

**THE STUDY OF ALTERNATIVE CHEMICAL STABILIZATION
OF CLAYS WITH AGRICULTURAL WASTE MATERIALS FOR
RURAL HOUSING**

By

**Robert Amoanyi
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@Department of Materials Engineering

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CERTIFICATION

I hereby declare that this submission is my own work towards the PhD and that, to the best of my knowledge; it contains no material previously published by another person nor material which has been accepted for the award of any other degree of the University, except where due acknowledgement has been made in the text.

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Robert Amoanyi (PG20034871)
Student Signature Date

Certified by:

Prof. F. W. Y. Momade
Supervisor Signature Date

Certified by:

Prof. S. Kwofie
Head of Department Signature Date

ABSTRACT

The stabilization of clay for improved structural properties was investigated using the Afari and Mfensi clays. Geotechnical chemical and phase analytical methods were used to characterize both the raw and treated clays. For stabilization, lime, cocoa pod husk ash (CPA) and oil palm empty bunch ash (PBA) were used. The linear and volumetric drying shrinkages, dry and wet compressive strength and water absorption of the samples were investigated. Some of the samples were kept in the open for two years for durability test. Results showed that plasticity, percentage linear and volumetric drying shrinkages were reduced on the addition of the additives. There was an increase in compressive strength of the treated samples with lime, CPA and PBA as additives. Among these three stabilizers tested, the lime plus CPA and lime plus PBA showed good durability behaviour. A maximum compressive strength of 5.85 N/mm^2 was obtained from treated test pieces made with Mfensi clay (75%) plus lime (10%) and CPA (15%). Minimum water absorption values of 27.75% and 17.78% were also obtained for the treated test pieces made with Afari clay (70%) plus lime (15%) and CPA (15%) and Mfensi clay (65%) plus lime (15%) and CPA (20%) respectively. Test pieces treated with the lime plus CPA and lime plus PBA as additives did not disintegrate after 28-day of soaking in water. XRD analysis showed that improvement in structural properties of the clays was due to the conversion of part of lime to calcium carbonate (Calcite), which helped in binding the clay particles together. Additionally, other components of the additives, such as potassium hydroxide entered into reaction with some of the components of the clays as muscovite, silica and kaolinite to produce cementitious material.

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DEDICATION

Dedicated to my dear wife (Vivian Sekyere Amoanyi) and beloved daughters (Viro Asantewaa Amoanyi and Vilberta Atwimaa Amoanyi)

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CHAPTER ONE

INTRODUCTION

1.1 Background to the Study

Clay stabilization by chemical additives has been in existence for many years and has been used by engineers for building roads, bridges, dams, and other constructional activities (Military Soil Engineering report, 1992). It is an outgrowth of ancient practice which has been modified by laboratory and field tests to fulfil variety of stabilization requirements. This is due to the fact that many types of clay cannot be used as engineering materials in their own natural state (Gogo, 1985).

There are various types of clay deposits in almost every district of Ghana (Kesse, 1985). Among these are the Afari and Mfensi clay deposits found in the Atwima Nwabiagya District of the Ashanti region of Ghana. Research conducted on these two clays by Boateng, (1992), Obeng and Atiemo, (2005) and Nsiah, (2007) revealed that these two clays exhibited properties such as sufficient plasticity for satisfactory shaping, do not shrink excessively on drying, kaolinite and quartz are the main phases which may influence the development of relevant matrix for stabilization by chemical additives. The prime motivation of this study stems from observations carried out at Mfensi and Afari towns. However, amidst the abundance of clay in these communities and the availability of large quantities of other agricultural waste such as cocoa pod husk, oil palm empty bunch and oyster shells in the country; most inhabitants near these materials use rammed earth as the main material for any structural building. Although this rammed earth possesses appreciable characteristics as a building material, it disintegrates easily after a period of contact with water. The study therefore seeks the need for the stabilization of the

abundant clay deposits found in these towns with abundant calcined cocoa pod husk, oil palm empty bunch and oyster shells as stabilizers for improvement in their building structures.

1.2 Statement of the Problem

In many rural communities, traditional method such as rammed earth is commonly used in building of houses. These buildings ensure a cool environment within, even when the temperature outside is high, and therefore suited for hot and humid environment. Although rammed earth may be initially strong for building, it is not very durable and has less resistance to erosion by wind and rain (erode after a couple of rainfalls). Consequently, the structure weakens and requires frequent maintenance or complete rebuilding, after a few years. In order to strengthen such a house and make it more durable, various materials such as palm fronds and bamboo sticks are used to reinforce the building. An example of rammed earth house in the deteriorated state is presented in Figure 1.1.



Figure 1.1 *Rammed earth house in the deteriorated state*

Cement which could be used as the alternative material is very expensive constituting about 10% - 15% of cost of housing construction in Ghana (Obeng and Atiemo, 2005). Clinker and gypsum used in the production of Portland cement in Ghana for building are imported. This importation can only be supported from the foreign exchange earning of the country. Again, prices of cement have been increasing steadily over the years. Statistics show that the price of a bag of cement was GH¢7.50 in 2004 (Ministry of Trade and Industry, Statistical Service, 2004). At the end of March 2012 the cost of a bag of cement was GH¢18.00. These factors have really made the cost of building in the country very high. In order to eliminate or reduce these costs, especially in the rural communities, the need to develop local building materials which have cementitious properties to be used as substitutes should be promoted.

In the production of burnt bricks which can be used as a substitute material for rammed earth for the rural folks, energy requirement for production is high as a result of high temperature needed for the maturity of the bricks (Ayetei, 1977). Plants involved in the production of burnt bricks use mainly firewood as fuel, or in certain cases residual oil. The use of firewood not supported by planned afforestation causes environment degradation, and the cost of producing burnt bricks is often prohibitive (Baxter, 1972).

A lot of encouraging results have been obtained from clay stabilization studies involving the use of chemical stabilizers such as lime, cement, aluminium sulphate, asphalt fly ash and sodium hydroxyl among others [Davidson (1959), Moh (1962), Ingles (1968, 1970, 1972), Baxter (1972), Broms and Boman (1979), Gogo (1985,

1993), Kennedy et al (1987), Transportation Research Board (1987), Bell (1988, 1996), Kamon and Nontanandh (1999), Jiru and Xing(2002), Tono et al (2004)]. These stabilizers or additives are not readily available locally and those readily available are costly which make their usage more unaffordable in the rural areas. There is therefore the need to look for local substitutes which can lead to the development of a durable and low cost building material for our rural communities.

1.3 Objectives of the Study

The main objective of this study is to investigate the use of cocoa pod husk ash (CPA), oil palm empty bunch ash (PBA) and lime (Calcined Battor oyster shells – COS) as local additives, for stabilizing clays to produce building materials that are durable, resistant to moisture and other weather effects.

The specific objectives include:

1. To obtain and characterize Afari and Mfensi clays using geotechnical methods, chemical and mineralogical analyses.
2. To investigate the possible use of cocoa pod husk ash, oil palm empty bunch ash and lime (calcined Battor oyster shells) as local stabilizer substitutes.
3. To determine the stabilization response of the stabilized clay in terms of strength, stability under moist environment, durability on exposure to various weather conditions.

1.4 Scope of the Study

The research is limited to the use of two clays (Mfensi and Afari clays) both in the Atwima Nwabiagya District in the Ashanti Region of Ghana by comparatively characterizing them for stabilization with identifiable stabilizers (lime from calcined

oyster shells, cocoa pod husk ash and oil palm empty bunch ash) which are readily available in Ghana.

1.5 Hypothesis

It is the hypothesis of the present study that on adding lime and ashes of cocoa pod husk and oil palm empty bunch:

- i) Chemical reactions will take place between the components of the materials in the mixture.
- ii) The reactions result in formation of such phases that act as binders of the clay particles resulting in a monolithic structure that impart good strength and less resistance to excessive moisture environment.

1.6 Importance of the Study

The importance of the study is seen in:

1. The utilization of agricultural waste materials (oil palm empty bunch ash and cocoa pod husk ash) as additives in improving the structural properties of clays by stabilization.
2. The provision of an indigenous, durable and affordable building material for use especially in the rural communities.

1.7 Definition of Technical Terms

Stabilizer: an additive used to treat clay material, and reacts with the clay to form a cementitious compound.

Water Absorption: The amount of water absorbed by a porous ceramic material or product under specified conditions, expressed as percentage of weight of the dry material.

Curing: The process of keeping freshly placed brick or concrete moist to ensure complete hydration so that maximum strength is attained.

Compressive Strength: The maximum load per unit area applied unto a material at a specified rate that the material will stand before it fails.

Linear Drying Shrinkage: The decrease in size that usually occurs when shaped product (clay ware or ceramic ware) is dried. It is usually expressed as a linear percentage contraction from the wet to the dried state.

Volumetric Drying Shrinkage: The decrease in volume that usually occurs when shaped product (clayware or ceramic ware) is dried. It is the contraction which occurs in all the dimensions of the shaped product from the wet to the dried state.

Clay Stabilization: is the process of improving the engineering properties of clay by binding the soil particles together so that a rigid, non-dispersible mass is obtained with high load-bearing strength and thus making it more stable, durable and resistant to erosion in the presence of excessive moisture.

1.8 Acronyms Used

CPA: Cocoa pod husk ash

PBA: Oil palm empty bunch ash

COS: Calcined oyster shells

XRF: X- Ray Fluorescence

XRD: X- Ray Diffraction

BS: British Standards

ASTM: American Standards for Testing Materials

CHAPTER TWO

REVIEW OF THE RELATED LITERATURE

2.1 Clays

Clay is one of the oldest building materials on the planet. According to Obeng and Atiemo, (2005) clay is defined as a fine-grained earthen material which contains clay minerals, and is plastic and cohesive. Clays shrink when dry and expand when wet and gain in strength with retention of shape on firing. Physically, clays have particle range of $2\mu\text{m}$ and below (BS 1377:1990). The most important source of rocks for clay formation according to Rhodes (1973) is the granite, which have mixtures of feldspar, quartz and mica. Feldspar is by far the most common mineral, and it is the decomposition of this material which largely accounts for clay formation. This decomposition process of feldspar is continuous and goes on everywhere; hence, clay is an extremely common and abundant material in nature.

According to Worrall (1986), two main types of clay are however recognised: residual and sedimentary clay. Residual clays are those clays that have not been transported by natural agencies and are found to be where they were formed. These types are relatively pure and lack plasticity, have low strength in their dry state. Sedimentary clays, by contrast, are those which have been removed from their origin by natural agencies. They are rarely obtained pure, because many impurities are picked up and retained during transportation. The fine-grained nature of many such impurities makes them difficult and uneconomic to remove. Elutriation process during transportation results in the attainment of plasticity, strength and colour. The moving clay comes into contact with various materials, minerals and oxides giving rise to its physical and chemical properties (Rado, 1988).

Clays vary in both chemical and physical properties. The variation in clay properties is dependent on the geology, mineralogy and chemical composition of the parent material. A particular clay type is chosen depending on the type of work to be done. Clay to be used in the manufacture of structural clay products (bricks, tiles etc.) should be sufficiently plastic for satisfactory shaping, should not shrink excessively on drying and vitrify without excessive shrinkage at its maturing temperature.

2.2 Clay Minerals

There are many different types of clay minerals, each with unique chemical and behavioural properties which arise from the structure of the clay minerals. Clay minerals by definition refer to phyllosilicate minerals and to minerals which impart plasticity to clay and which harden upon drying or firing (Guggenheim and Martin, 1995). But nearly all clays contain just two basic components which occur in different arrangements. These two basic building blocks of all clay minerals are the silica tetrahedral and the aluminium octahedral shown in Figures 2.1. According to researchers such as Gogo (1985) and Little (1999), kaolinite and montmorillonite are the types of clay minerals that play important role in their response to the chemical stabilizers used in clay stabilization. Kaolinite clay mineral responds better to chemical stabilizers than montmorillonite. As a result, the characteristics and behaviour of the two main clay mineral types have been reviewed in the thesis as follows.

When scientists talk about 1:1 or 2:1 clays, they refer to the ratio of silica tetrahedral sheets to aluminium octahedral sheets. A ratio of 1:1 clay has one of each sheet and a ratio of 2:1 clays have two tetrahedral sheets on either side of an aluminium

octahedral sheet. These tetrahedral and octahedral sheets are variously arranged and modified during mineral formation to create several types of clay minerals.

Kaolinite is one of the clay minerals with ratio 1:1 clay minerals (Barak and Nater, 2003). It does not shrink when dry or swell when wet, which makes it well-suited for uses such as construction of roads and buildings, for septic adsorption fields, and pottery. The arrangement of closely packed sheets in kaolinite is likened to that of a closed book result in a much less external surface area than other clay minerals. No internal surface area and less capacity for holding water and cations.

The ratios of 2:1 clay minerals look much different (Figure 2.1). Using X-ray diffraction analysis, montmorillonite (one of the smectite clay minerals) looks like a sponge (Barak and Nater, 2003). The larger interlayer spaces in the 2:1 clay minerals have the capacity to hold water molecules and a variety of cations (some of which, like Na^+ , cause the clay to disperse) with important advantages for plant growth. Also, with larger interlayer spaces comes a greater tendency for shrink/swell behaviour (not all 2:1 clays expand). If a clay swells when wet, it is poorly suited for building site development or for septic leach fields. However, these clays are excellent for sewage lagoons or wildlife ponds; if they remain wet they "seal" and hold water. Table 2.1 presents a summary of the difference in kaolinite and montmorillonite clay minerals

Table 2.1 Summary of the differences in kaolinite and montmorillonite clay minerals
(Barak and Natar, 2003)

Characteristic	Kaolinite	Montmorillonite
Layer type	1:1	2:1
Typical chemical formula	$[\text{Si}_4] \text{Al}_2\text{O}_5(\text{OH})_2$	$[\text{Si}_8] \text{Al}_{3.2} \text{Fe}_{0.2} \text{Mg}_{0.6} \text{O}_{20}(\text{OH})_4$
Particle size (μm)	0.5 – 5.0	0.01 – 1.0
Specific Surface area (m^2/g)	7 – 30	600 - 800
Shrink/swell potential	non-expansive	highly expansive
Interlayer space	none (very small)	very large
Cation Exchange Capacity (mmol_c/kg)	2 - 15	80 - 150

