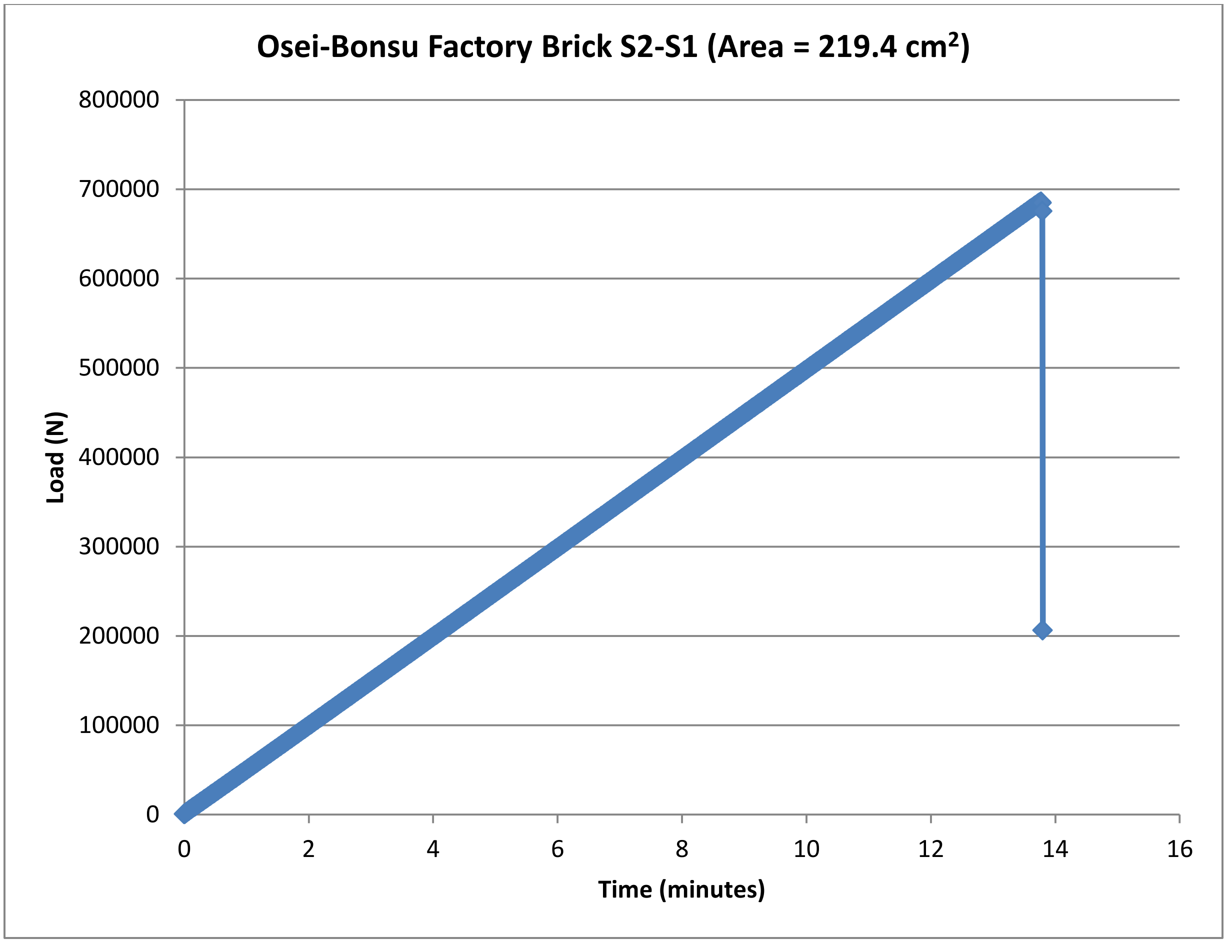

Adams Factory Brick S1 (Area = 233.2 cm²)
Load (N)
800000
700000
600000
500000
400000
300000
200000
100000
0
0
5
10
15
20
25
30
Time (minutes)

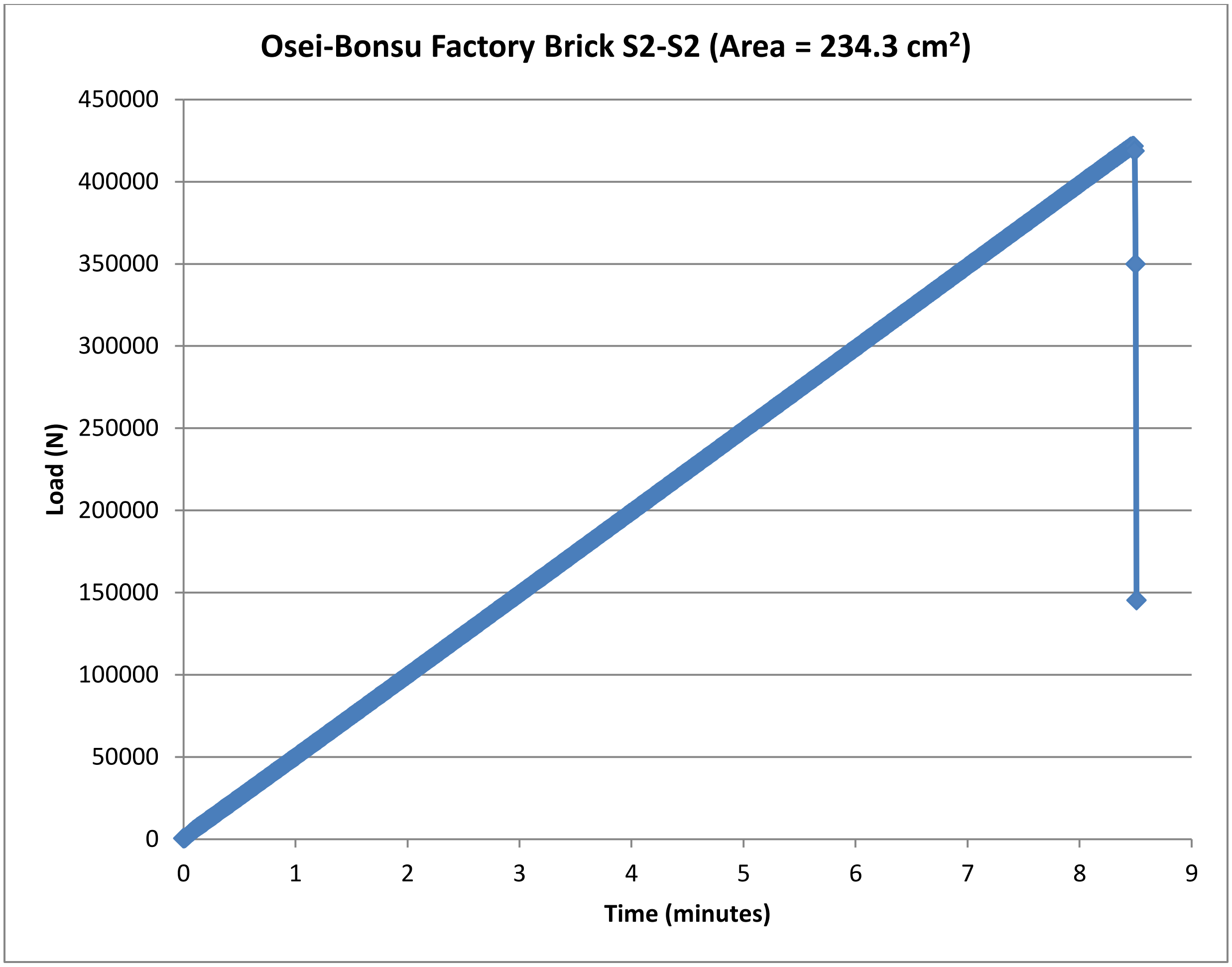


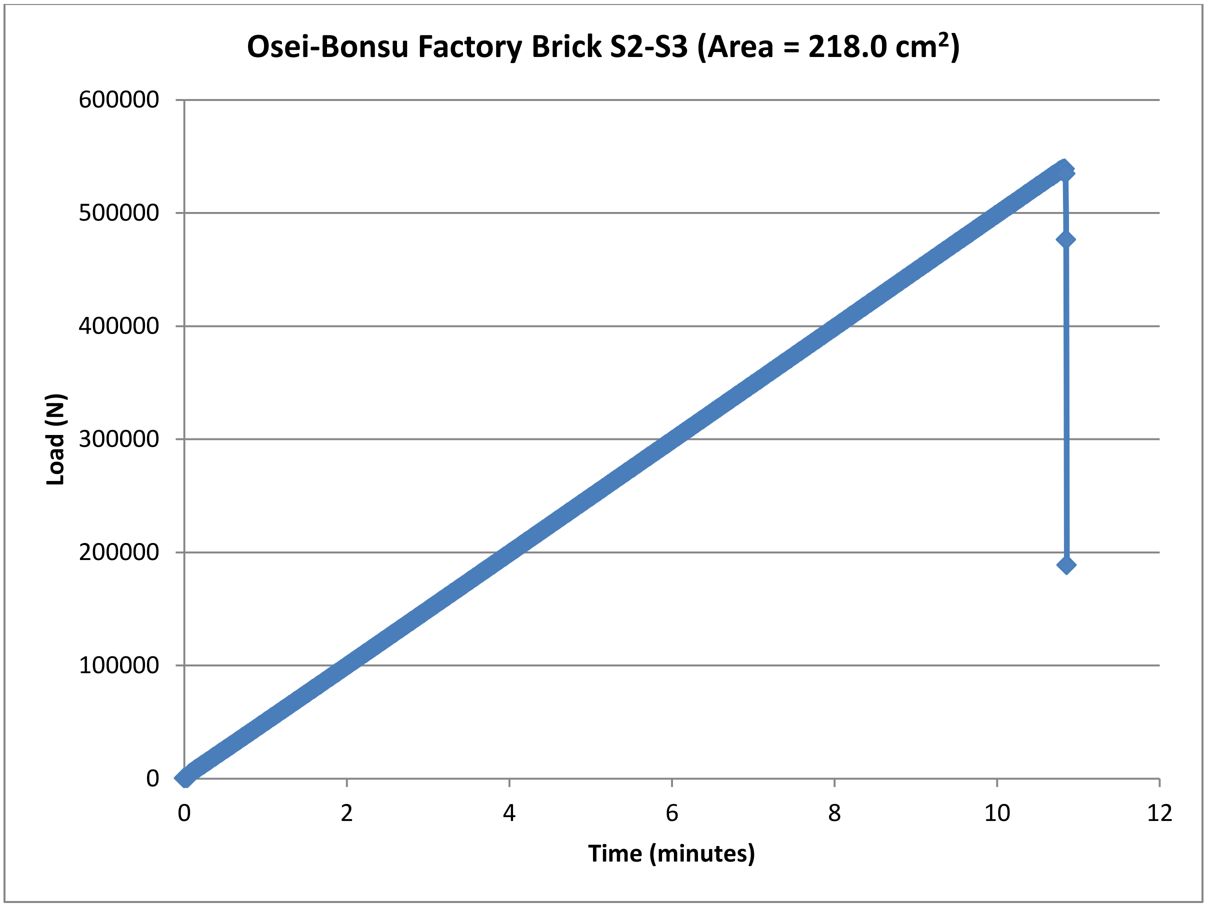
Adams Factory Brick S2 (Area = 226.6 cm²)
600000
500000
400000
300000
200000
100000
0
Load (N)
0
2
4
6
8
10
12
Time (minutes)



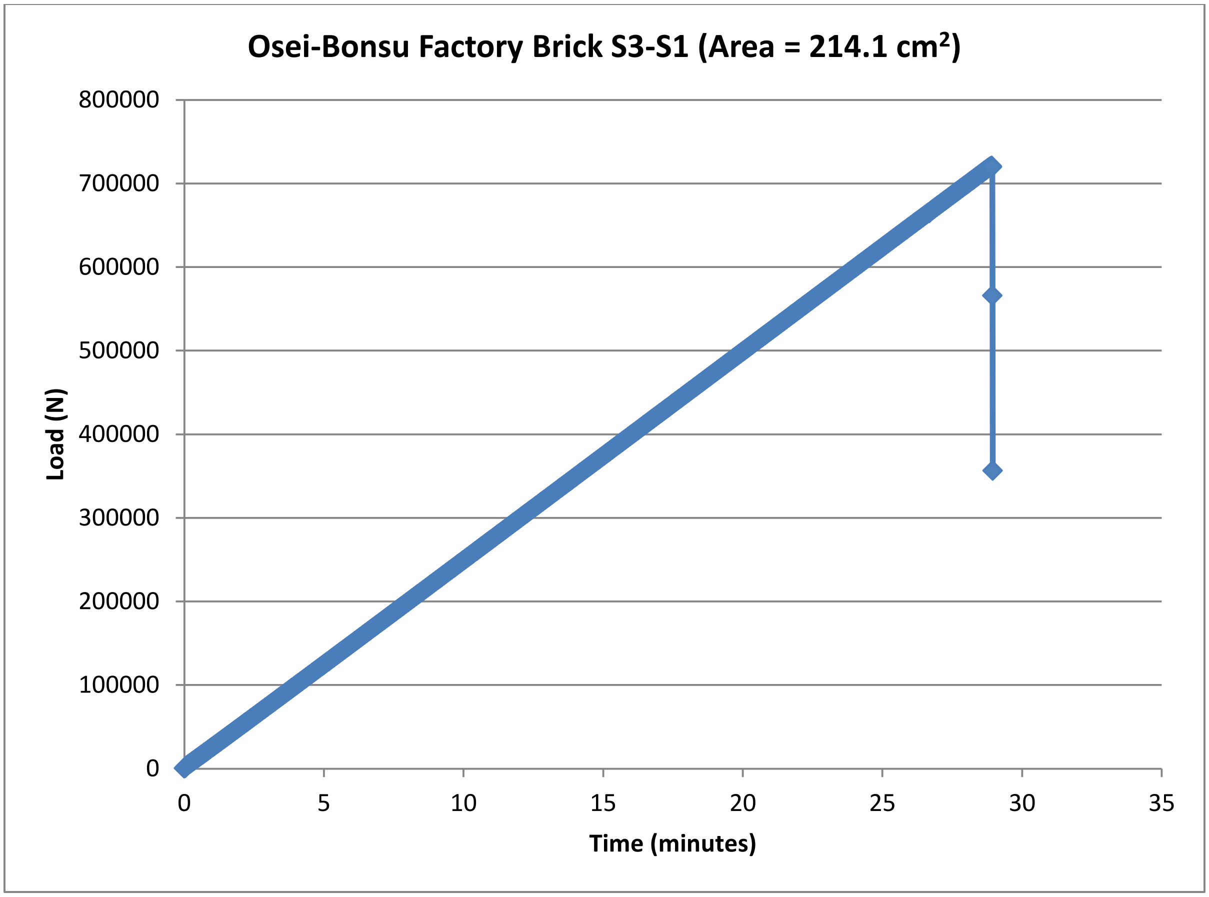
Adams Factory Brick S3 (Area = 243.1 cm²)
600000
500000
400000
300000
200000
100000
0
Load (N)
0
2
4
6
8
10
12
Time (minutes)


Osei-Bonsu Factory Brick S2-S1 (Area = 219.4 cm²)
800000
700000
600000
500000
400000
300000
200000
100000
0
Load (N)
0
2
4
6
8
10
12
14
16
Time (minutes)

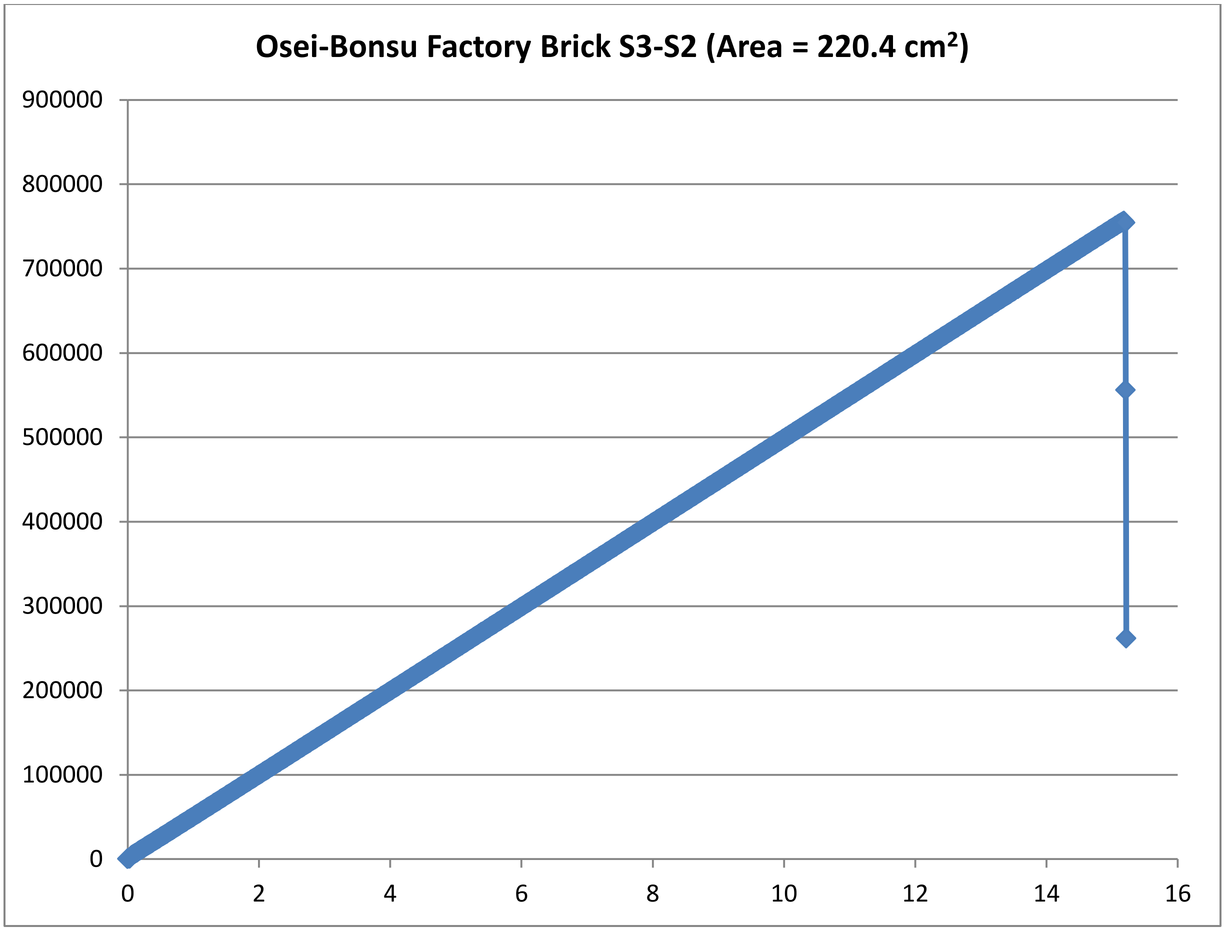

Osei-Bonsu Factory Brick S2-S2 (Area = 234.3 cm²)
450000
400000
350000
300000
250000
200000
150000
100000
50000
0
Load (N)
0
1
2
3
4
5
6
7
8
9
Time (minutes)