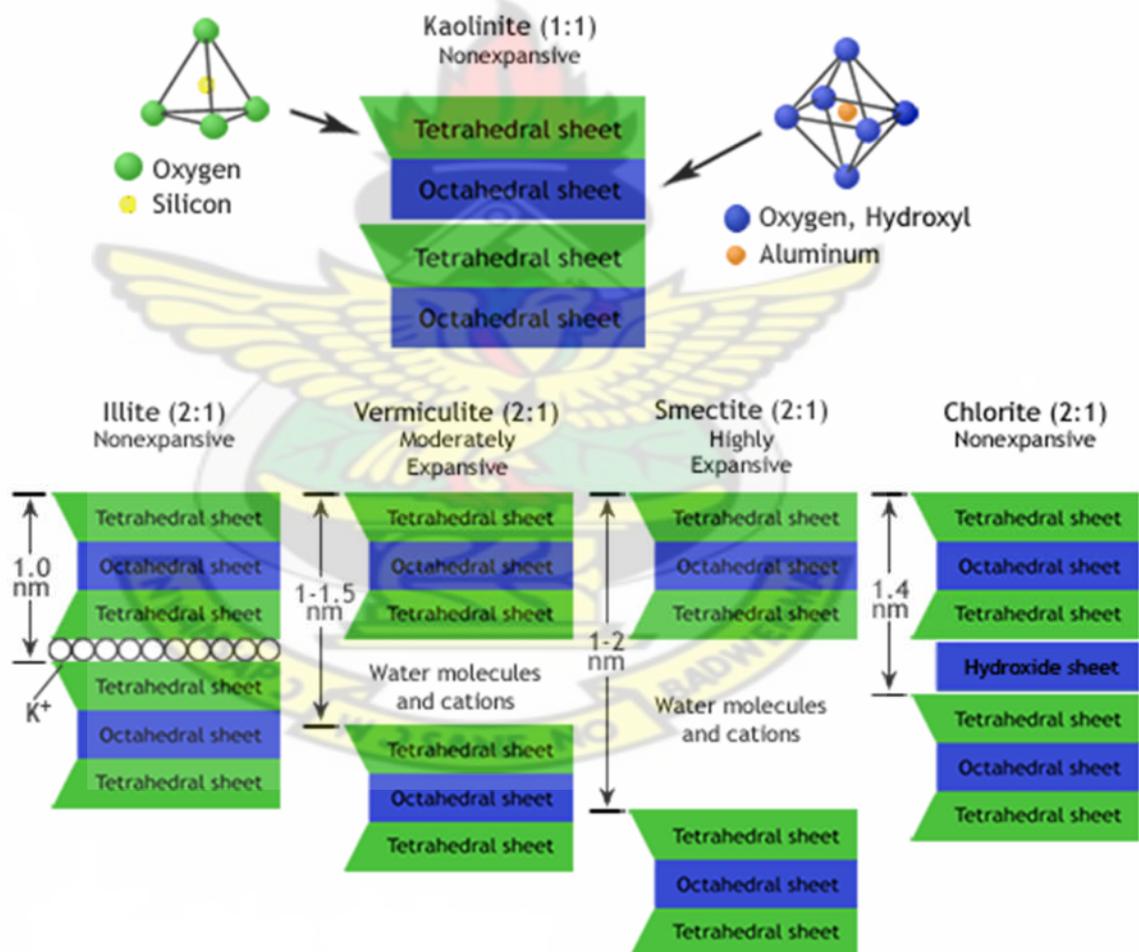


Figure 2.1 Pictorial diagrams of various types of clay minerals (Barak and Natar, 2003)

2.3 Cocoa Pod Husk Ash (CPA) and Oil Palm Empty Bunch Ash (PBA)

According to Woode and Hammond (2001), cocoa pod husk ash can serve as a good source of organic potash and it is estimated that Ghana can access over 50,000 tonnes of potash annually with a market value of some millions of dollars from the cocoa pod husks thrown away as agricultural wastes. Potash from ashes of agricultural wastes (cocoa pod husk ash and oil palm empty bunch ash), referred to as organic potash has marked advantage over mined potash, especially for the food industry, in being totally free from arsenic.

This potash also has a wide range of industrial uses such as potassium salts, dehydrating agents, fertilizers i.e. KCl, printing inks, laboratory reagents, special glasses for optical and colour TV tubes. The rest are potassium silicates for glass and refractories, bicarbonate for baking powders, soft drinks, fire extinguishers, pigments, food additives, soft soap and detergents (Woode and Hammond, 2001).

Aside the numerous uses of the potash from these ashes (CPA and PBA), they have not been used as additives for clay stabilization. The present study seeks to use these ashes as chemical additives to stabilized locally available clays (Afari and Mfensi clays) to improve their engineering properties for rural housing.

2.4 Lime

Lime is the most widely used and researched material for chemical treatment for engineering stabilization of cohesive soil. It is either in the oxide or hydrated form (Hayden, 1975). Lime is also normally used in conjunction with additives such as surfactants and silicates to improve properties and reduce permeability, or with

pozzolanic materials to form composites with cementitious properties (Hursthouse, 2001).

It is produced from calcium carbonate in the form of limestone, sea shells and oyster shells. When the calcium carbonate is burnt to about 600°C, carbon dioxide is given off as gas and the resulting product is calcium oxide or quicklime.

Calcium oxide, apart from being used as a chemical stabilizer of clay in this study, is widely used in industry for other purposes such as in making porcelain and glass; in purifying sugar; in preparing bleaching powder, calcium carbide, calcium cyanamide; in water softeners; and in mortars and cements. In agriculture, it is used for treating acidic soils (liming) (Hayden, 1975).

2.5 Soil Stabilization

Soil stabilization is the process of maximizing the suitability of soil for a given construction purpose. The necessity of improving the engineering properties of soils has been recognized for as long as construction has existed (Caterpillar, 2006). Many ancient cultures, including the Chinese, Indians and Incas, utilized various techniques to improve soil stability, some of which were so effective that many of the buildings and roadways they constructed still exist today and some are still in use (Caterpillar, 2006). Stabilized earths were used in the construction of the pyramids in the ancient Mesopotamia and Egypt and that the Greeks and Romans used soil-lime mixtures (Bell, 1996).

Modern era of soil stabilization began during the 1960s and 1970s in the United State, when general shortage of aggregates and petroleum resource forced engineers to consider alternatives to the conventional techniques of replacing poor soil at building site with shipped in aggregates that possessed more favourable engineering characteristics. Soil stabilization then fell out of favour, mainly due to faulty application, techniques and misunderstanding. Soil stabilization has recently once again become popular trends as global demand for raw materials, fuel and infrastructure has increased (Caterpillar, 2006).

There many advantages of soil stabilization. Among them are: Waterproofs the soil, improves soil strength, improve soil durability, dries wet soil, reduce cost of building and conserve energy.

2.6 Methods of Soil Stabilization

There are two primary methods of soil stabilization used today: mechanical and chemical. The most common form of mechanical method of soil stabilization is compaction of the soil, while the addition of cement, lime bituminous or other agents is referred to chemical method of soil stabilization (Caterpillar, 2006).

Over the past 60 years, progress has been made in improving the engineering properties of clays by chemical stabilization with various additives such as asphalt/bitumen, aluminium sulphate, lime, cement, sodium hydroxide and many others. The following are the review of the responses of using these chemical additives as stabilizers in stabilization of clays.

2.6.1 Asphalt Stabilization

Asphalt stabilization is the process of adding asphalt to an inorganic soil to act as a binder thus serving as cementing agent. As explained by Baxter (1972), asphalt soil stabilizer consists of asphalt globules of microscopic sizes, which remain suspended in water without any coalescence of the asphalt. However, the stabilizer must be stored and used at a temperature above freezing. Freezing causes the asphalt to settle out of emulsion and it becomes unusable for brick making. When the stabilizer is mixed into a clay-bearing soil in the presence of water, the water carries the asphalt globules into direct contact with the surface of the clay particles.

Since the water-carrying capacity of the clay many times exceeds that of the sand and small rock particles, practically all the asphalt is brought into close contact with the clay. As evaporation progresses, the asphalt globules are drawn into very thin film asphalt globules so dense that the asphalt forms a practically solid coating which is irremovable from the surface of each clay particle. The amount required to coat clay particles is minimal when compared to most other coating particles. The coating is so thin that the soil darkens only very slightly. When fully dried, the entire mass of the clay treated with asphalt emulsion has an improved compressive strength than the dried untreated soil mixed with water only (Baxter, 1972).

Moreover, according to Kimmons and Matteson (1968), the asphalt stabilizer does not diminish the cohesive qualities of the clay particles in the soil. However, it should be noted that since the asphalt films are repellent to water, the clay particles cannot become wet and return the soil to mud state again. Some absorption of water

may occur upon prolonged exposure, but the fine clay particles do not expand and lose cohesion in the presence of such moisture.

According to Joint Departments of the Army and Air Force, USA (1994), Stabilization of soils and aggregates with asphalt differs greatly from cement and lime stabilization. The basic mechanism involved in asphalt stabilization of fine-grained soils is a waterproofing phenomenon. Soil particles or soil agglomerates are coated with asphalt that prevents or slows the penetration of water which could normally result in a decrease in soil strength. In addition, asphalt stabilization can improve durability characteristics by making the soil resistant to the detrimental effects of water such as volume. In non-cohesive materials, such as sands and gravel, crushed gravel, and crushed stone, two basic mechanisms are active: waterproofing and adhesion. The asphalt coating on the cohesionless materials provides a membrane which prevents or hinders the penetration of water and thereby reduces the tendency of the material to lose strength in the presence of water. The second mechanism has been identified as adhesion. The aggregate particles adhere to the asphalt and the asphalt acts as a binder or cement (Joint Departments of the Army and Air Force, USA, 1994). Though with the good performance of the asphalt as a chemical stabilizer to clay, they are not readily available and are expensive in Ghana.

2.6.2 Aluminium Sulphate Stabilization

The use of aluminium sulphate as a chemical stabilizer has received very little attention. As pointed out by Demirel, Benn and Davidson, (1961), aluminium sulphate has been used to some extent to provide metallic ions to be used with phosphoric acid in soil stabilization to give sufficient gain in strength. Hayden

(1975) also used aluminium sulphate as a chemical stabilizer for dispersive clay. From the analyses of Demirel *et al*, (1961) and Hayden (1975) this stabilizer appeared to be good for the treatment of dispersive clay, its negative effect is the increase in exchangeable aluminium resulting in an increase in soil acidity.

2.6.3 Lime Stabilization

As described by Little (1999), lime stabilization occurs when lime is added to a reactive soil (clay) to generate substantial strength gains through short and long-term reactions. The short-term process involves ion exchange between calcium ions from lime and cations near the clay particle surface. Ion exchange can be quite beneficial, because it tends to transform the soil from a weakly dispersed structure to a strong flocculated structure. The long-term pozzolanic reactions begin as an increase in hydroxide ions from the lime which causes an increase in the pH of the soil water, which then dissolves the silicate and aluminate sheets of the clay. As the silica and alumina are released, they combine with the calcium to form calcium silicate hydrate or calcium aluminate hydrate, which cement the clay particles together (Little, 1999 McKinley *et al*, 2001). Only long-term pozzolanic reactions occur in lime stabilization of kaolinite, whereas short-term ion exchange must be completed before long-term pozzolanic reactions occur in lime stabilization of montmorillonite (Little, 1999).

Haydens (1975) and McDowell (1986) also suggested a third chemical reaction called carbonation which occur in soil-lime mixture. This is the slowest reaction involving the absorption of carbon dioxide from the atmosphere to react with the

calcium hydroxide to form calcium carbonate or limestone. The treated soil-lime mixture must be thoroughly compacted before this reaction can take place.

2.6.4 Cement Stabilization

Cement stabilization is by mixing clay and ordinary Portland cement with water and compaction of the mix to attain a strong material. The main compounds of ordinary Portland cement are tricalcium silicate (C_3S), dicalcium silicate (C_2S), tricalcium aluminate (C_3A) and tetracalcium aluminoferrites (C_4AF) (where $C = Ca$, $S = SiO_2$, $A = Al_2O_3$ and $F = Fe_2O_3$) (Prusinski *et al.* 1999). When water is added to cement, the ingredient of the cement reacts chemically and forms complicated compounds which includes calcium silicate hydrate and calcium hydroxide. The calcium silicate hydrate stabilizes the soil by forming hard structure around the soil particles (Prusinski and Bhattacharja, 1999). As the chemical reaction can take place under water, cement is said to be hydraulic additive, which is set under water (Varghese, 2005). In another finding by Rafalko *et al.* (2007), the calcium hydroxide stabilizes the soil through ion exchange, hence, flocculation of the clay particles.

2.6.5 Fly ash Stabilization

Fly ash is also used as stabilizer in soil stabilization. Soils can be treated with self-cementing fly ash to modify engineering properties as well as produce rapid strength gain in unstable soils like clay (White *et al.*, 2005). Fly ash is a waste from the combustion of coal-fired electric utilities which is a majority source of electricity in the United States (White *et al.*, 2005). The burning of coal results in over 117 million tons of coal combustion by-products, most of which is in the form of fly ash (ACAA, 2003). Although utilization of fly ash is continuing to grow, less than 32%

of coal combustion by-products are recycled (ACAA, 2003). The most widely used application of fly ash is as a partial replacement for cement in Portland cement concrete. States such as Iowa have allowed up to 15% replacement of cement with fly ash, which can improve various concrete mix properties and strength gain (Kosmatka and Panarese 1994). The primary benefits of using self cementing fly ash for soil stabilization are (1) environmental incentives, because material used does not have to be wasted; (2) cost savings, because fly ash is typically cheaper than cement and lime especially in the USA; and (3) availability, because fly ash sources are distributed geographically across the states (White *et al*, 2005). Although the benefits from fly ash is more encouraging but it is available in Ghana to be used as substitute.

2.6.6 Lime plus Sodium Hydroxide Stabilization

Davidson, Mateos and Katti, (1959) argue that the addition of small amount of sodium hydroxide (NaOH) to some clays activates stabilizing action of lime on these clays. The sodium hydroxide (NaOH) reacts with siliceous material to produce sodium silicate. The sodium silicate subsequently reacts with lime (Ca(OH)_2) to form sodium hydroxide (NaOH) and cementitious insoluble calcium silicates. The amount of (OH^-) ions increased due to the presence of NaOH. These accelerate the pozzolanic reactions by increasing the solubility of the siliceous material in the clay.

2.6.7 Lime plus Sodium Silicate Stabilization

The addition only sodium silicate to clay may actually negatively affect soil stabilization (Ding *et al*, 1996). Clay particles typically have a net negative charge on their face and a positive charge along the edges because of broken bonds. When

sodium silicate is added to clay, the negative silicate ions from the sodium silicate are attracted and attached to clay particles edges, causing entire clay particles to become negatively charged. If the entire clay particles have a negative charge, they will repel one another and the clay structure will become dispersed and weak (Rafalko et al 2007). Although sodium silicate may weaken clay when added alone, it may strengthen clay if lime is added along with the sodium silicate (Rafalko et al 2007). The lime can be as a source of calcium ions and with the presence of both calcium ions and silicate ions, calcium silicate gel can be form, hydrate and harden there by cementing the clay particles together (Rafalko et al 2007).

2.6.8 Lime plus Salt (NaCl) Stabilization

Gueddouda *et al* (2011) evaluated the stabilization effect of salt, lime, cement, combinations of lime and cement, and combinations of lime and salt on the swelling potential of three Algeria expansive soils where several cases were reported disorders characterized by cracks in the superstructure and the foundation level. Among the encouraging results obtained from the additives added, cement additions produces similar results to that of lime. The combination of lime and cement also exhibited result similar to those of lime or cement alone. But with the Stabilization of lime + salt, the result is better than the combined lime + cement stabilization. Gueddouda *et al* (2011) recommended the use of (lime + salt) as an alternative economical and effective for the treatment of swelling clays. These results are in good agreement with results obtained by Nalbantoglu (2001), Abu Baker et al, 2004 and Bekkouche et al (2007).

Yunus *et al* (2012) did a similar work on organic clay using lime and chloride salts (CaCl_2 and NaCl). Scanning Electron Microscope (SEM) images of lime-treated organic clay show the flocculated and aggregated structure, without appearance of cementation. In contrast, a clear evidence of cemented structure is observed when lime-treated organic samples are stabilised with addition of 0.5% CaCl_2 and 0.5% NaCl .

2.6.9 Lime plus Silica Stabilization

Silica was incorporated into clay bearing soils in addition to the application of lime by McKennon *et al* (1994). Silica addition appears to significantly improve the reactivity potential of clay bearing soils with lime used in traditional lime stabilization techniques. The addition of silica in the concentration is effective to promote and speed up the formation of calcium silicate hydrates over the formation of calcium aluminate hydrates in the resulting pozzolanic reaction occurring in the bearing soils.

2.6.10 Lime plus Ground Granulated Blast Furnace Slag Stabilization

According to Higgins (2005), lime plus ground granulated blast furnace slag used as additives in soil stabilization are effective and provide technical benefits especially with clay soils which have sulphate or sulphide. Lime plus ground granulated blast furnace slag stabilisation is now an established technique in the UK because ground granulated blast furnace is readily available throughout the UK. They are used to replace between 40 and 70% of Portland cement in concrete in the UK (Higgins, 2005). It was found that inclusion of ground granulated blast furnace slag increase

the compressive strength of stabilized clays, relative to that achieved by lime-only (Higgins, 2005).