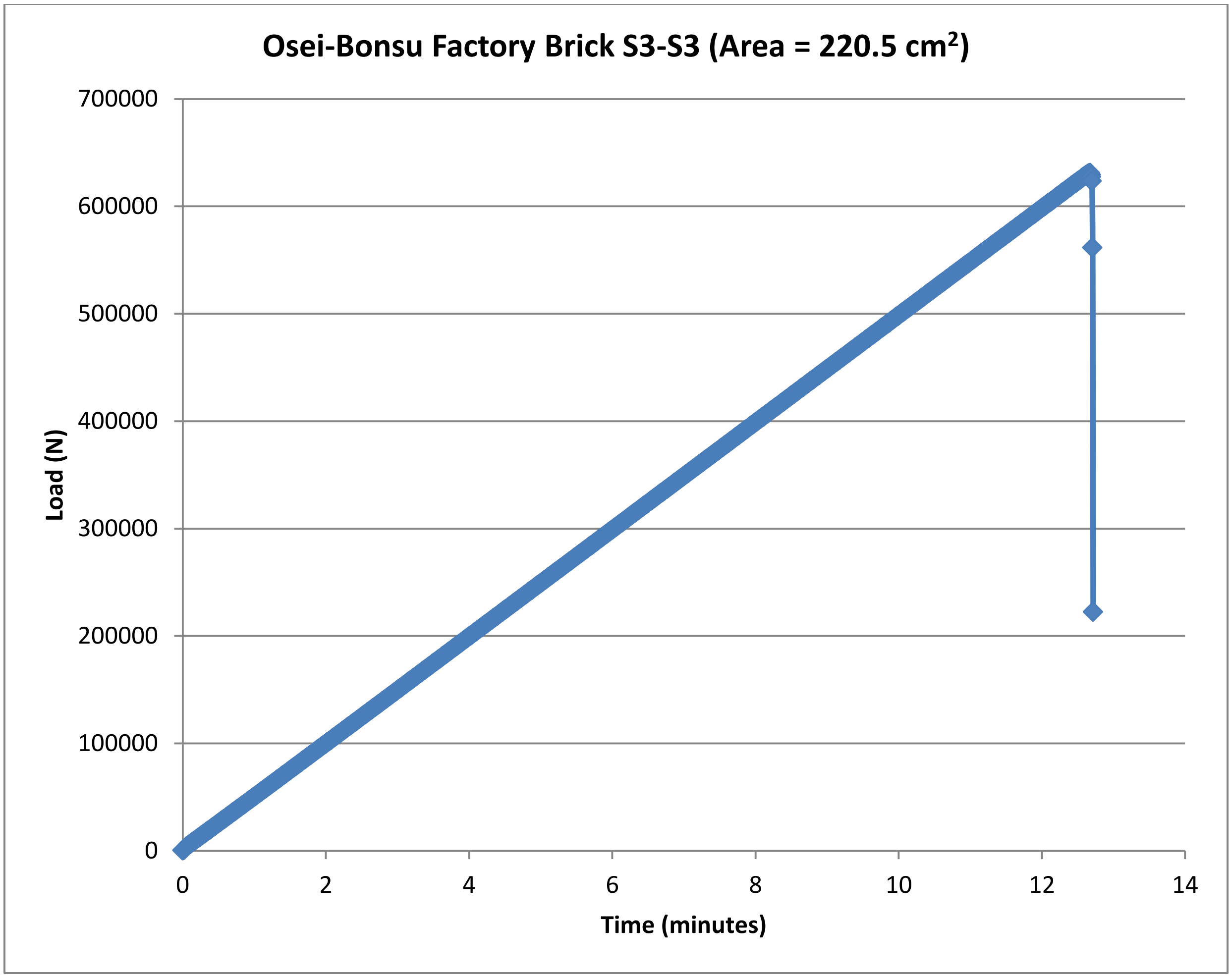
Osei-Bonsu Factory Brick S2-S3 (Area = 218.0 cm²)
600000
500000
400000
300000
200000
100000
0
Load (N)
0
2
4
6
8
10
12
Time (minutes)

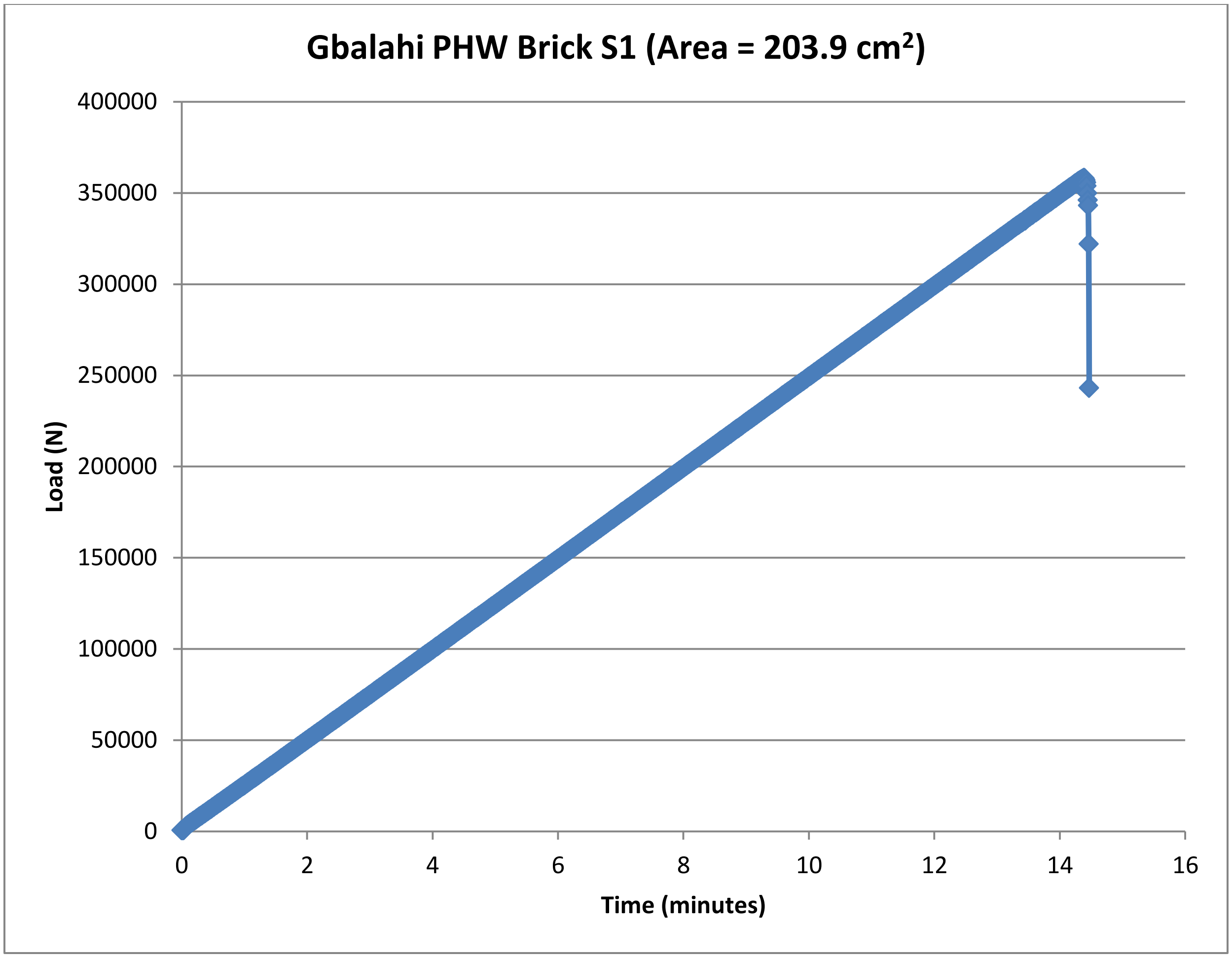


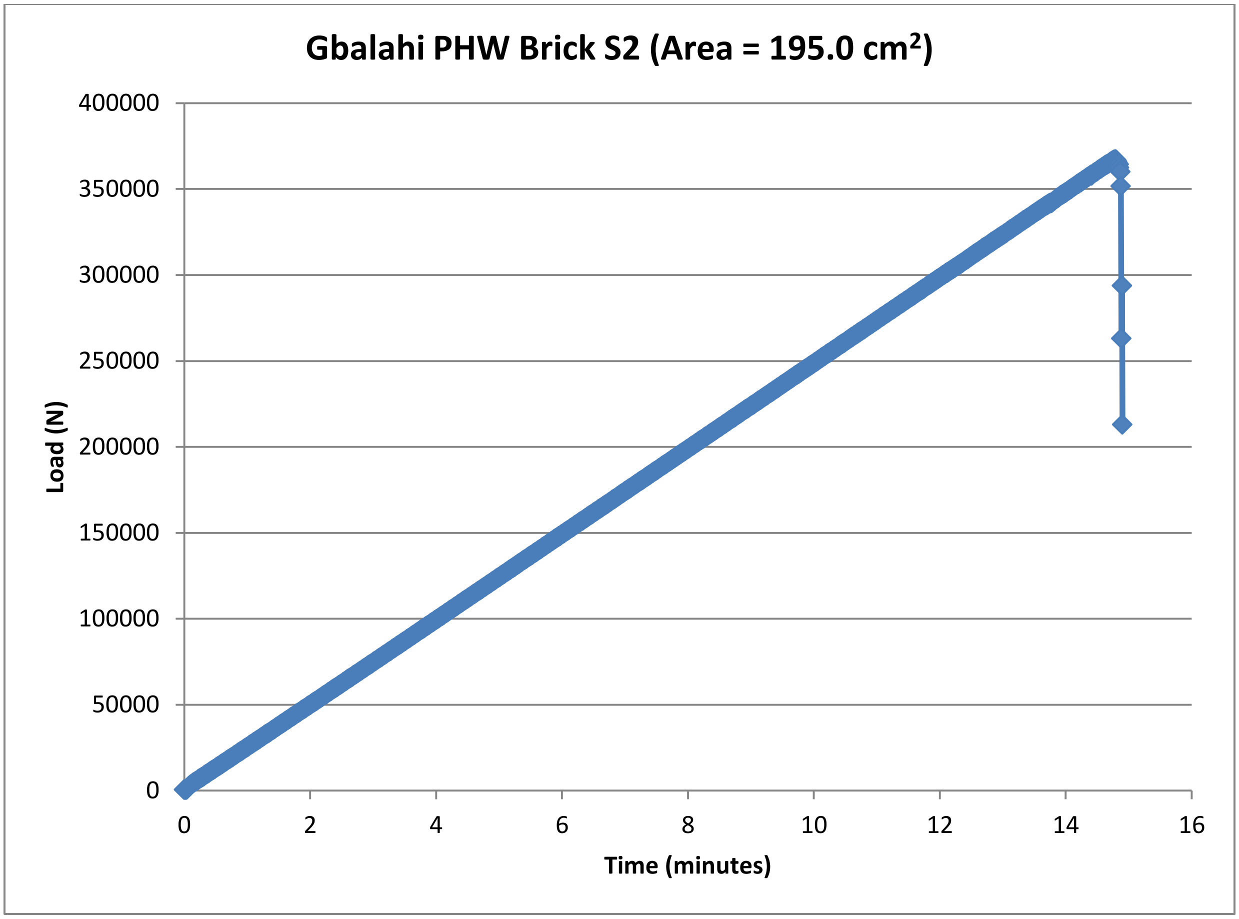
Osei-Bonsu Factory Brick S3-S1 (Area = 214.1 cm²)
800000
700000
600000
500000
400000
300000
200000
100000
0
Load (N)
0
5
10
15
20
25
30
35
Time (minutes)