2.6.11 Cement and Lime plus Fiber Stabilization

Over the past 60 years, cement and lime have been the most effective stabilizers for road and airfield applications, although recent developments show promise from non-traditional stabilizers, such as reinforcing fibers. The benefits derived from fibers may depend on whether they are used alone or in combination with cement and lime as chemical stabilizers (Rafalko *et al* 2006). Research has been done by Rafalko *et al* (2006) using cement and lime as the primary stabilizer with reinforcing fibers (Polypropylene Fibers, Nylon Fibers and Poly(vinyl) Alcohol (PVA) Fibers) for strength and toughness of two soft clay soils.

Polypropylene is a common material used for fiber reinforcement of soils, and it is manufactured in two forms: monofilament and fibrillated. Monofilament fibers are individual, cylindrical fibers. Fibrillated fibers are flat, tape-like fibers that can be described as a latticework of “stems and webs” as the fibers break apart during mixing and compaction (Fletcher and Humphries, 1991).

Nylon fibers are used as reinforcement in concrete to increase its ductility, durability, and toughness. When nylon fibers are used in concrete, they can absorb water, allowing the fibers to cure the concrete from the inside out (Zellers and Cruso, 2002). This absorbed water also contributes to adhesion between the fibers and concrete. Although scant research has been done on the use of nylon fibers with clay soil, these fibers mechanically and chemically stabilized the two soft clay soils combined with cement and lime (Rafalko *et al* 2006).

Poly(vinyl) Alcohol (PVA) fibers are typically not used for soil stabilization, but they are used as reinforcement in concrete to increase ductility, durability, and toughness because hydrogen bonds form between the hydroxide groups of the PVA fibers and cement particles (Kanda and Li 1998). However, clay has been stabilized with PVA solution instead of PVA fibers, where hydrogen bonds have also formed between the hydroxide groups of the PVA molecules and the silicate sheets of the clay (de Bussetti and Ferreiro, 2004). Combining these two findings, the hydroxide groups of the PVA fibers should theoretically form hydrogen bonds with the silicate sheets of the clay and could be effective stabilizing the clay soil both chemically and mechanically. If the soil is also treated with cement in addition to PVA fibers, the fibers may bond better to a clay-cement mixture than clay alone, since bonding between fibers and cement has been verified. Occasionally, the hydrogen bonding between the PVA fibers and concrete is so strong that the PVA fibers rupture instead of pulling out of the cement matrix (Kanda and Li, 1998). If the PVA fibers do rupture, this fiber reinforced concrete may be too brittle for a particular application. To counteract this phenomenon, some PVA fibers are coated with an oiling agent so that the PVA fibers will pull out of the cement matrix instead of rupturing.

The combination of cement as chemical stabilizer and the fibers was most effective in treating the two clays, since the chemical stabilizer greatly increased the UCS and the fibers significantly increased the toughness. Because soil treated with only a chemical stabilizer is often brittle, the addition of the fibers was very important (Rafalko *et al* 2006).

2.6.12 Liquid chemical Stabilization

Liquid-formed chemicals such as Con-Aid, Choline chloride and Choline bicarbonate and Potassium chloride among others have been used as additives or stabilizers on improvement of engineering properties of soils especially clay soils instead of the prevalent solid chemical additives such as lime, cement or fly ash among others (Abadjieva 2001, Ou *et al*, 2011 and Ali 2012). These liquid chemicals are non-toxic and environmentally friendly. Based on the results obtained in the used of these liquid stabilizers, the following conclusions can be made on the performances of these liquid stabilizers:

- (i) It reduces plasticity and shrinkage by eliminating re-absorption of water molecules.
- (ii) It reduces optimum moisture content by ionizing and exchanging the water molecules on the surface of the clay platelets.
- (iii) It increases maximum dry density by neutralizing and orderly re-arranging the clay platelets.
- (iv) It increases the compressive strength by increasing the inter particles bonding.

Beside the encouraging results obtained with good performance on the liquid stabilizers, they are not really available locally.

2.6.13 Sodium Hydroxide Stabilization

As pointed out by Ingles in his publications (1968, 1970, 1972), clays rich in aluminium minerals, for instance kaolinite perform better when mixed with sodium hydroxide (NaOH) as stabilizer than clays which are montmorillonitic. This was also confirmed by Olaniyan (2008) that the sodium hydroxide reacts very effectively with soil rich in aluminium.

They initially showed a slight decrease in strength but with time they increase in strength. This is due to the fact that sodium hydroxide (NaOH) on clay attacks the clay mineral lattice and produces sodium silicate and sodium aluminate. Sodium aluminate then proceeds to precipitate insoluble sodium aluminium hydro-silicate which gives the soil considerable durability.

Gogo (1985) did a similar work on two clays supplied from France. He used sodium hydroxide (NaOH) as a single stabilizer and concluded that kaolinitic clays can successfully be stabilized with sodium hydroxide to produce materials with highly improved strength and water resistance. In realising the success and benefits in clay stabilization, Gogo (1985) recommended that a replacement of sodium hydroxide (which was the stabilizer he used for his work) with local substitutes be made since they are not readily available and are expensive to buy. The replacement of these stabilizers with local substitutes can lead to the development of a durable and cheap building material that could play a key role in improving the living conditions in many poor communities.

From the review of the related literature on the response of using aluminium sulphate, lime, cement, asphalt, liquid chemicals and sodium hydroxide, sodium silicate among others as chemical additives or stabilizers in stabilization of clays and combination of two or more of these additives or stabilizers, encouraging results were reported from these studies. These stabilizers or additives are not readily available locally; those readily available are costly which make their usage expensive. There is therefore the need for replacement of these stabilizers or

additives with local substitutes which can lead to the development of a durable and cheap building material for many poor communities.

KNUST



2.7 Clay Deposits in Ghana

Information on clay deposits in each region of Ghana as of 1985 is given in Tables 2.2 - 2.3 (Kesse, 1985). This information includes the area, location and reserves in metric tonnes. Figure 2.2 shows the location of the deposits. It must be noted that the information on clay deposits in the Upper West Region is excluded since at the time of compiling the statistics, Upper West Region had not been created (Kesse, 1985).

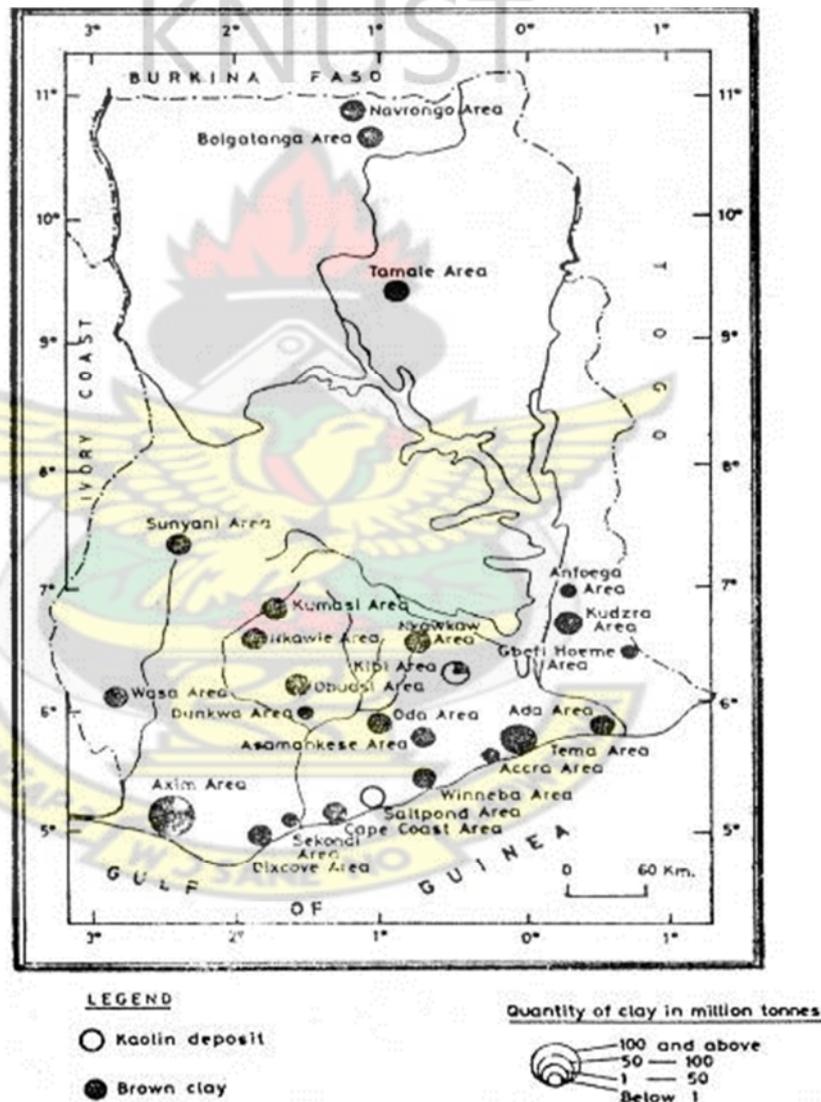


Figure 2.2 Clay deposits in each region of Ghana as of 1985 (Kesse, 1985)

Table 2.2 Clay deposits in the Greater Accra, Brong Ahafo, Upper, Central Regions of Ghana (Kesse, 1985)

Greater Accra Region					
Area	Location	Reserve (tonnes)	Area	Location	Reserve (tonnes)
Accra	Alajo	48,600	Tema	Afiinya East	24,194,681
	Ashiaman	18,677,175		Afiinya West	5,514,894
	Prampram A	21,779,929	Ada	Mobole	15,000,000
	Prampram B	74,350		Kasseh/Bedaku	42,661,830
	Prampram C	43,771		Big Ada	51,242,553
	Kpone	10,960,115			
	Oyibi	6,735			
Kwabanya	2,326,596				
Brong Ahafo Region			Upper Region		
Area	Location	Reserve (tonnes)	Area	Location	Reserve (tonnes)
Sunyani	Sunsan Valley	661,188	Bolgatanga/ Navrongo	Gambibigo	12,419,998
	Tanoso	16,200,200		Sumbrungu	4,020
	Adantia	530,665		Tono	8,477,333
			Sobolo	649,997	
Eastern Region					
Area	Location	Reserve (tonnes)	Area	Location	Reserve (tonnes)
Nkawkaw	Adihima/Asuoya	2,240,099	Asamankese	Asamankese	840,000
	Abepotia	7,614,793		Apinmang	2,801,250
	Framase	41,687	Akim Oda	Akim Swedru	33,173,335
Kibi	Tamfoi	1,285,084		Akim Awisa	1,285,553
	Anyinam	Moseaso	444,000	Akim Abonase	4,561,000
Abomosu		4,081,434	Akwapim	Adawso	1,027,000
			Somanya	Okwenya	34,862,223
Central Region					
Area	Location	Reserve (tonnes)	Area	Location	Reserve (tonnes)
Cape Coast	Nkuntraw	7,527,168	Winneba	Esuakyir No 2	1,800,000
	Kakum Valley	42,800		Simbrofo	3,100,000
	Atrankwa	12,000,000		Mprumen	35,877
	Ochiso	15,441,702		Kasua/Oduponkpehe	51,702,127
	Ampia Ajumaku	195,000		Nyanyanu	1,107,191
Ajumaku	Esuakyir No 1	6,800,000	Gomoa	Gomoa Brofo	268,968
Dunkwa	Subin Valley	162,000	Komanda	Domenase	3,952,551

Table 2.3 Clay deposits in the Northern, Western, Ashanti and Volta Regions of Ghana (Kesse, 1985)

Northern Region					
Area	Location	Reserve (tonnes)	Area	Location	Reserve (tonnes)
Tamale	Koblimahago	9,455,892	Tamale	Kunkuo	234,502
	Kpaliga	259,200		Yapei	38,694
	Nyankpala	48,600			
Western Region					
Area	Location	Reserve (tonnes)	Area	Location	Reserve (tonnes)
Nzima	Alenda Wharf	2,956,522	Sekondi	Inchanban	2,668,600
	Aluku	17,860,944		Shama	7,163,082
	Esiama-Kakam	113,550,239	Takoradi	Dixcove (Mfruma)	9,469,979
	Teleku Bokaso	74,456,122		Wasa Akropong	614,249
	Nimzimirim	9,343,117	Amanfi	Asankragwa	8,629,200
	Bou-Bamakpolo	31,493,879		Enchi	226,330
	Bokazo	221,600,000		Manso Amanfi	597,780
	Nzima East	241,190,133			
Ashanti Region					
Area	Location	Reserve (tonnes)	Area	Location	Reserve (tonnes)
Kumasi	Womasi	164,570	Obuasi	Asokwa	33,865,955
	Kaasi (Tuantem)	1,086,993		Nkawie	Mfensi
	Sisai	113,400	Afari		2,055,900
	Kokobriko	21,061	Jankoba		139,999
	Dichemso Valley	81,000	Ahatawsu (Mpasatia)		100,560
	Aboabo	162,017	Awrenfena		268,801
	Dichemso-Aprapong	162,017			
	Satang No 1	32,400			
	Satang No 2	162,017			
	Subin Valley	162,900			
Volta Region					
Area	Location	Reserve (tonnes)	Area	Location	Reserve (tonnes)
Ho	Adidome No 1	7,755,319	Bowiri	Kalakpa	501,440
	Anfoega	469,800		Tuwotsive	1,944
	Tangidome	7,614		Amanfro/Anyinase	2,000,000
Gbefi-Hoeme	Nuzeme	10,083	Dayi	Dayi River Basin	997,900
	Toga	42,163		Ketekrachi	Woroto
	Kpetoe	29,160	Adankpe		2,273,361
	Aveyiboe	27,540	Hohoe	Adutor	35,854,085
Kudzra	Valexo	16,300	Kadjebi	Kpoglo	9,413,582
	Aklamapata	6,318		Kadjebi	97,742,979
	Have	6,430			
	Agbeditive	12,961			

CHAPTER THREE

MATERIALS AND METHODS

3.1 Materials

Materials used for the study included Afari and Mfensi clays, lime, cocoa pod husk ash and oil palm empty bunch ash.

3.1.1 Afari and Mfensi Clays

Clay samples were taken from deposits in Afari on the Kumasi - Nkawie road and Mfensi along the Kumasi - Sunyani road both in the Atwima Nwabiagya District of Ashanti Region. Random sampling was used to obtain the clay samples.

The clay samples obtained were lumpy as shown Figures 3.1 and 3.2 representing Afari and Mfensi clays respectively. Afari clay was yellowish-orange in colour while that of Mfensi clays was greenish-grey.



Figure 3.1 A picture of raw Afari clay



Figure 3.2 A picture of raw Mfensi clay

3.1.2 Cocoa Pod Husk Ash (CPA) and Oil Palm Empty Bunch Ash (PBA)

Dried cocoa pod husks and dried oil palm empty bunch were obtained from Mfensi and dumpsite of Juaben Oil Mills Ltd in the Ejisu District respectively. The cocoa pod husks and oil palm empty bunches were oven dried at 105°C for 24 h and then calcined into ashes at 600°C for two hours at a heating rate of 5°C/min in an electric kiln similar to Woode and Hammond, 2001. The ashes were further milled using the vibratory mill for 5 minutes into fine particles.

Both ashes (CPA and PBA) were found to be hygroscopic; hence, the ashes were kept in sealed containers.

3.1.3 Lime (Calcined Oyster Shells - COS)

Battor oyster shells were oven dried at 105°C for 24 h and then calcined into ashes at 600°C for two hours at a heating rate of 5°C/min in an electric kiln. The calcined Battor oyster shells were further milled using the vibratory mill for 5 minutes into fine particles.

3.2 Methods

3.2.1 Processing of Clays

50 kg each of Mfensi and Afari clays were oven dried at 105°C for 24 h. The clays were then crushed and pulverised using the cone crusher and the vibratory mill.

3.2.1 Physical characterisation of Afari and Mfensi Clays

The physical characterization of Afari and Mfensi clays were determined. . The properties examined included particles size distribution and Atterberg limits (plastic limits, liquid limit and plasticity index), linear and volumetric drying shrinkages.

3.2.1.1 Particle size distribution of Afari and Mfensi clays

Sieve Grading (Dry):

The particle size distributions of the raw clays were performed by sieve grading. Series of sieves (No.14 (1.18 mm), No.25 (0.600 mm), No.36 (0.425 mm), No.52 (0.300 mm), No.72 (0.212 mm), No.100 (0.150 mm) and No.200 (0.075 mm) were nested together with the coarsest sieve (No. 14) upper most grading down to the finest (No. 200) at the bottom with the receiver (or pan) at the bottom to collect fines. Weighted amounts of the clays were poured on the coarse sieve and vibrated. The weighted amount retained on each sieve was recorded and the percentage of the total passing each sieves calculated. This was done in accordance with (BS 410).

Sedimentation (Hydrometer Method):

50 g of sodium hexametaphosphate (dispersing agent) was dissolved in a litre of distilled water. 50g each of Afari and Mfensi clays were added to 200ml of the dispersing agent solution to form a suspension, stirred and aged for 24hrs. . The aged clay suspensions were transferred into measuring cylinders and topped up to the litre mark with distilled water. The suspension was shaken and then set upright on a plane horizontal surface. The hydrometer was then inserted into the clay suspension. The hydrometer and the temperature readings were taken at various time intervals of 0.5, 1, 2, 4, 8, 15, 30, 60, 120, 240 and 1440 minutes (BS 1377:1990).

3.2.1.2 Atterberg Limits of Raw Clays (Plastic Limit, Liquid Limit, Plasticity Index)

The workability of the clays was evaluated by determining its plasticity by the Atterberg limits which is the most accepted indicator among the indicators of the

physical behaviour of very fine-grained soils in which clay minerals predominate. The limits are based on the concept that a fine-grained soil can exist in any of the four states (solid, semisolid, plastic and liquid) depending on its water content. Thus, a soil is solid when dry, but when water is added it will become semisolid, then plastic and finally liquid. There are therefore three limits namely; shrinkage limit, plastic limit and liquid limit (BS 1377:1990 and ASTM D4318:1979).

The cone penetrometer method was used in determining the **liquid limit** of Afari and Mfensi clays since it is often considered to be a more consistent method as it minimizes the possibility of human variations when carrying out the test. For the determination of liquid limit, 200g of each clay was measured and appropriately mixed with water to a subjective plasticity. It was filled in the cup of the liquid limit apparatus and a standard cone was released to penetrate into the clay. The measurement of the penetration was taken and recorded on the Atterberg limits Data Work Sheet. This was repeated five times. The liquid limit is the water content at 20mm penetration of the standard cone into the clay (BS 1377:1990).

Plastic limit is the water content at which plastic deformation can be initiated. The clays in their plastic state were rolled into a thread 3mm thickness and weighed. They were then placed in a dryer at 105°C for 24 hours and weighed thereafter. The plastic limit is the minimum water content at which the clay was rolled into a thread 3mm thick (BS 1377:1990).

Plasticity Index (PI) is the range of water content over which the clay remains in the plastic condition. It is the difference between the liquid limit and the plastic limit:

$$PI = LL - PL \quad (3.1)$$

Where: *PI* is Plasticity index

LL is Liquid limit

PL is Plastic limit

3.2.1.3 Percentage Linear Drying Shrinkages of Mfensi and Afari Clays

Ten test cubes each of the two clays of 50 mm x 50 mm x 50 mm in dimension were made with two marks on the diagonal lines across each cube measuring 50 mm apart. After drying in the oven at 105°C for 24 hours, the distances between the two diagonal lines marked across each cube were measured. Similar tests were repeated after the clays were treated with lime, CPA and PBA additives (BS 3921:1985).

3.2.1.4 Percentage Volumetric Drying Shrinkages of Mfensi and Afari Clays

Ten test cubes each of the two clays (Mfensi and Afari clays) were made measuring 50 mm x 50 mm x 50 mm. After drying in the oven at 105°C for 24 hours, the width, height and length of each cube were measured. The volumetric drying shrinkages of test cubes of Afari and Mfensi clays were recorded from which the percentage volumetric drying shrinkages were calculated using the shrinkage formulae (4.3). Similar tests were repeated after the clays were also treated with lime, CPA and PBA additives (BS 3921:1985).

3.2.2 Chemical Characterisation

The chemical composition of the clays and the ashes were obtained by x-ray fluorescence spectrometry on Spectro X-Lab 2000 Polarized Energy Dispersive X-

Ray Fluorescence Spectrometer (EDXRF) equipment at the laboratories of the Geological Survey Department, Accra.

The samples were dried at 105°C for 24 hours and placed in desiccators to cool. Forty (40) grams of each sample were weighed, mixed with 0.9 grams of Hoechst wax and milled in a vibratory mill to less than 100µm for 3minutes. The milled samples were pressed in a die to form tablets using the Sniec hydraulic press at 5 tons. The pellets were arranged in the EDXRF for the chemical compositional analysis of the samples.

3.2.3 Mineralogical Characterisation

Sample of clays and ashes were analysed for their phase or mineralogical composition. The clay and the ash samples were pulverised and pressed into sample holders and their x-ray diffraction patterns taken using a Siemens D 5000 x-ray diffractometer and analysed using the database of the x-ray diffractometer.

3.4 Preparation of Test Pieces

Test pieces were prepared with various combinations of materials for the preparation of test pieces as shown in Figure 3.3.

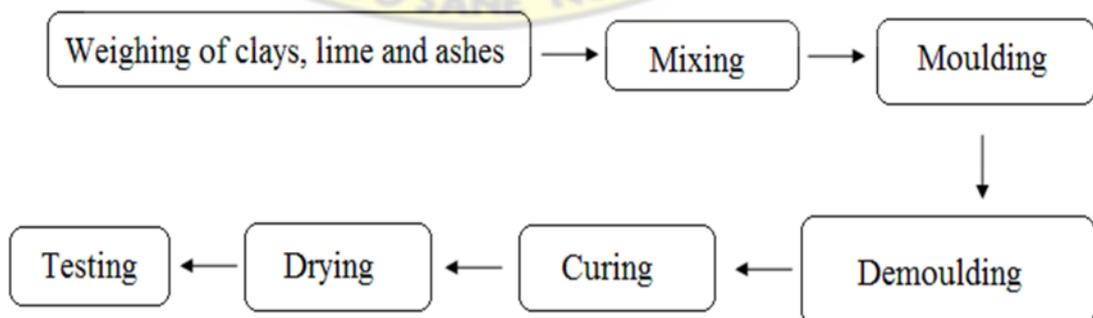


Figure 3.3 The various steps used in the preparation of the test pieces

3.4.1 Batch Formulation

The materials used in the batch formulation of test pieces were: Afari and Mfensi clays, lime and ash (cocoa pod husk ash or oil palm empty bunch ash). Various batches were formulated by weighing the materials in percentage proportions as shown in Tables 3.1 and 3.2 and graphically represented in triaxial diagrams as shown in Figures 3.4, 3.5, 3.6 and 3.7.

Table 3.1 Percentage compositions of Afari clay + lime + CPA or PBA

Label	Afari clay %	Lime %	CPA %	Label	Afari clay %	Lime %	PBA %
A0	100	0	0	AP0	100	0	0
A1	95	0	5	AP1	95	0	5
A2	90	0	10	AP2	90	0	10
A3	85	0	15	AP3	85	0	15
A4	95	5	0	AP4	95	5	0
A5	90	5	5	AP5	90	5	5
A6	85	5	10	AP6	85	5	10
A7	80	5	15	AP7	80	5	15
A8	90	10	0	AP8	90	10	0
A9	85	10	5	AP9	85	10	5
A10	80	10	10	AP10	80	10	10
A11	75	10	15	AP11	75	10	15
A12	85	15	0	AP12	85	15	0
A13	80	15	5	AP13	80	15	5
A14	75	15	10	AP14	75	15	10
A15	70	15	15	AP15	70	15	15

Table 3.2 Percentage compositions of Mfensi clay + lime + CPA or PBA

Label	Mfensi clay %	Lime %	CPA %	Label	Mfensi clay %	Lime %	PBA %
M0	100	0	0	MP0	100	0	0
M1	95	0	5	MP1	95	0	5
M2	90	0	10	MP2	90	0	10
M3	85	0	15	MP3	85	0	15
M4	95	5	0	MP4	95	5	0
M5	90	5	5	MP5	90	5	5
M6	85	5	10	MP6	85	5	10
M7	80	5	15	MP7	80	5	15
M8	90	10	0	MP8	90	10	0
M9	85	10	5	MP9	85	10	5
M10	80	10	10	MP10	80	10	10
M11	75	10	15	MP11	75	10	15
M16	70	10	20	MP16	70	10	20
M12	85	15	0	MP12	85	15	0
M13	80	15	5	MP13	80	15	5
M14	75	15	10	MP14	75	15	10
M15	70	15	15	MP15	70	15	15
M17	65	15	20	MP17	65	15	20

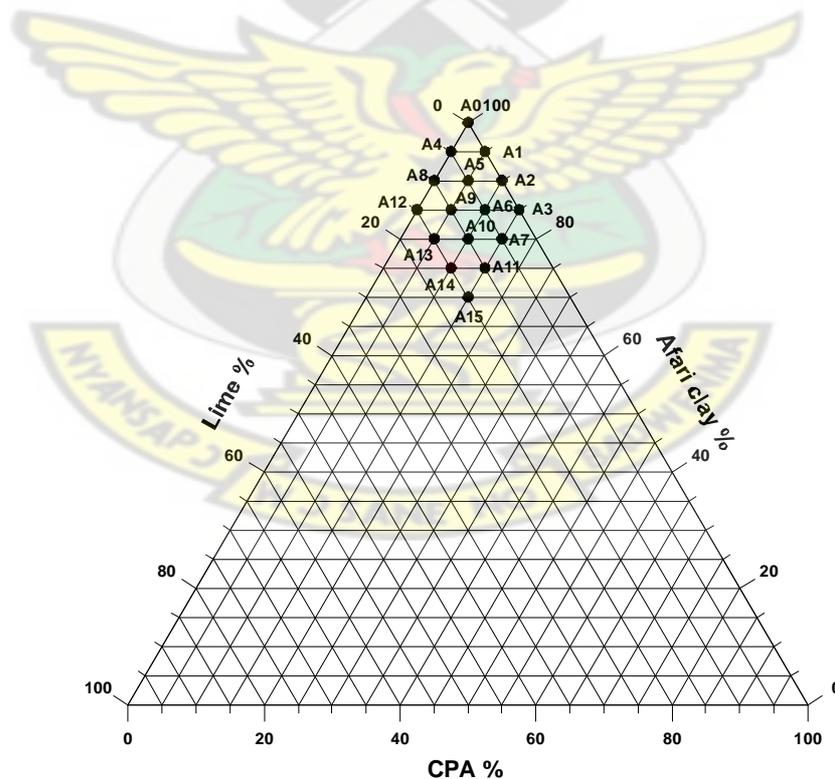


Figure 3.4 Triaxial representation of percentage compositions of Afari clay + lime + CPA - (A)

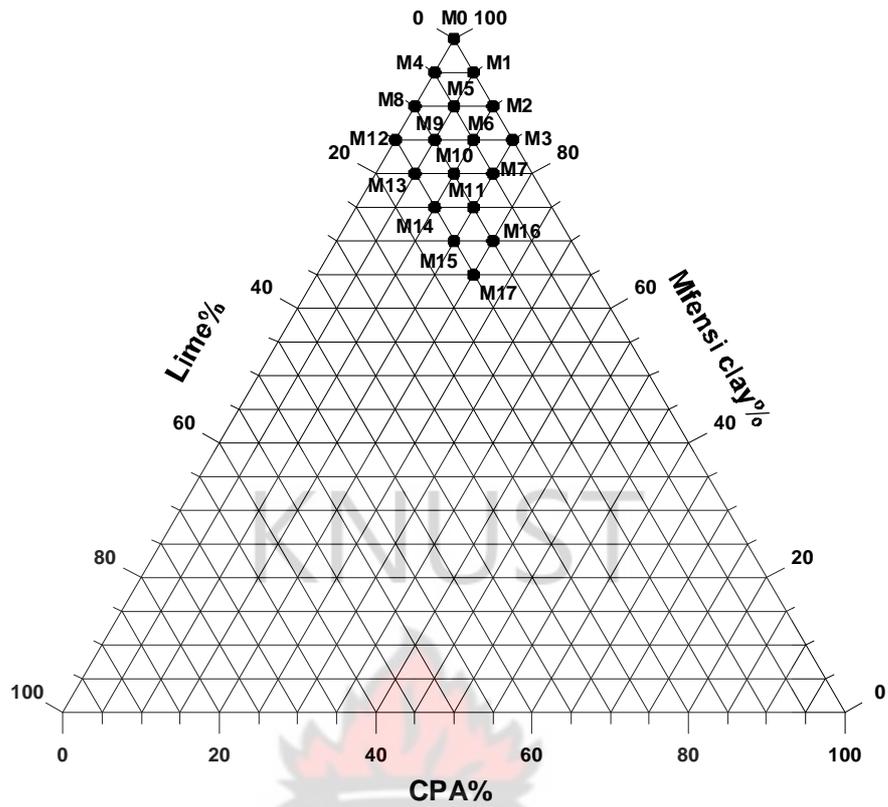


Figure 3.5 Triaxial representation of percentage compositions of Mfensi clay + lime + CPA - (M)

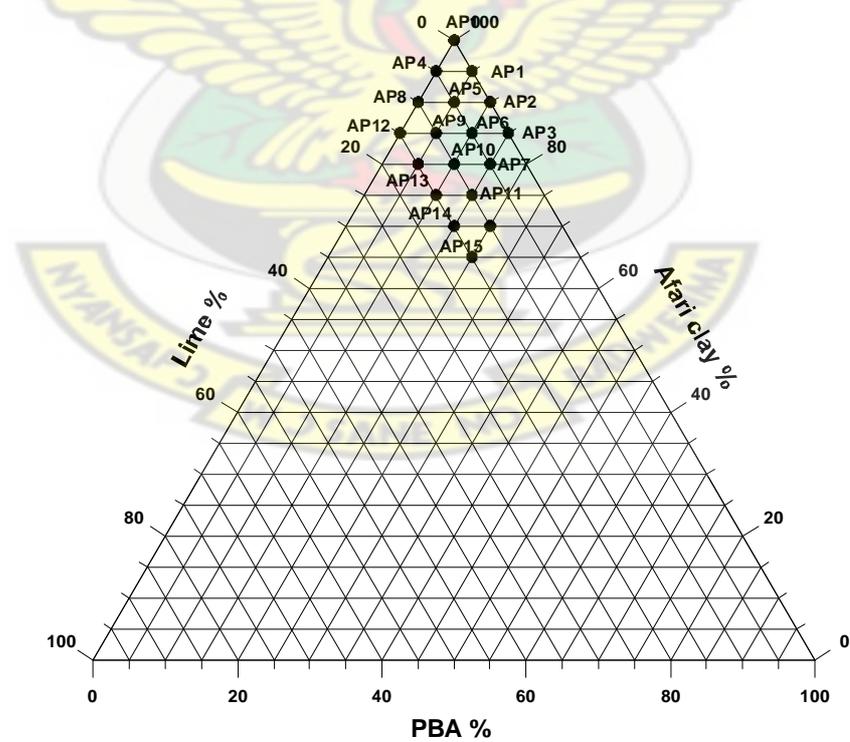


Figure 3.6 Triaxial representation of percentage compositions of Afari clay + lime + PBA - (AP)