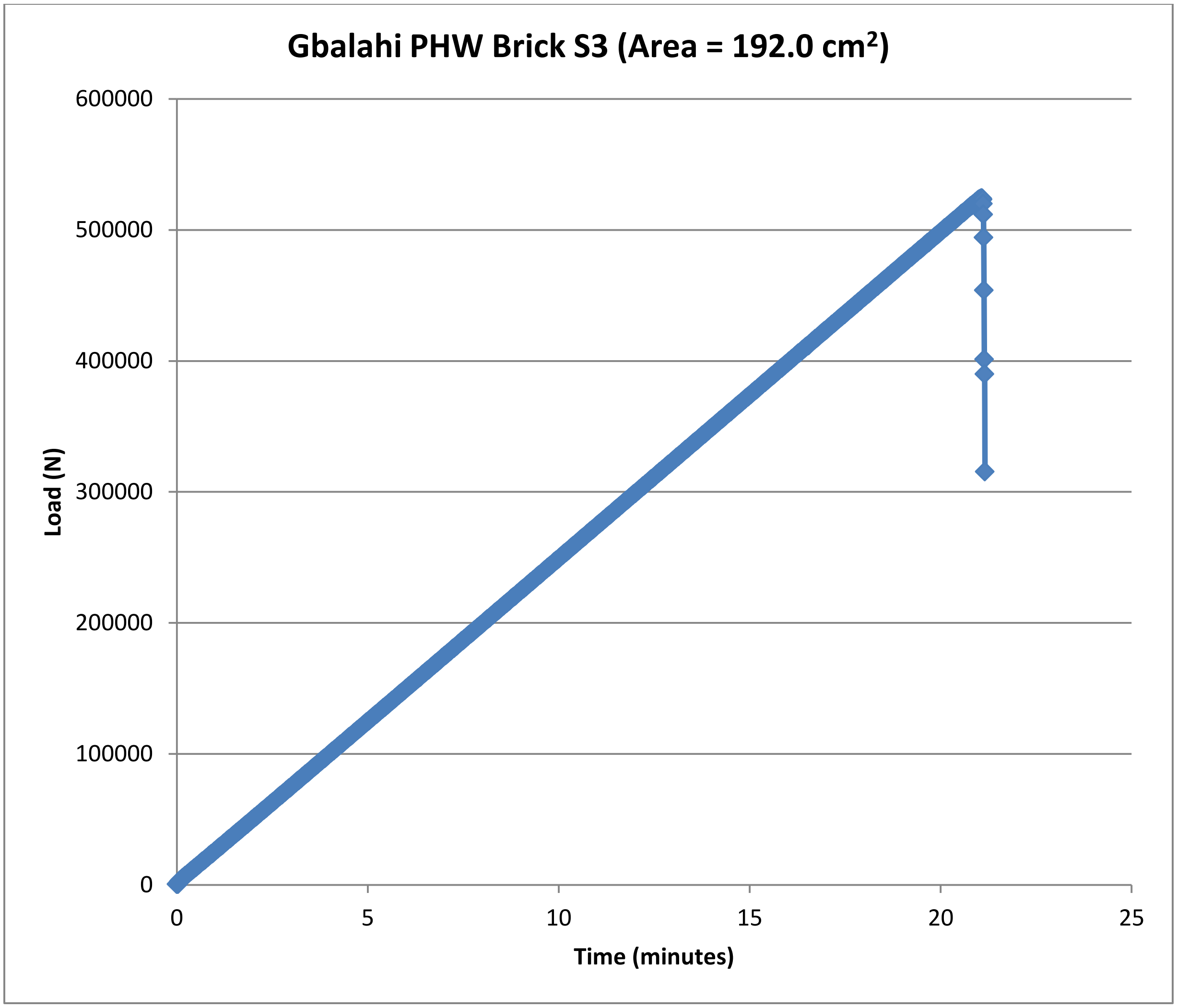


Osei-Bonsu Factory Brick S3-S2 (Area = 220.4 cm²)
900000
800000
700000
600000
500000
400000
300000
200000
100000
0
0
2
4
6
8
10
12
14
16

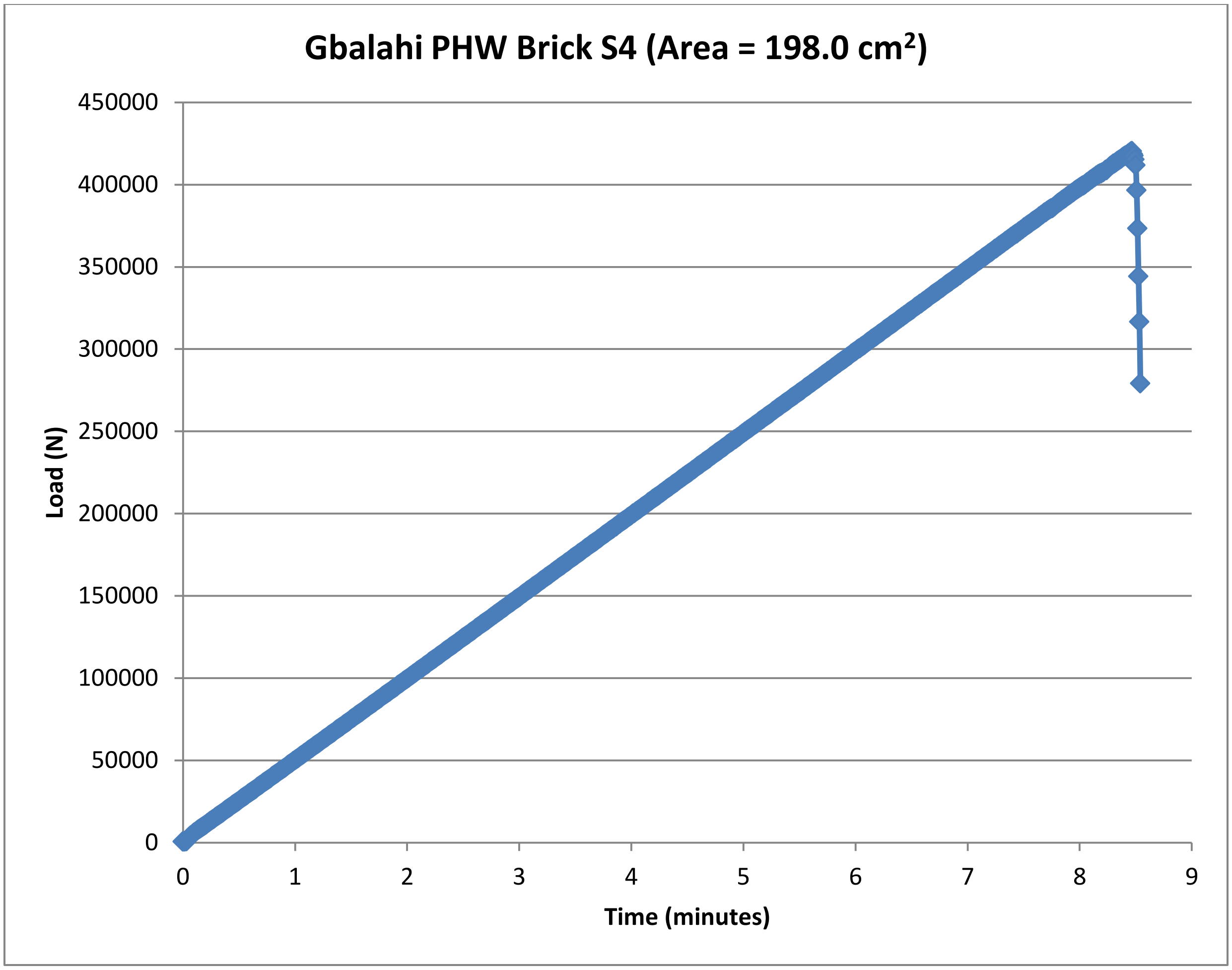

Osei-Bonsu Factory Brick S3-S3 (Area = 220.5 cm²)
Load (N)
700000
600000
500000
400000
300000
200000
100000
0
0
2
4
6
8
10
12
14
Time (minutes)


Gbalahi PHW Brick S1 (Area = 203.9 cm²)
Load (N)
400000
350000
300000
250000
200000
150000
100000
50000
0
0
2
4
6
8
10
12
14
16
Time (minutes)