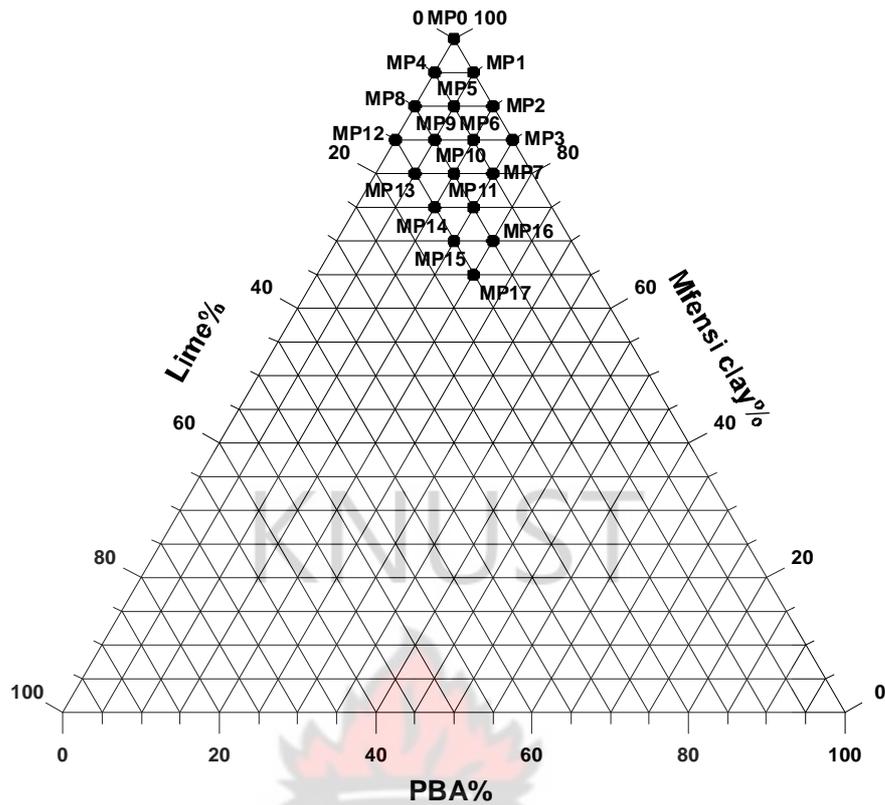


Figure 3.7 Triaxial representation of percentage compositions of Mfensi clay + lime + PBA (MP)

3.4.2 Mixing

The mixing was done manually with hand. The weighed clay, ash and lime were initially dry mixed in a plastic container. Water (in the range of 25% to 45% depending on the clay – lime ratio) was then added in bits while stirring until a workable mass was obtained.

3.4.3 Moulding

Moulding of the test pieces was started immediately after mixing. This was necessary to avoid the drying out of the paste to decrease its workability. Moulding was done manually in a steel mould prepared for this work. The dimensions of the mould were 50 mm x 50 mm x 50 mm. The inside of the steel mould was first wetted with water before moulding of each test piece to enhance easy de-moulding

of the test pieces. The paste was made into balls and put in the mould. A moulding stick made in the dimension of 150 mm in length, 40 mm in width and breath was used to ram the paste. Approximately 25 blows were applied to each test piece made. The excess was cut off by running a knife across the top of the mould. Ten (10) test pieces were made for each batch. The samples were labelled according to the batch.

3.4.4 Curing and Drying

The freshly made test pieces were cured in polythene bags for 7 days to ensure complete hydration so that maximum strength is attained. After 7 days of curing, the test pieces were air-dried for 7 days and afterwards oven-dried at a temperature of 60°C for 24 hours. This temperature of 60°C seemed to be suitable for slow drying of the samples and avoid the development of cracks in the test pieces.

3.5 Testing of Test Pieces

The test pieces produced with the various batches were then tested for various characteristics after curing and drying. These include percentage linear and volumetric drying shrinkages, dry and wet compressive strengths, percentage water absorption and phase composition. Accelerated weathering studies (durability test) were also performed on test pieces of all compositions.

3.5.1 Stability of Test Pieces in Water

After drying, the test pieces were allowed to cool in the open in the laboratory. To determine the stability of test pieces in water and water absorption, some were weighed and soaked by total immersion in water in plastic containers. The test pieces were kept in water for 28 days. During this period of soaking, their weights were

monitored weekly (7th, 14th, 21st and 28th day) by dabbing the surfaces of the soaked test pieces with clean cloth before weighing. This was repeated at the end of the soaking period and the unbroken test pieces were prepared for wet compressive strength test.

3.5.2 Dimensional Changes

Percentage linear and volumetric drying shrinkages of the test pieces were also determined as described in sections 3.2.1.3 and 3.2.1.4.

3.5.3 Dry and Wet Compressive Strength

Dry compressive strength tests were performed on test pieces using ELE California Bearing Ratio (CBR) Compressive strength machine. This was done to ascertain strength at which each test piece will stand before it fails at the maximum load per unit area applied at a specified rate. This was also in accordance with BS 3921 (1985). Flat steel plates were placed on the top and bottom of the test pieces. The test piece was placed at the centre of the plates. It was ensured that there were no gaps between the flat plates and the test piece to be tested. The load was applied on the test cube and the machine stopped when the brick failed or got broken. The readings in PSI unit were taken and converted to N/mm^2 . The above procedure was repeated for wet compressive strength test on test pieces after 28-day soaking in water. The equipment is shown in Figures 3.8 and 3.9.



Figure 3.8 *Test piece in the compressive strength machine*



Figure 3.9 *Test piece broken/ failed under load*

3.5.4 Water Absorption of Test Pieces

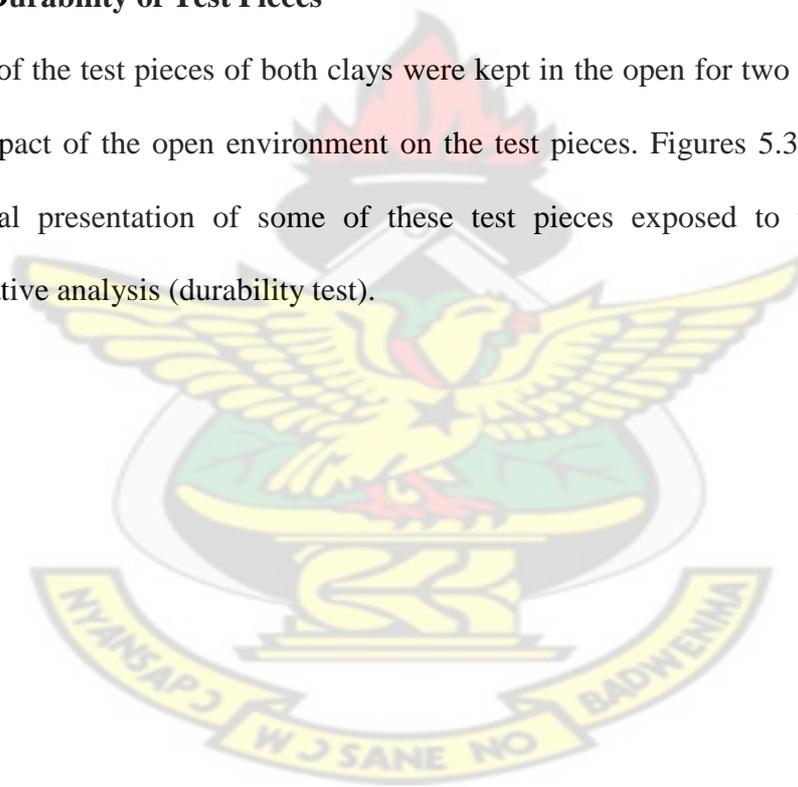
Measurements of water absorption were taken during the soaking of the test pieces as described in section 3.5.1. After 7 days of soaking the test pieces were taken out of the water, wiped clean of water with a clean cloth and weighed. This was repeated after 14, 21 and 28 days.

3.5.5 Phase/Mineralogical Composition

Selected samples based on the results of the compressive strength measurements were taken for phase/mineralogical analysis. This was important in the characterisation of the products of the batches to determine the relationship if any between the components/phases formed and the properties developed by the products. The selected samples were pulverised, pressed into sample holders and their x-ray diffraction patterns taken and analysed.

3.5.6 Durability of Test Pieces

Some of the test pieces of both clays were kept in the open for two years to observe the impact of the open environment on the test pieces. Figures 5.33 – 5.45 are the pictorial presentation of some of these test pieces exposed to the weather for qualitative analysis (durability test).



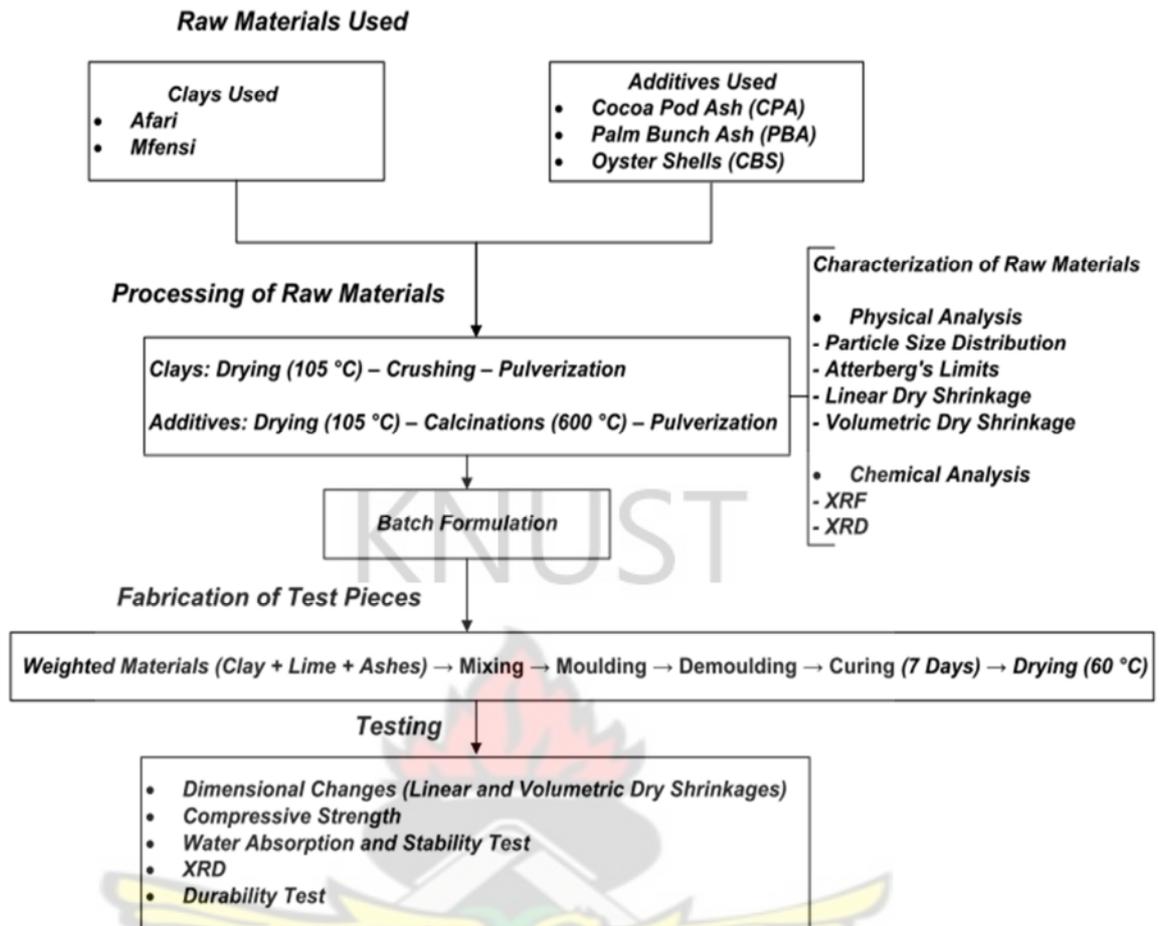


Figure 3.10 Summary representations of the Materials and Methods used for execution of the project

CHAPTER FOUR

RESULTS

4.1 Observations During the Fabrication of the Test Pieces

The following observations were made during and after the fabrication of the test pieces (mixing, moulding and soaking).

4.1.1 Mixing

During the mixing, the following were noticed:

- There was evolution of heat when water was added to the mixture with lime and the heat increased as lime addition increased. This was because the reaction of lime with water is exothermic:



- The water needed to improve the workability of the mixture with clay and lime with no additions of ashes increased as the amount of lime was increased. This is due to the fact that water is taken up by the lime-water reaction.
- The mixture appeared to be soapy to touch when the clays were mixed with the ashes. The ashes were alkaline in nature and therefore produced that effect.

4.1.2 Moulding

During moulding of clay-lime mixture, it was observed that due to the less plastic nature of the clay-lime mixture, compaction was difficult, hence moulding of test pieces with clay-lime mixture was relatively more difficult.

4.1.3 Soaking

The following observations were made during the 28 days of soaking of the test pieces of both clays in water for water absorption tests:

- Afari and Mfensi clay test pieces with no additives incorporated disintegrated in the water within a period of an hour.
- Afari and Mfensi clay test pieces made with the ashes (CPA/PBA) as the only additives also disintegrated in 7 days of soaking in water.
- Afari and Mfensi clay test pieces made with lime as the only additive were able to maintain their shapes in water for 28 days period of soaking without disintegrating, but some slight damages were noticed at the edges of the test pieces due to flaking off of the edges.
- Generally, both Afari and Mfensi clay test pieces made with lime and ashes (CPA/PBA) appeared to be of good quality and were able to maintain their shapes in water during the 28 days period of soaking without distortions.

4.2 Physical Properties of Afari and Mfensi Clay

Tests to determine the physical properties of the two clays (Afari clay and Mfensi clay) used for the research were carried out to obtain data of the characteristics of the clays as possible engineering materials. The properties determined were plasticity, particles size distribution, drying and volumetric shrinkages. The methods employed in the study were in accordance with the BS 1377:1990, and the results are presented in the following sections.

4.2.1 Atterberg Limits of Raw Clays (Liquid Limit, Plastic Limit, Plasticity Index)

The results of the Atterberg limit tests of Afari clay have been presented in Tables 4.1, 4.2 and 5.1 for the liquid limit, plastic limit and plasticity index respectively, whilst that of Mfensi clay is presented in Tables 4.3 and 4.4.

Table 4.1 Results of Liquid Limits tests on the Afari clay

Parameter	Test 1	Test 2	Test 3	Test 4	Test 5
Weight of container	3.72	3.71	3.73	3.71	3.76
Penetration mm	12.2	14.3	16.1	22.4	25.8
Wet sample + container	16.19	13.96	16.85	16.69	18.76
Dry sample + container	11.65	10	11.47	10.98	12.01
Weight of water	4.54	3.96	5.38	5.71	6.75
Weight of dry sample	7.93	6.29	7.74	7.27	8.25
Water content %	57.25	62.96	69.51	78.54	81.82

Table 4.2 Results of Plastic Limit tests on the Afari clay

Parameter	Test 1	Test 2
Weight of container	3.63	3.76
Wet sample + container	13.73	13.98
Dry sample + container	11.6	11.8
Weight of water	2.13	2.18
Weight of dry sample	7.97	8.04
Water content %	26.73	27.11
Average Water content % : 26.92		

Table 4.3 Results of Liquid Limits tests on the Mfensi clay

Parameter	Test 1	Test 2	Test 3	Test 4	Test 5
Weight of container	3.63	3.67	3.58	3.47	3.68
Penetration (mm)	13.1	18.65	23.15	26.75	28.15
Wet sample + container	15.48	17.95	16.64	17.8	18.68
Dry sample + container	12.19	13.73	12.53	13.16	13.7
Weight of water	3.29	4.22	4.11	4.64	4.98
Weight of dry sample	8.56	10.06	8.95	9.69	10.02
Water content %	38.43	41.95	45.92	47.88	49.70

Table 4.4 Results of Plastic Limit tests on the Mfensi clay

Parameter	Test 1	Test 2
Weight of container	3.8	3.54
Wet sample + container	17.88	17.86
Dry sample + container	15.45	15.4
Weight of water	2.43	2.46
Weight of dry sample	11.65	11.86
Water content %	20.86	20.74
Average Water content %		: 20.80

4.2.2 Particle Size Distribution of Raw Afari and Mfensi Clays

Results of particle size analysis were recorded on the Particle-Size Distribution Data Work Sheet presented in Tables 4.5- 4.6 for Afari clay and Tables 4.7 – 4.8 for Mfensi clay. These are graphically represented in particle size distribution curve in Figure 5.3.

Table 4.5 Data on grading test of Afari clay sample

Sieve size		Weight retained g	Percentage retained %	Percentage passing %
BS designation	Metric mm			
No. 14	1.18	0.00	0.00	100.00
No. 25	0.600	0.06	0.20	99.80
No. 36	0.425	0.08	0.27	99.53
No. 52	0.300	0.12	0.40	99.13
NO. 72	0.212	0.90	3.00	96.13
No. 100	0.150	1.29	4.30	91.83
No. 200	0.075	2.23	7.43	84.40

Table 4.6 Data on hydrometer readings of Afari clay sample

Elapsed time, min	Temp (° c)	Direct hydrometer readings	Viscosity	D mm	K %
0.50	27.00	1.0160	0.847	0.066	75.43
1.00	27.00	1.0150	0.847	0.048	70.01
2.00	27.00	1.0145	0.847	0.034	67.30
4.00	27.00	1.0143	0.847	0.024	66.22
8.00	27.00	1.0140	0.847	0.017	64.59
15.00	27.00	1.0135	0.847	0.013	61.89
30.00	26.00	1.0134	0.867	0.009	59.99
60.00	25.00	1.0127	0.888	0.006	54.90
120.00	24.00	1.0124	0.909	0.005	52.03
240.00	23.00	1.0120	0.932	0.003	48.68
1440.00	26.50	1.0110	0.857	0.001	47.66

Table 4.7 Data on grading test of Mfensi clay sample

Sieve size		Weight retained (g)	Percentage retained (%)	Percentage passing (%)
BS designation	Metric (mm)			
No. 14	1.18	0.00	0.00	100.00
No. 25	0.600	0.00	0.00	100.00
No. 36	0.425	0.00	0.00	100.00
No. 52	0.300	0.04	0.13	99.87
NO. 72	0.212	0.08	0.27	99.60
No. 100	0.150	0.50	1.67	97.93
No. 200	0.075	1.07	3.57	94.37

Table 4.8 Data on Hydrometer readings of Mfensi clay sample

Elapsed time,(min)	Temp (° c)	Direct hydrometer readings	Viscosity	D mm	K %
0.50	27.00	1.0170	0.847	0.065	80.84
1.00	27.00	1.0157	0.847	0.047	73.80
2.00	27.00	1.0145	0.847	0.034	67.30
4.00	27.00	1.0138	0.847	0.024	63.51
8.00	27.00	1.0130	0.847	0.017	59.18
15.00	27.00	1.0125	0.847	0.013	56.47
30.00	26.00	1.0119	0.867	0.009	51.86
60.00	25.00	1.0114	0.888	0.007	47.86
120.00	24.00	1.0105	0.909	0.005	41.74
240.00	23.00	1.0100	0.932	0.003	37.85
1440.00	26.50	1.0088	0.857	0.001	35.74

4.2.3 Percentage Linear Drying Shrinkages of Raw Afari and Mfensi Clays

Percentage linear drying shrinkages of test cubes of the raw Afari and Mfensi clays are presented in Table 4.11 and 4.12 respectively. In calculating the linear drying shrinkages the following formula was used:

$$ls = \frac{wl-dl}{wl} \times 100 \quad (4.2)$$

Where: *ls* is % drying shrinkage

wl is wet length mm

dl is dry length mm

Table 4.9 Percentage linear drying shrinkages of raw Afari clay

Afari clay	Wet length (<i>wl</i>) mm	Dry length (<i>dl</i>) mm	Linear shrinkages %
Af1	50	46	8
Af2	50	45	10
Af3	50	44	12
Af4	50	45	10
Af5	50	44	12
Af6	50	46	8
Af7	50	46	8
Af8	50	46	8
Af9	50	45	10
Af10	50	46	8

The average percentage linear drying shrinkages for the raw Afari clay is 9.4%

Table 4.10 Percentage linear drying shrinkages of raw Mfensi clay

Mfensi clay	Wet length (<i>wl</i>) mm	Dry length (<i>dl</i>) mm	Linear shrinkages %
Mf1	50	46	8
Mf2	50	47	6
Mf3	50	46	10
Mf4	50	47	6
Mf5	50	46	8
Mf6	50	46	8
Mf7	50	47	6
Mf8	50	47	6
Mf9	50	45	10
Mf10	50	47	6

The average percentage linear drying shrinkages for the raw Mfensi clay is 7.4%

4.2.4 Percentage Volumetric Drying Shrinkage of Raw Afari and Mfensi Clays

Percentage volumetric drying shrinkages of sample cubes of the raw Afari and Mfensi clays are presented in Tables 4.11 and 4.12 respectively. The values were determined using the following formula

$$v_s = \frac{wv-dv}{wv} \times 100 \quad (4.3)$$

where, v_s is % volumetric shrinkage

wv is wet volume

dv is dry volume

Table 4.11 Percentage volumetric drying shrinkage of raw Afari clay

Afari clay	Wet volume (wv) mm^3	Dry volume (dv) mm^3	Volumetric shrinkage %
Af11	125000	93150	25.48
Af12	125000	87120	30.30
Af13	125000	89100	28.72
Af14	125000	87120	30.30
Af15	125000	89100	28.72
Af16	125000	91080	27.14
Af17	125000	93150	25.48
Af18	125000	93100	25.52
Af19	125000	89100	28.72
Af20	125000	95220	23.82

The average percentage volumetric shrinkage of raw Afari clay is 27.42%

Table 4.12 Percentage volumetric drying shrinkage of raw Mfensi clay

Mfensi clay	Wet volume (wv) mm^3	Dry volume (dv) mm^3	Volumetric shrinkage %
Mf11	125000	97340	22.13
Mf12	125000	99410	20.47
Mf13	125000	99460	20.43
Mf14	125000	97290	22.17
Mf15	125000	97340	22.13
Mf16	125000	97340	22.13
Mf17	125000	97290	22.17
Mf18	125000	97290	22.17
Mf19	125000	96280	22.98
Mf20	125000	97290	22.17

The average percentage volumetric shrinkage of the raw Mfensi clay is 21.89%

4.3 Chemical Composition of Afari and Mfensi Clays, CPA, PBA and Lime (COS)

The chemical composition of the Afari clay, Mfensi clay and cocoa pod husk ash and oil palm empty bunch ash were obtained by fluorescence spectrometry on Spectro X-Lab 2000, Polarized Energy Dispersive X-ray Fluorescence Spectrometer (EDXRF) equipment at the x-ray fluorescence laboratory of the Geological Survey Department, Accra. The results obtained are shown in Table 4.13.

Table 4.13 Chemical composition of Afari and Mfensi clays, CPA, PBA and lime (COS)

Oxides	Composition %				
	Afari clay	Mfensi clay	CPA	PBA	Lime (COS)
SiO ₂	48.88	58.62	8.05	22.43	0.54
Al ₂ O ₃	26.56	23.44	2.28	1.54	0.81
Fe ₂ O ₃	6.66	3.63	0.89	0.63	-
CaO	0.24	0.14	8.43	5.21	54.81
MnO	0.01	0.02	0.10	0.07	-
MgO	1.61	1.41	5.16	7.83	-
Na ₂ O	1.73	2.06	0.44	2.23	0.52
K ₂ O	0.13	1.28	37.39	36.39	-
TiO ₂	0.79	0.9	0.14	0.08	-
P ₂ O ₅	0.06	0.13	2.33	2.92	-
SO ₃	0.17	0.18	2.09	3.46	-
Cl	-	-	0.01	0.27	-
LOI	12	8	32.00	16.50	42.34
Total	98.84	99.82	99.29	99.56	99.02

4.4 Phase/ Mineralogical Composition of the Raw Clays and Some Selected Test Pieces.

The raw Afari and Mfensi clay samples and some selected treated test samples based on the results of the compressive strength measurements were taken for phase/mineralogical analysis. The results are presented in Figures 5.4 to 5.5 and 5.29 to 5.32 under discussions.

4.5 Physical Properties of Test Pieces

4.5.1 Percentage Linear and Volumetric Drying Shrinkages of Test Pieces

(Clays + Lime + CPA)

Percentage linear and volumetric drying shrinkages of Afari and Mfensi clay test pieces were measured against variations of lime and cocoa pod husk ash content.

The results are tabulated in Tables 4.14 to 4.18.

Table 4.14 Percentage linear and volumetric drying shrinkages of Afari and Mfensi clay test pieces plus CPA only

Composition %			Linear shrinkage %		Volumetric shrinkage %	
CPA	Afari clay	Mfensi clay	Afari clay	Mfensi clay	Afari clay	Mfensi clay
0	100	100	9.4	7.4	27.42	21.89
5	95	95	9.0	6.8	26.25	19.84
10	90	90	8.6	6.4	25.09	18.67
15	85	85	8.2	6.2	23.92	18.09

Table 4.15 Percentage linear and volumetric drying shrinkages of Afari and Mfensi clay test pieces plus lime only

Composition %			Linear shrinkage %		Volumetric shrinkage %	
Lime	Afari clay	Mfensi clay	Afari clay	Mfensi clay	Afari clay	Mfensi clay
0	100	100	9.4	7.4	27.42	21.89
5	95	95	7.8	6.2	22.75	18.09
10	90	90	7.4	5.8	21.89	16.92
15	85	85	7.0	5.4	20.42	15.75

Table 4.16 Percentage linear and volumetric drying shrinkages of Afari and Mfensi clay test pieces with 5% lime and percentage variations of CPA

Composition %			Linear shrinkage %		Volumetric shrinkage %	
CPA	Afari clay	Mfensi clay	Afari clay	Mfensi clay	Afari clay	Mfensi clay
0	95	95	7.8	6.2	22.75	18.09
5	90	90	7.4	5.8	21.89	16.92
10	85	85	7.0	5.4	20.42	15.75
15	80	80	6.8	5.2	19.84	15.17

Table 4.17 Percentage linear and volumetric drying shrinkages of Afari and Mfensi clay test pieces with 10% lime and percentage variations of CPA

Composition %			Linear shrinkage %		Volumetric shrinkage %	
CPA	Afari clay	Mfensi clay	Afari clay	Mfensi clay	Afari clay	Mfensi clay
0	90	90	7.4	5.8	21.89	16.92
5	85	85	7.0	5.4	20.42	15.75
10	80	80	6.6	5.0	19.25	14.59
15	75	75	6.2	4.8	18.09	14.00
20	-	70	-	4.6	-	13.42

Table 4.18 Percentage linear and volumetric drying shrinkages of Afari and Mfensi clay test pieces with 15% lime and percentage variations of CPA

Composition %			Linear shrinkage %		Volumetric shrinkage %	
CPA	Afari clay	Mfensi clay	Afari clay	Mfensi clay	Afari clay	Mfensi clay
0	85	85	7.0	5.4	20.42	15.75
5	80	80	6.6	5.0	19.25	14.59
10	75	75	6.2	4.6	18.09	13.42
15	70	70	6.0	4.4	17.50	12.83
20	-	65	-	4.2	-	12.27

4.5.2 Percentage Linear and Volumetric Drying Shrinkages of Test Pieces (Clays + Lime + PBA)

Percentage linear and volumetric drying shrinkages of Afari and Mfensi clay test pieces were measured against variations of lime and oil palm empty bunch ash (PBA) content. The results are shown in Tables 4.19 – 4.22.

Table 4.19 Percentage linear and volumetric drying shrinkages of Afari and Mfensi clay test pieces plus oil palm empty bunch ash (PBA) with no lime addition

Composition %			Linear shrinkage %		Volumetric shrinkage %	
PBA	Afari clay	Mfensi clay	Afari clay	Mfensi clay	Afari clay	Mfensi clay
0	100	100	9.4	7.4	27.42	21.89
5	95	95	9.2	7.0	26.84	20.42
10	90	90	8.8	6.8	25.67	19.84
15	85	85	8.4	6.6	24.50	19.25

Table 4.20 Percentage linear and volumetric drying shrinkages of Afari and Mfensi clay test pieces with 5% lime and percentage variations of PBA

Composition %			Linear shrinkage %		Volumetric shrinkage %	
PBA	Afari clay	Mfensi clay	Afari clay	Mfensi clay	Afari clay	Mfensi clay
0	95	95	7.8	6.2	22.75	18.09
5	90	90	7.6	6.0	22.17	17.50
10	85	85	7.2	5.6	21.00	16.34
15	80	80	7.0	5.4	20.42	15.75

Table 4.21 Percentage linear and volumetric drying shrinkages of Afari and Mfensi clay test pieces with 10% lime and percentage variations of PBA

Composition %			Linear shrinkage %		Volumetric shrinkage %	
PBA	Afari clay	Mfensi clay	Afari clay	Mfensi clay	Afari clay	Mfensi clay
0	90	90	7.4	5.8	21.89	16.92
5	85	85	7.2	5.6	21.00	16.34
10	80	80	6.8	5.2	19.84	15.17
15	75	75	6.6	5.0	19.25	14.59
20	-	70	-	4.8	-	14.00

Table 4.22 Percentage linear and volumetric drying shrinkages of test pieces of Afari and Mfensi clays with 15% lime and percentage variations of PBA

Composition %			Linear shrinkage %		Volumetric shrinkage %	
PBA	Afari clay	Mfensi clay	Afari clay	Mfensi clay	Afari clay	Mfensi clay
0	85	85	7.0	5.4	20.42	15.75
5	80	80	6.8	5.2	19.84	15.17
10	75	75	6.4	4.8	18.67	14.00
15	70	70	6.2	4.6	18.09	13.42
20	-	65	-	4.4	-	12.83

4.6.1 Compressive Strength of Test Pieces (Clays + Lime + CPA)

The results of the compressive strength test conducted on Afari and Mfensi clay test pieces with variations in lime and cocoa pod husk ash (CPA) have been tabulated in Tables 4.23- 4.27.