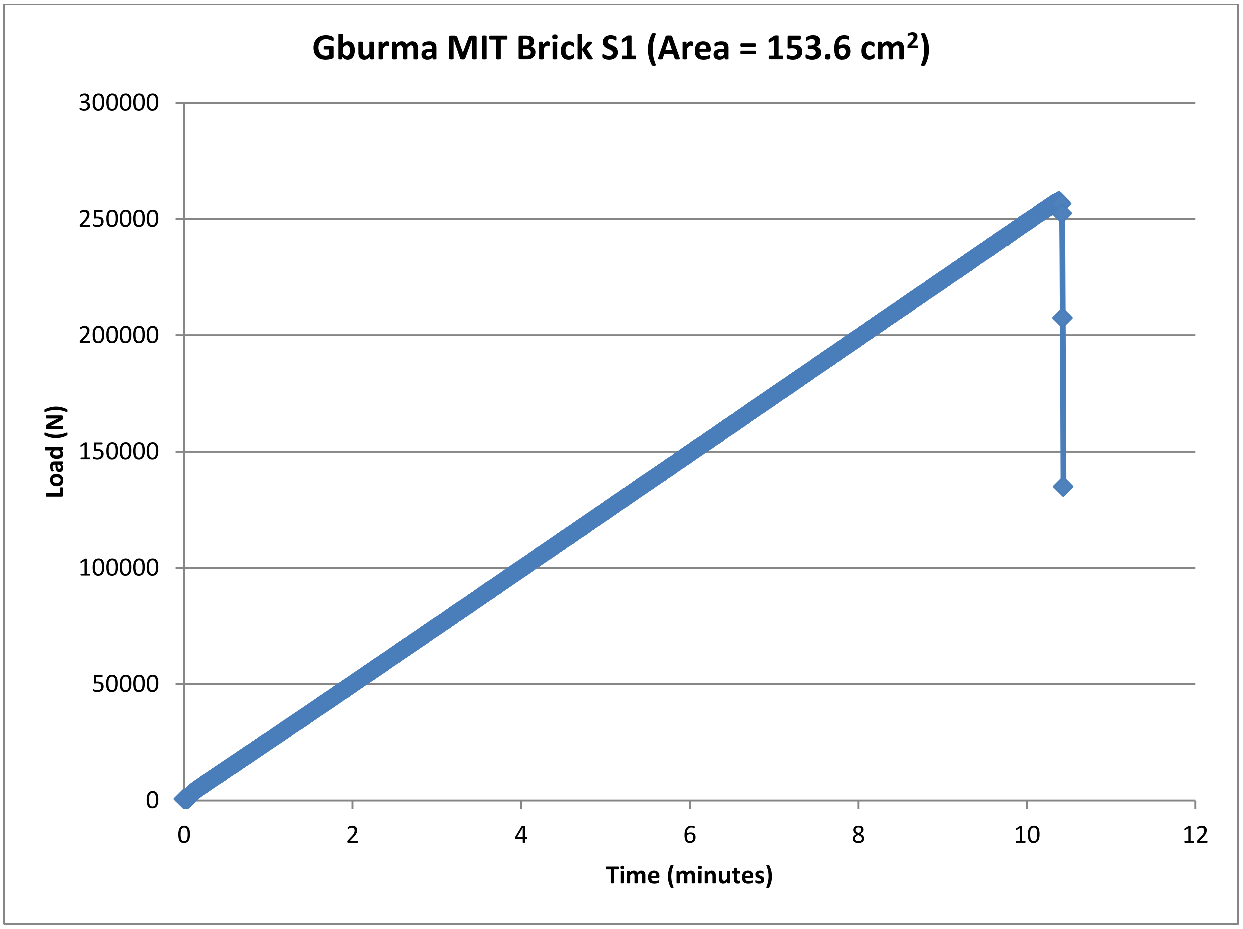

Gbalahi PHW Brick S2 (Area = 195.0 cm²)
400000
350000
300000
250000
200000
150000
100000
50000
0
Load (N)
0
2
4
6
8
10
12
14
16
Time (minutes)



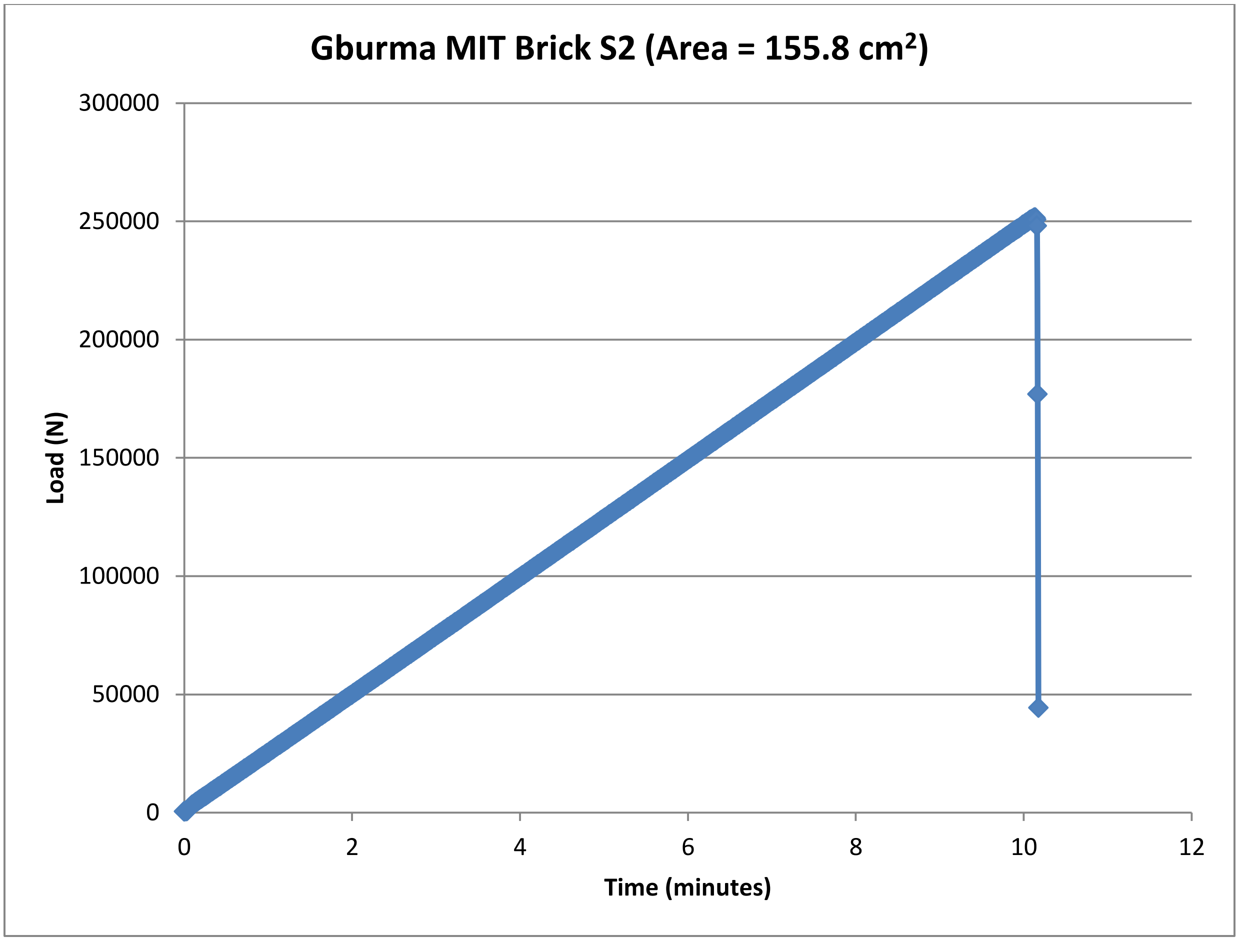
Gbalahi PHW Brick S3 (Area = 192.0 cm²)
600000
500000
400000
300000
200000
100000
0
Load (N)
0
5
10
15
20
25
Time (minutes)