Table 4.23 Compressive strength of Afari and Mfensi clay test pieces plus 0% CPA

Composition %			Compressive strength N/mm ²	
CPA	Afari clay	Mfensi clay	Afari clay	Mfensi clay
0	100	100	0.80	0.91
5	95	95	1.12	1.29
10	90	90	0.97	1.36
15	85	85	0.82	1.20

Table 4.24 Compressive strength of Afari and Mfensi clay test pieces with 0% lime

Composition %			Compressive strength N/mm ²	
Lime	Afari clay	Mfensi clay	Afari clay	Mfensi clay
0	100	100	0.80	0.91
5	95	95	0.57	0.64
10	90	90	0.71	0.79
15	85	85	0.85	0.95

Table 4.25 Compressive strength of Afari and Mfensi clay test pieces with 5% lime and percentage variations of CPA

Composition %			Compressive strength N/mm ²	
CPA	Afari clay	Mfensi clay	Afari clay	Mfensi clay
0	95	95	0.57	0.64
5	90	90	1.34	1.95
10	85	85	1.13	2.50
15	80	80	0.91	1.87

Table 4.26 Compressive strength of Afari and Mfensi clay test pieces with 10% lime and percentage variations of CPA

Composition %			Compressive strength N/mm ²	
CPA	Afari clay	Mfensi clay	Afari clay	Mfensi clay
0	90	90	0.71	0.79
5	85	85	1.65	2.08
10	80	80	1.49	4.85
15	75	75	1.14	5.85
20	-	70	-	3.71

Table 4.27 Compressive strength of Afari and Mfensi clay test pieces with 15% lime and percentage variations of CPA

Composition %			Compressive strength N/mm ²	
CPA	Afari clay	Mfensi clay	Afari clay	Mfensi clay
0	85	85	0.85	0.95
5	80	80	1.86	2.26
10	75	75	2.07	2.98
15	70	70	1.80	4.63
20	-	65	-	3.16

4.6.2 Compressive Strength of Test Pieces (Clays + Lime + PBA)

The results of compressive strength of Afari clay and Mfensi clays test pieces with percentage variations of lime and oil palm empty bunch ash (PBA) are presented in the Tables 4.28- 4.31.

Table 4.28 Compressive strength of Afari and Mfensi clay test pieces plus variations of PBA with 0% lime addition

Composition %			Compressive strength N/mm ²	
PBA	Afari clay	Mfensi clay	Afari clay	Mfensi clay
0	100	100	0.80	0.91
5	95	95	1.04	1.18
10	90	90	0.84	1.26
15	85	85	0.81	1.12

Table 4.29 Compressive strength of Afari and Mfensi clay test pieces with 5% lime plus variations of PBA

Composition %			Compressive strength N/mm ²	
PBA	Afari clay	Mfensi clay	Afari clay	Mfensi clay
0	95	95	0.57	0.64
5	90	90	1.14	1.44
10	85	85	1.05	2.28
15	80	80	0.87	1.34

Table 4.30 Compressive strength of Afari and Mfensi clay test pieces with 10% lime plus percentage variations of PBA

Composition %			Compressive strength N/mm ²	
PBA	Afari clay	Mfensi clay	Afari clay	Mfensi clay
0	90	90	0.71	0.79
5	85	85	1.99	2.31
10	80	80	1.42	2.94
15	75	75	1.31	2.77
20	-	70	-	2.37

Table 4.31 Compressive strength of Afari and Mfensi clay test pieces with 15% lime plus percentage variations of PBA

Composition %			Compressive strength N/mm ²	
PBA	Afari clay	Mfensi clay	Afari clay	Mfensi clay
0	85	85	0.85	0.95
5	80	80	1.28	2.10
10	75	75	1.64	2.84
15	70	70	1.09	2.50
20	-	65	-	2.21

4.7.1 Water Absorption and Wet Compressive Strength of Test Pieces (Clays + Lime + CPA)

Water absorption tests were performed on Afari and Mfensi clays test pieces with percentage variation of lime and cocoa pod husk ash. Measurements were taken during and immediately after 28days of soaking. Wet compressive strength tests were also performed on these test pieces immediately after 28days of soaking. The results are presented in the Tables 4.32 - 4.35 for the Afari clay and Tables 4.36 - 4.39 for Mfensi clay. The values of the percentage water absorption tests were determined using the following formula;

$$wa = \frac{sw-dw}{dw} \times 100 \quad (4.4)$$

Where; *wa* is Water absorption %

sw is soaked weight (grams)

dw is dry weight (grams)

Table 4.32 Percentage water absorption and wet compressive strength of Afari clay test pieces with 0% lime plus percentage variations of CPA

CPA %	Afari clay %	Weight of test pieces, g		Water absorption %	Compressive strength after soaking N/mm ²
		Dried wt.	Soaked wt. (28 Days)		
0	100	186	Disintegrated	-	-
5	95	177	Disintegrated	-	-
10	90	182	Disintegrated	-	-
15	85	187	Disintegrated	-	-

Table 4.33 Percentage water absorption and wet compressive strength of Afari clay test pieces with 5% lime plus percentage variations of CPA

CPA %	Afari clay %	Weight of test pieces, g		Water absorption %	Compressive strength after soaking N/mm ²
		Dried wt.	Soaked wt. (28 Days)		
0	95	157	Flaked off	-	-
5	90	155	210	35.48	0.42
10	85	160	215	34.38	0.54
15	80	161	221	33.94	0.33

Table 4.34 Percentage water absorption and wet compressive strength of Afari clay test pieces with 10% lime plus percentage variations of CPA

CPA %	Afari clay %	Weight of test pieces, g		Water absorption %	Compressive strength after soaking N/mm ²
		Dried wt.	Soaked wt. (28 Days)		
0	90	155	Flaked off	-	-
5	85	161	212	32.10	0.89
10	80	167	215	30.67	0.91
15	75	174	222	27.75	0.83

Table 4.35 Percentage water absorption and wet compressive strength of Afari clay test pieces with 15% lime plus percentage variations of CPA

CPA %	Afari clay %	Weight of test pieces, g		Water absorption %	Compressive strength after soaking N/mm ²
		Dried wt.	Soaked wt. (28 Days)		
0	85	158	Flaked off	-	-
5	80	163	213	31.68	0.77
10	75	162	214	28.74	0.87
15	70	173	221	27.59	0.80

Table 4.36 Percentage water absorption and wet compressive strength of Mfensi clay test pieces with 0% lime plus percentage variations of CPA

CPA %	Mfensi clay %	Weight of test pieces, g		Water absorption %	Compressive strength after soaking N/mm ²
		Dried wt.	Soaked wt. (28 Days)		
0	100	186	Disintegrated	-	-
5	95	191	Disintegrated	-	-
10	90	190	Disintegrated	-	-
15	85	194	Disintegrated	-	-

Table 4.37 Percentage water absorption and wet compressive strength of Mfensi clay test pieces with 5% lime plus percentage variations of CPA

CPA %	Mfensi clay %	Weight of test pieces, g		Water absorption %	Compressive strength after soaking N/mm ²
		Dried wt.	Soaked wt. (28 Days)		
0	95	181	Flaked off	-	-
5	90	182	222	22.03	0.83
10	85	185	222	20.85	0.95
15	80	187	223	19.61	0.74

Table 4.38 Percentage water absorption and wet compressive strength of Mfensi clay test pieces with 10% lime plus percentage variations of CPA

CPA %	Mfensi clay %	Weight of test pieces, g		Water absorption %	Compressive strength after soaking N/mm ²
		Dried wt.	Soaked wt. (28 Days)		
0	90	175	Flaked off	-	-
5	85	177	216	21.98	1.09
10	80	182	220	20.48	2.08
15	75	181	217	19.30	2.67
20	70	182	217	19.23	1.82

Table 4.39 Percentage water absorption and wet compressive strength of Mfensi clay test pieces with 15% lime plus percentage variations of CPA

CPA %	Mfensi clay %	Weight of test pieces, g		Water absorption %	Compressive strength after soaking N/mm ²
		Dried wt.	Soaked wt. (28 Days)		
0	85	170	Flaked off	-	-
5	80	175	213	21.71	1.01
10	75	178	212	19.10	1.19
15	70	180	213	18.33	1.42
20	65	180	212	17.78	1.23

4.7.2 Water Absorption and Wet Compressive Strength of Test Pieces (Clays + Lime + PBA)

Water absorption tests were performed on Afari and Mfensi clays test pieces with percentage variation of lime and oil palm empty bunch ash (PBA) during and immediately after 28days of soaking. Wet compressive strength tests were also performed on these test pieces immediately after 28days of soaking. The results are presented in the Tables 4.40- 4.43 for the Afari clay and Tables 4.44- 4.47 for Mfensi clay. The values of the percentage water absorption tests were determined using the same formula indicated under water absorption of test pieces (clays + lime + CPA).

Table 4.40 Percentage water absorption and wet compressive strength of Afari clay test pieces with 0% lime plus percentage variations of PBA

PBA %	Afari clay %	Weight of test pieces, g		Water absorption %	Compressive strength after soaking N/mm ²
		Dried wt.	Soaked wt. (28 Days)		
0	100	186	Disintegrated	-	-
5	95	166	Disintegrated	-	-
10	90	163	Disintegrated	-	-
15	85	173	Disintegrated	-	-

Table 4.41 Percentage water absorption and wet compressive strength of Afari clay test pieces with 5% lime plus percentage variations of PBA

PBA %	Afari clay %	Weight of test pieces, g		Water absorption %	Compressive strength after soaking N/mm ²
		Dried wt.	Soaked wt. (28 Days)		
0	95	157	Flaked Off	-	-
5	90	137	187	36.50	0.32
10	85	158	212	34.44	0.47
15	80	151	202	34.18	0.27

Table 4.42 Percentage water absorption and wet compressive strength of Afari clay test pieces with 10% lime plus percentage variations of PBA

PBA %	Afari clay %	Weight of test pieces, g		Water absorption %	Compressive strength after soaking N/mm ²
		Dried wt.	Soaked wt. (28 Days)		
0	90	155	Flaked Off	-	-
5	85	159	213	33.96	0.52
10	80	164	214	31.48	0.62
15	75	173	223	29.59	0.54

Table 4.43 Percentage water absorption and wet compressive strength of Afari clay test pieces with 15% lime plus percentage variations of PBA

PBA %	Afari clay %	Weight of test pieces, g		Water absorption %	Compressive strength after soaking N/mm ²
		Dried wt.	Soaked wt. (28 Days)		
0	85	158	Flaked Off	-	-
5	80	163	216	32.15	0.70
10	75	162	213	30.49	0.73
15	70	169	219	28.73	0.69

Table 4.44 Percentage water absorption and wet compressive strength of Mfensi clay test pieces with 0% lime plus percentage variations of PBA

PBA %	Mfensi clay %	Weight of test pieces, g		Water absorption %	Compressive strength after soaking N/mm ²
		Dried wt.	Soaked wt. (28 Days)		
0	100	186	Disintegrated	-	-
5	95	177	Disintegrated	-	-
10	90	182	Disintegrated	-	-
15	85	187	Disintegrated	-	-

Table 4.45 Percentage water absorption and wet compressive strength of Mfensi clay test pieces with 5% lime plus percentage variations of PBA

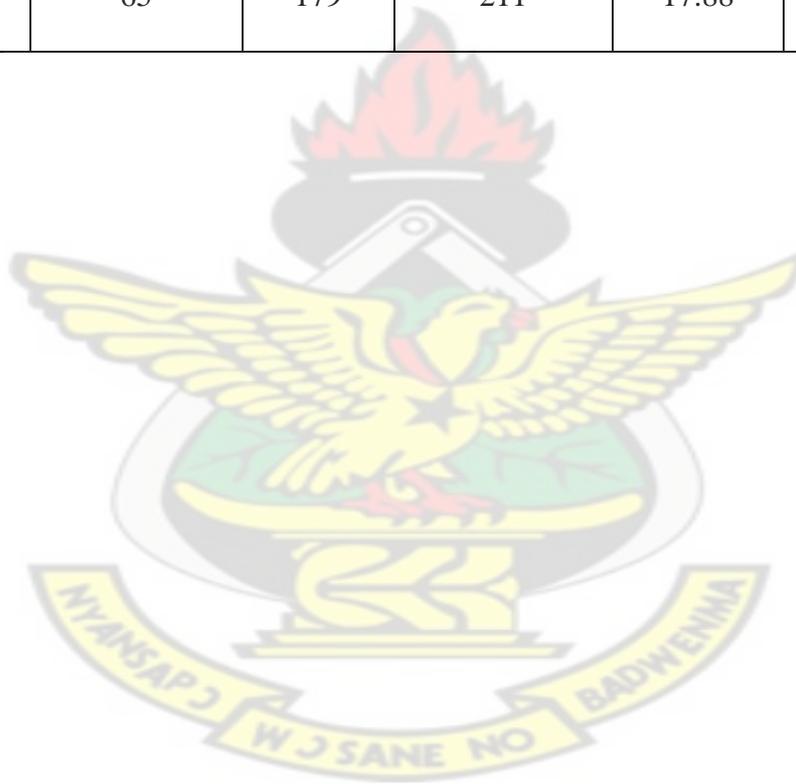
PBA %	Mfensi clay %	Weight of test pieces, g		Water absorption %	Compressive strength after soaking N/mm ²
		Dried wt.	Soaked wt. (28 Days)		
0	95	181	Flaked off	-	-
5	90	176	216	22.86	0.63
10	85	180	218	21.11	0.90
15	80	181	219	20.99	0.73

Table 4.46 Percentage water absorption and wet compressive strength of Mfensi clay test pieces with 10% lime plus percentage variations of PBA

PBA %	Mfensi clay %	Weight of test pieces, g		Water absorption %	Compressive strength after soaking N/mm ²
		Dried wt.	Soaked wt. (28 Days)		
0	90	175	Flaked off	-	-
5	85	181	222	22.73	1.04
10	80	183	221	20.77	1.27
15	75	182	218	19.78	1.12
20	70	181	216	19.33	1.07

Table 4.47 Percentage water absorption and wet compressive strength of Mfensi clay test pieces with 15% lime plus percentage variations of PBA

PBA %	Mfensi clay %	Weight of test pieces, g		Water absorption %	Compressive strength after soaking N/mm ²
		Dried wt.	Soaked wt. (28 Days)		
0	85	170	Flaked off	-	-
5	80	175	215	22.65	0.98
10	75	179	214	19.55	1.18
15	70	180	214	18.89	1.08
20	65	179	211	17.88	0.97



CHAPTER FIVE

DISCUSSION

5.1 Physical Characteristics of Raw Afari and Mfensi Clays

5.1.1 Atterberg Limits of Raw Afari and Mfensi Clays (Plastic Limit, Liquid Limit, Plasticity Index)

Tables 4.1 and 4.3 show the results of the liquid limits of Afari and Mfensi clays which are graphically represented in Figures 5.1 and 5.2 respectively. The liquid limit which is the water content at 20mm penetration of the standard cone into the clay is indicated with arrows in Figures 5.1 and 5.2. Afari clay has liquid limit of 73.40% while that of the Mfensi clay is 43.34%. Tables 4.2 and 4.4 also show plastic limit results of 26.92% and 20.80% for Afari and Mfensi clays respectively. The differences in liquid and plastic limits give the plasticity index value. The plasticity indices show a high value of 46.48% for Afari clay and low value of 22.54% for Mfensi clay as shown in Tables 5.1.