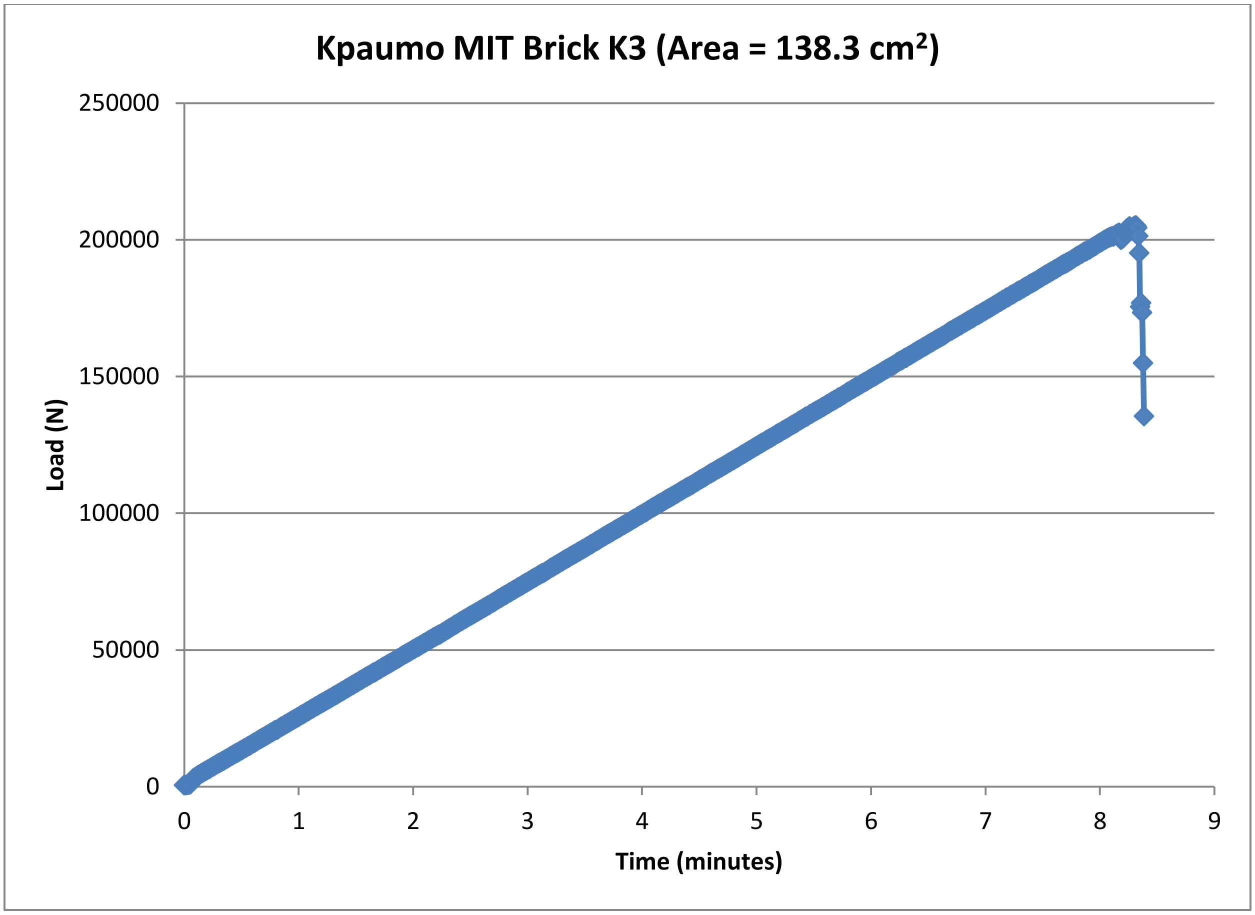
Gbalahi PHW Brick S4 (Area = 198.0 cm²)
450000
400000
350000
300000
250000
200000
150000
100000
50000
0
Load (N)
0
1
2
3
4
5
6
7
8
9
Time (minutes)



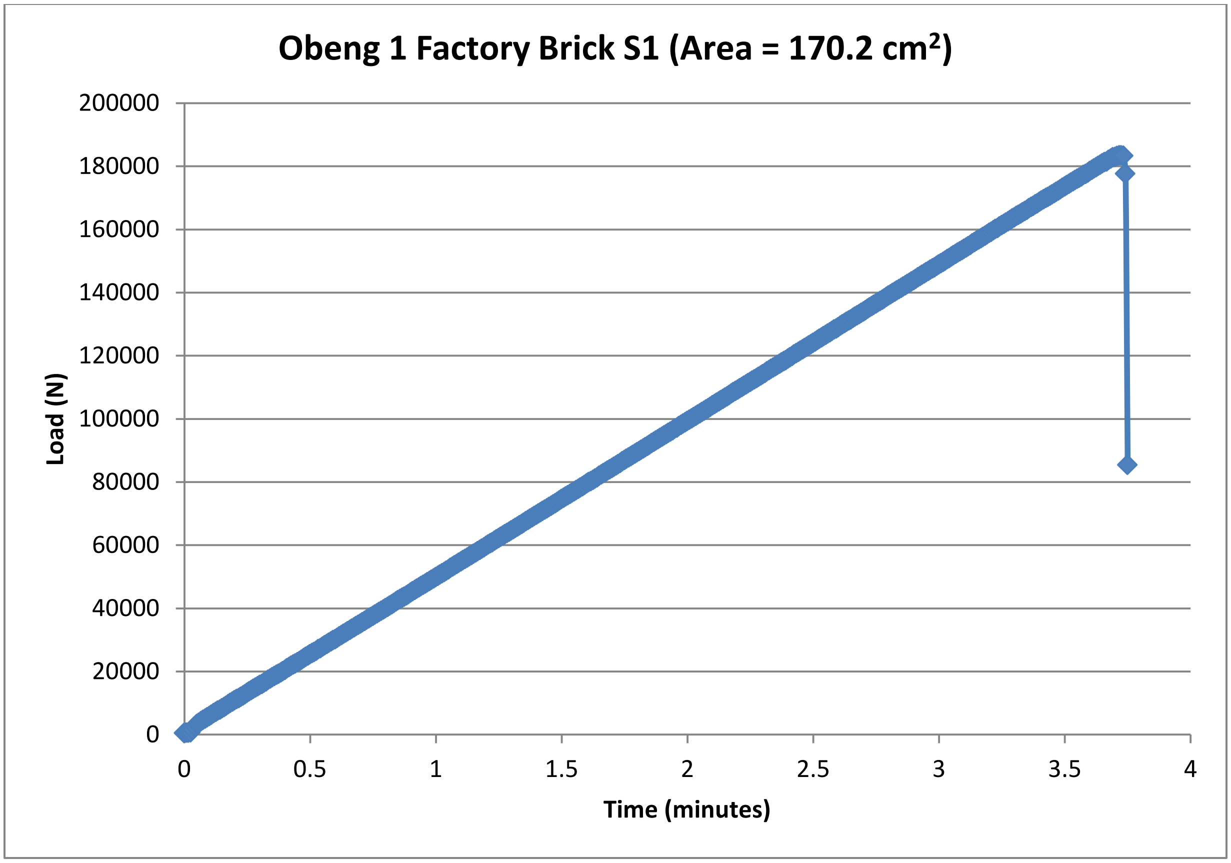
Gburma MIT Brick S1 (Area = 153.6 cm2)
300000
250000
200000
150000
100000
50000
0
Load (N)
0
2
4
6
8
10
12
Time (minutes)

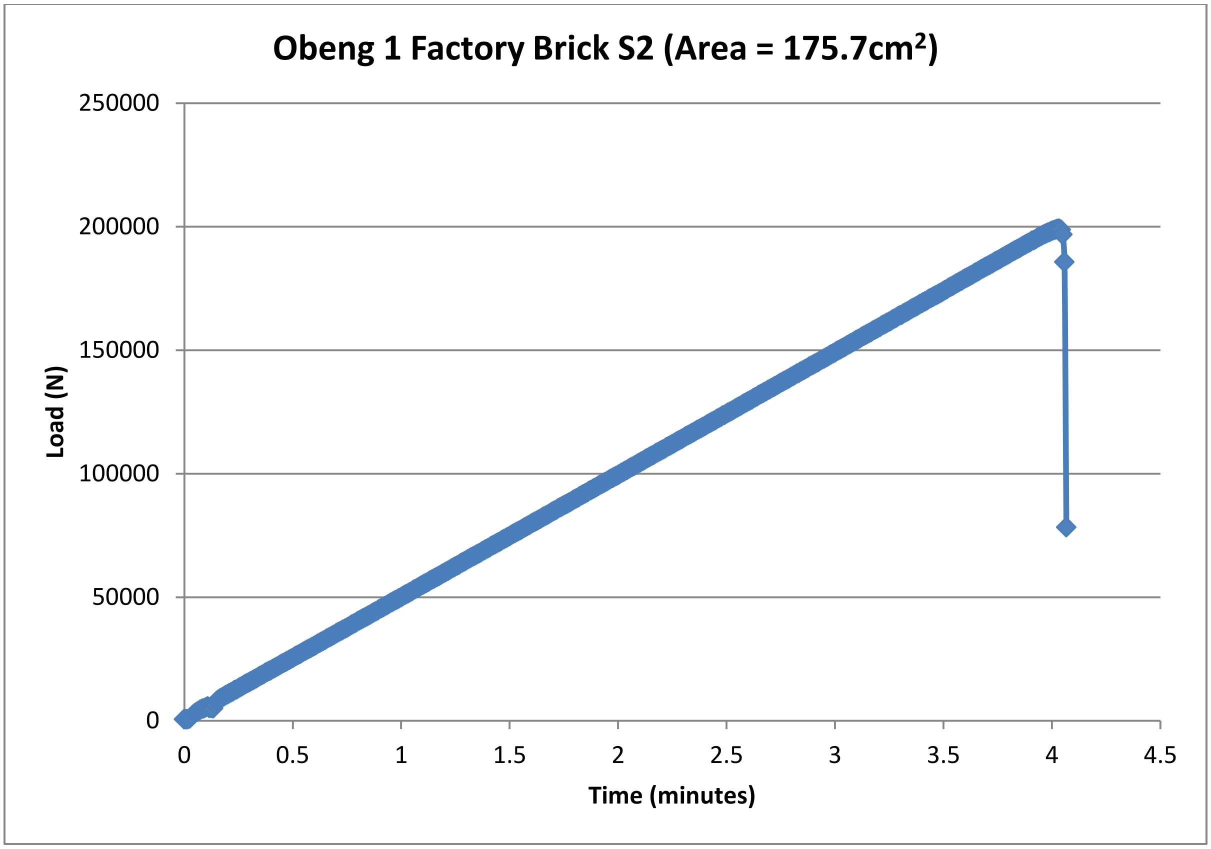


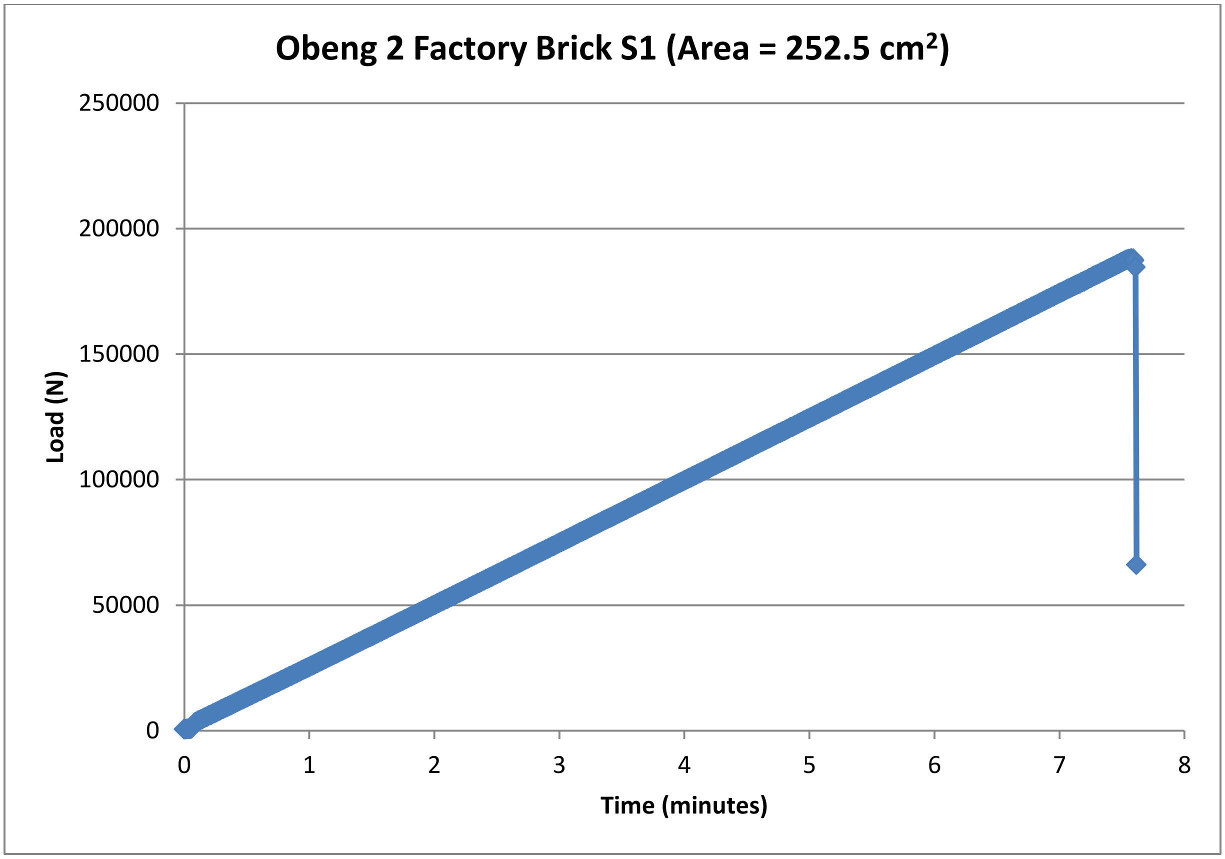
Gburma MIT Brick S2 (Area = 155.8 cm2)
300000
250000
200000
150000
100000
50000
0
Load (N)
0
2
4
6
8
10
12
Time (minutes)



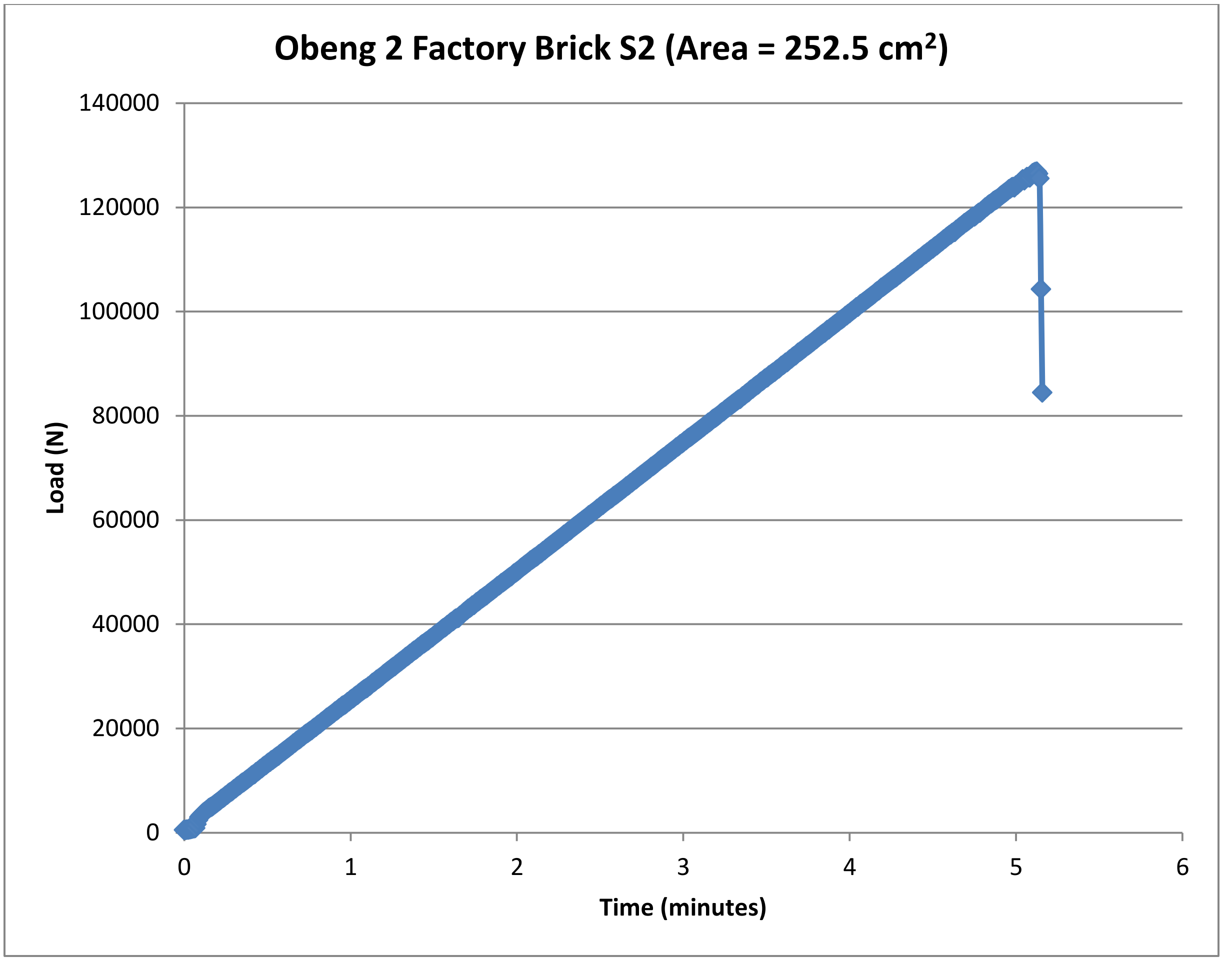
Kpaumo MIT Brick K3 (Area = 138.3 cm²)
250000
200000
150000
100000
50000
0
Load (N)
0
1
2
3
4
5
6
7
8
9
Time (minutes)

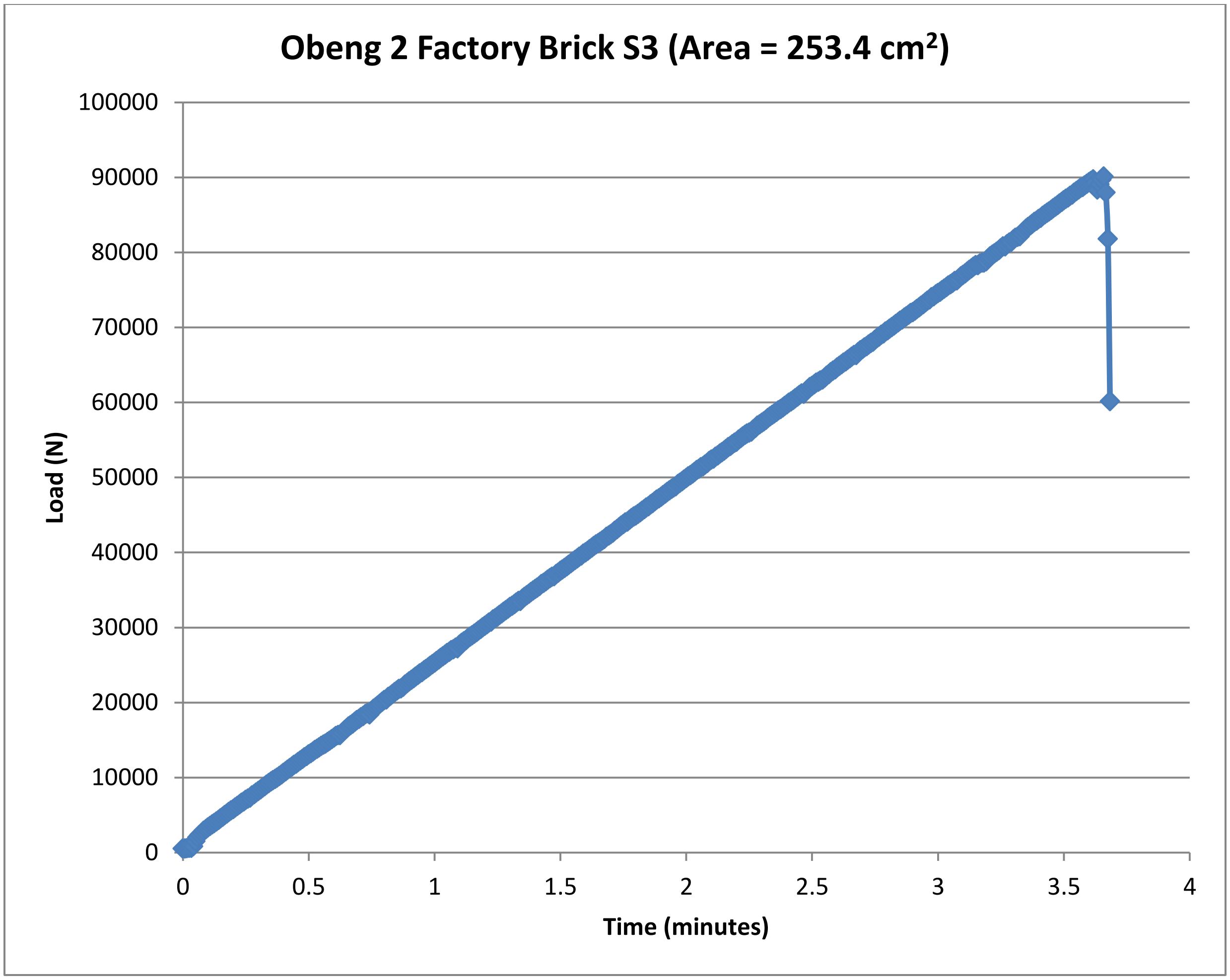

Obeng 1 Factory Brick S1 (Area = 170.2 cm²)
Load (N)
200000
180000
160000
140000
120000
100000
80000
60000
40000
20000
0
0
0.5
1
1.5
2
2.5
3
3.5
4
Time (minutes)


Obeng 1 Factory Brick S2 (Area = 175.7cm²)
250000
200000
150000
100000
50000
0
Load (N)
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
Time (minutes)

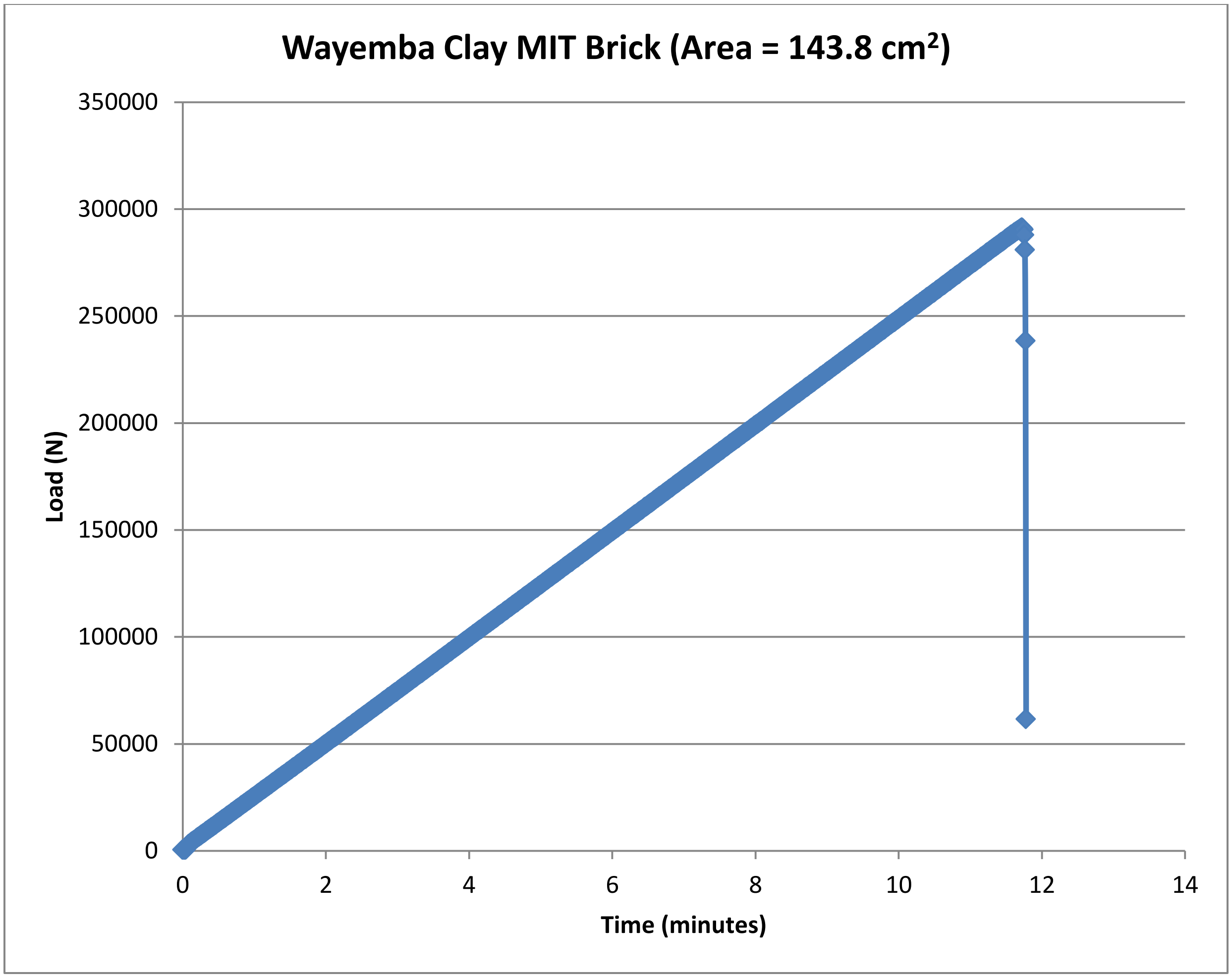


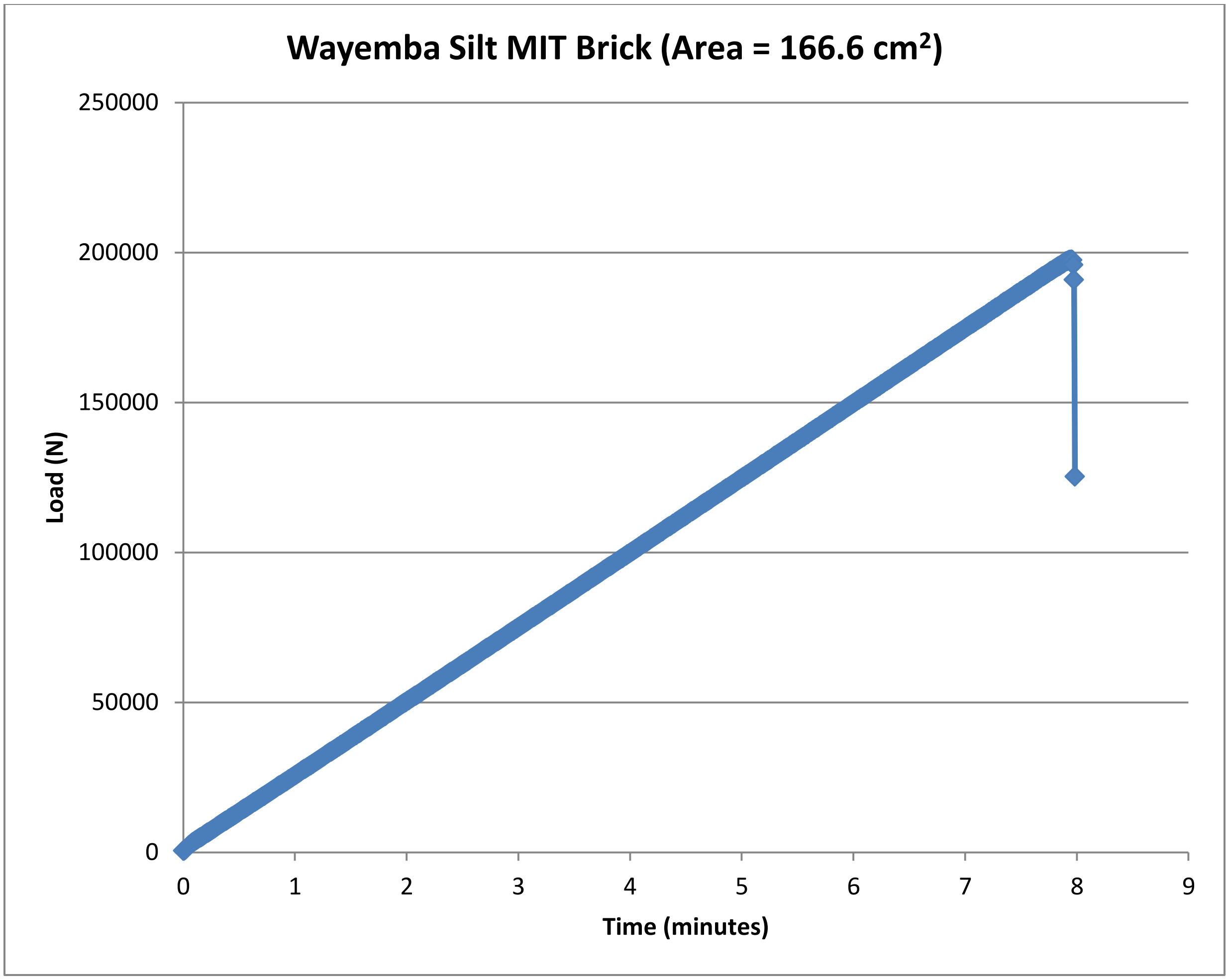
Obeng 2 Factory Brick S1 (Area = 252.5 cm²)
250000
200000
150000
100000
50000
0
Load (N)
0
1
2
3
4
5
6
7
8
Time (minutes)


Obeng 2 Factory Brick S2 (Area = 252.5 cm²)
Load (N)
140000
120000
100000
80000
60000
40000
20000
0
0
1
2
3
4
5
6
Time (minutes)



Obeng 2 Factory Brick S3 (Area = 253.4 cm²)
100000
90000
80000
70000
60000
50000
40000
30000
20000
10000
0
Load (N)
0
0.5
1
1.5
2
2.5
3
3.5
4
Time (minutes)


Wayemba Clay MIT Brick (Area = 143.8 cm²)
Load (N)
350000
300000
250000
200000
150000
100000
50000
0
0
2
4
6
8
10
12
14
Time (minutes)



Wayemba Silt MIT Brick (Area = 166.6 cm²)
250000
200000
150000
100000
50000
0
Load (N)
0
1
2
3
4
5
6
7
8
9
Time (minutes)