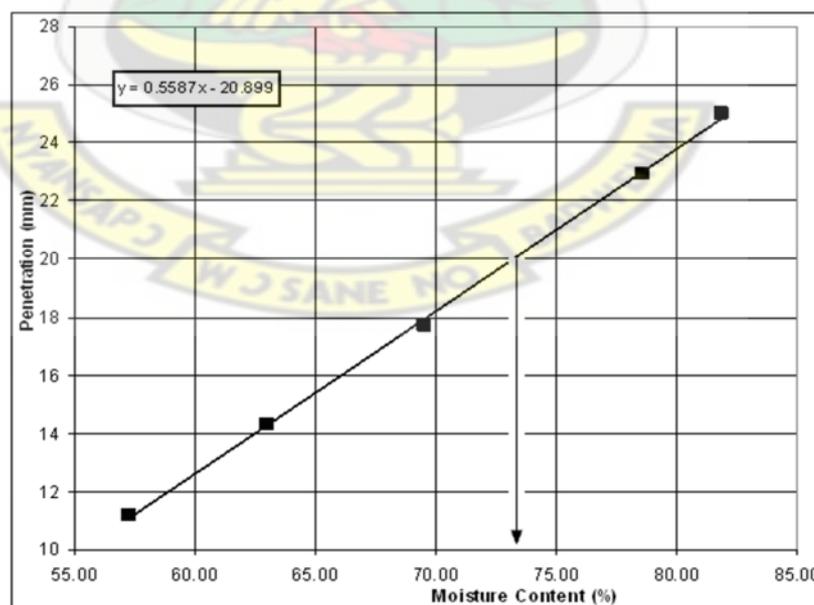


Figure 5.1 Graphical representation of liquid limit of Afari clay sample

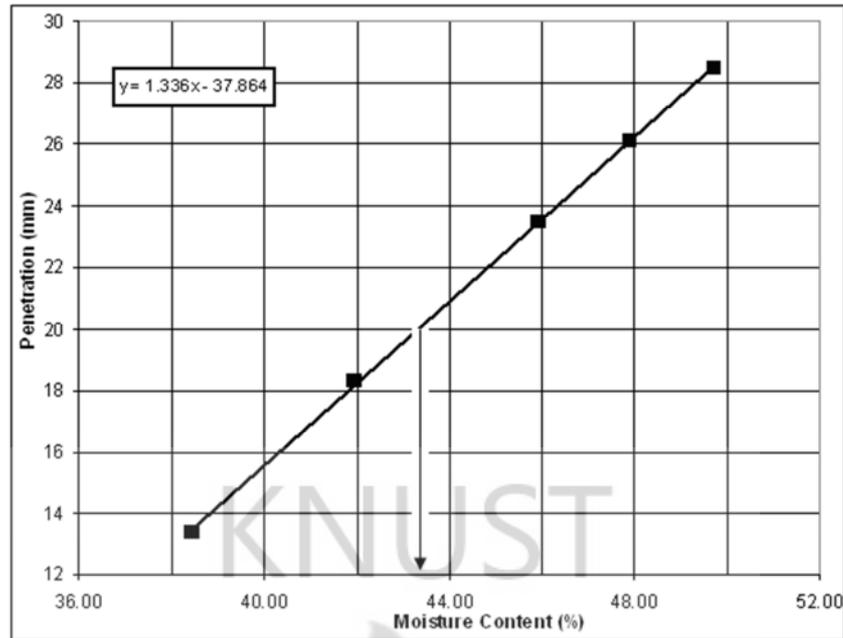


Figure 5.2 Graphical representation of liquid limit of Mfensi clay sample

Table 5.1 Results of Plasticity Index tests on the Afari and Mfensi clays

Sample	Liquid Limit (LL)	Plastic Limit (PL)	Plasticity Index (PI)
Afari clay	73.40	26.92	46.48
Mfensi clay	43.34	20.80	22.54

As pointed out by Gogo (1993), plasticity characteristics give an indication of the approximate water content which is likely to give the optimum workability during mixing and therefore plays an important role in stabilization. The amount of water used during mixing for optimum workability was found to be between 25% and 40% for Afari clay and 20% and 35% for Mfensi clay. From this result, Afari clay has a relatively high plasticity index. This suggests that Afari clay has a considerable amount of particle sizes less than $2\mu\text{m}$, representing clay fraction; thus making Afari clay more plastic and absorbing more water than Mfensi clay which has a relatively

low plasticity index. Hence, from the plasticity index, Afari clay has a relatively high shrinkage than Mfensi clay.

5.1.2 Particle Size Distribution of Raw Afari and Mfensi Clays

Particle size distribution is an important characteristic for the development of structural strength of an article. It could also determine the rate of heterogeneous reaction that may involve the particles. Additionally, the degree of packing in a bulk and the amount of inter particle void is determined by the particle size distribution in bulk.

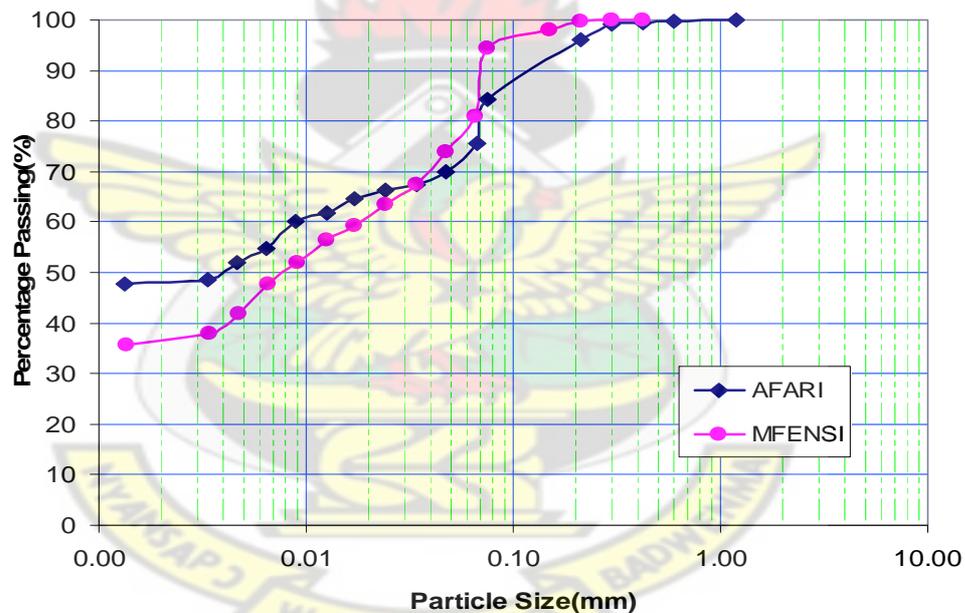


Figure 5.3 Particle size distribution curves of Afari and Mfensi clays

Figure 5.3 shows the particle size distribution curves of Afari and Mfensi clays derived from grading test and hydrometer readings of Afari and Mfensi clays shown in Tables 4.5 to 4.8. Both clays were associated with smaller particle size but the particle size of Afari clay is relatively smaller than that of Mfensi clay. This will

affect the level of inter-particle packing, the level of inter-particle void and therefore water absorption and shrinkage.

5.1.3 Percentage Linear and Volumetric Drying Shrinkages of Raw Afari and Mfensi Clays

Tables 4.9 to 4.12 present the percentage linear and volumetric drying shrinkages of raw Afari and Mfensi clays. The result shows that the percentage linear drying shrinkages of Afari and Mfensi clays are 9.4% and 7.4% respectively while the percentage volumetric drying shrinkage are 27.42% for Afari clay and 21.89% for Mfensi clay. Comparing the two clays, Afari clay has a high shrinkage in terms of linear and volume than Mfensi clay. This is probably due to the particle size distribution as mentioned above and confirmed with the Atterberg limits tests.

5.2 Chemical Composition of Raw Afari and Mfensi Clays

Table 4.13 shows the chemical composition of Afari and Mfensi clays used in this work. From the results Afari clay has 48.88% SiO₂, 26.56% Al₂O₃ and 2.10% (CaO, K₂O and Na₂O) while Mfensi clay has 58.62% SiO₂, 23.44% Al₂O₃ and 4.48% (CaO, K₂O and Na₂O). According (Worrall, 1986) both clays show typical characteristics of kaolinitic clays but Afari clay exhibited more plasticity in nature due to some montmorillonite peaks found in the raw XRD patterns as shown in Figure 5.4.

5.3 Mineralogical Analysis of Raw Afari and Mfensi Clays

Figures 5.4 and 5.5 show the XRD patterns of raw Afari and Mfensi clays respectively. The phases present in the raw Afari clay are quartz with hexagonal and

rhombo hexagonal lattice structure), montmorillonite (triclinic and monoclinic lattice structure), kaolinite (triclinic and monoclinic lattice structure) and albite and the raw Mfensi clay has quartz (hexagonal and rhombo hexagonal lattice structure), kaolinite (triclinic and monoclinic lattice structure) and muscovite (monoclinic lattice structure).

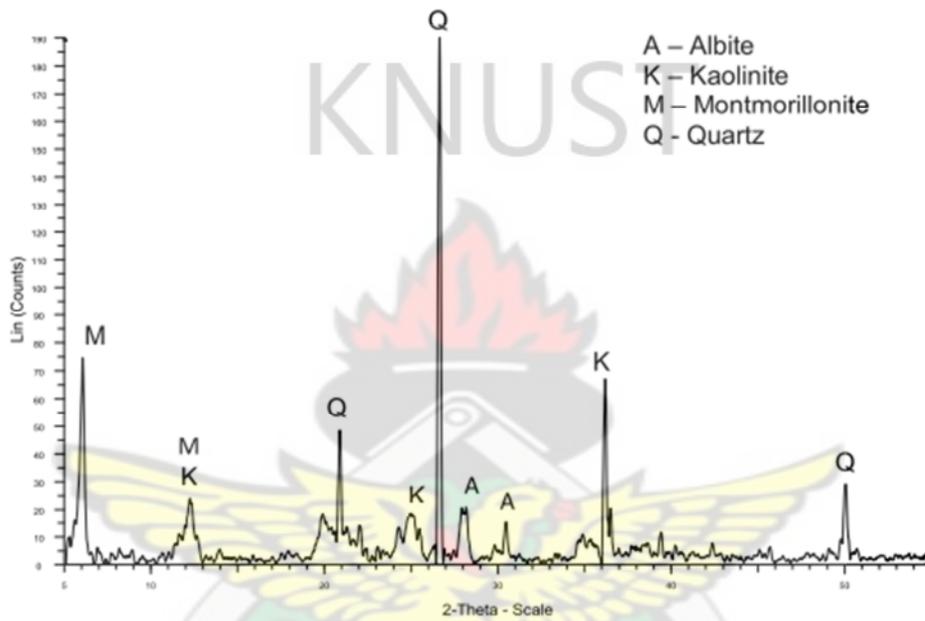


Figure 5.4 X-ray pattern diffractogram of the raw Afari clay (AO)

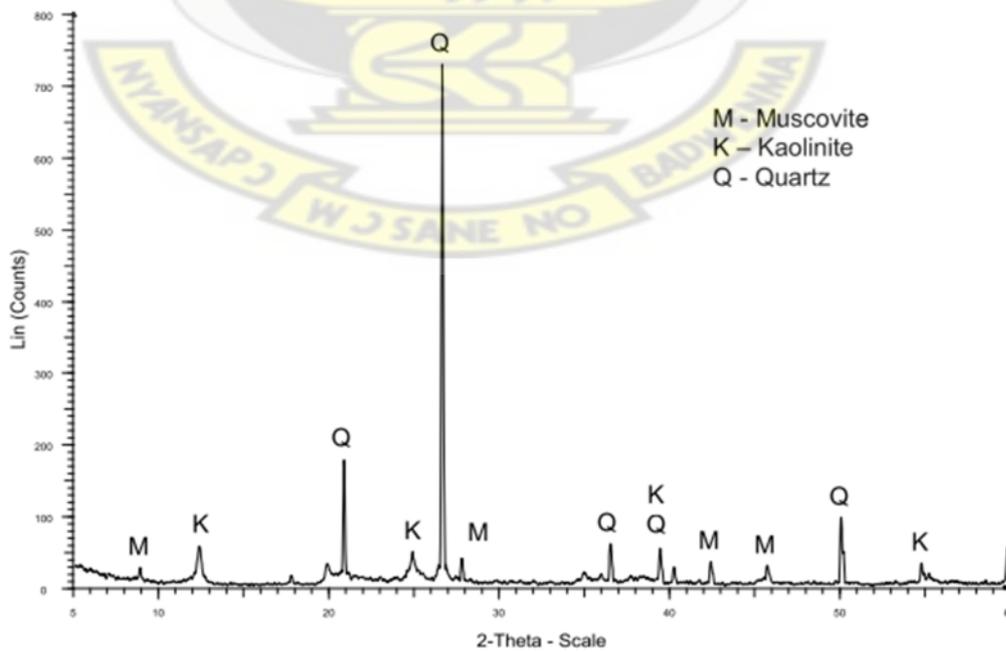


Figure 5.5 X-ray pattern diffractogram of the raw Mfensi clay (MO)

Comparing the XRD patterns of both raw Afari and Mfensi clays shown in Figures 5.4 to 5.5, the following conclusions were drawn:

1. The presence of montmorillonite in only raw Afari clay is in agreement with the plasticity index value of 46.48% in Table 5.1 which confirms the relatively high shrinkage in Afari clay than Mfensi clay. This is expected in clays with plasticity index above 29% as reported by Solanki and Zaman (2012).
2. The strong peaks detected in both patterns correspond to Quartz. This is in agreement with the amounts of SiO₂ (48.88% and 58.62%) respectively for Afari and Mfensi clays in the chemical compositions presented in Table 4.13.
3. The dominant phase observed in both patterns is quartz and the minor phases in raw Afari clay were montmorillonite, kaolinite and albite while that of raw Mfensi clay were kaolinite and muscovite.

5.4 Chemical Composition of Cocoa Pod Husk Ash, Oil Palm Empty Bunch Ash and Lime (Calcined Battor Shell)

Table 4.13 shows also the chemical composition of cocoa pod husk ash, oil palm empty bunch ash and lime (calcined Battor shell) used in this study. The analyses indicate that both ashes have a relatively high amount of potassium oxide (K₂O). Thus CPA has K₂O content of 37.39% and that of PBA is 36.39%. These are the expected alkali compounds in both ashes which may act as chemical stabilizers in reacting with the clays to form a cementitious matrix. There is also an appreciable amount of calcium oxide (CaO) in cocoa pod husk ash (8.43%) and oil palm empty bunch ash (5.21%). The Lime has oxide contents of 54.81% CaO, 0.54% SiO₂, 0.81% Al₂O₃, Na₂O 0.52% and LOI of 42.34%. The high loss on ignition in both

ashes CPA (32%) and PBA (16.5%) could be attributed to the hygroscopic nature of both ashes.

5.5 Physical Characteristics of the Test Pieces

5.5.1 Percentage Linear Drying Shrinkages of Test Pieces (Clays + Lime + CPA or PBA)

Percentage linear drying shrinkages tests were conducted on the treated test pieces with weighted % proportions of (clay + lime + CPA/PBA) of both Afari and Mfensi clays as shown in Tables 4.14 to 4.22. The graphical representation of the results of percentage linear drying shrinkages of Afari and Mfensi clay test pieces with varying weighted % proportions of (clay + lime + CPA/PBA) are shown in Figures 5.6 to 5.10.



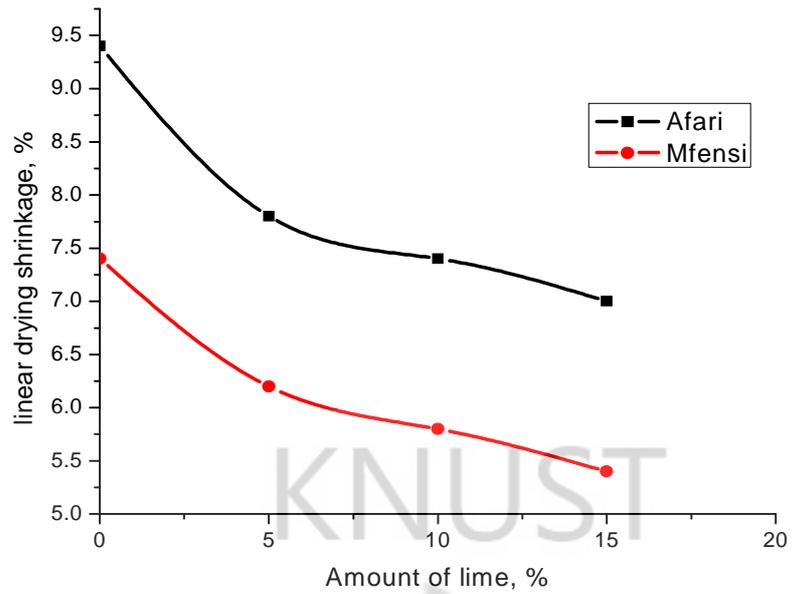


Figure 5.6 Percentage linear drying shrinkages of Afari and Mfensi clay test pieces with lime only

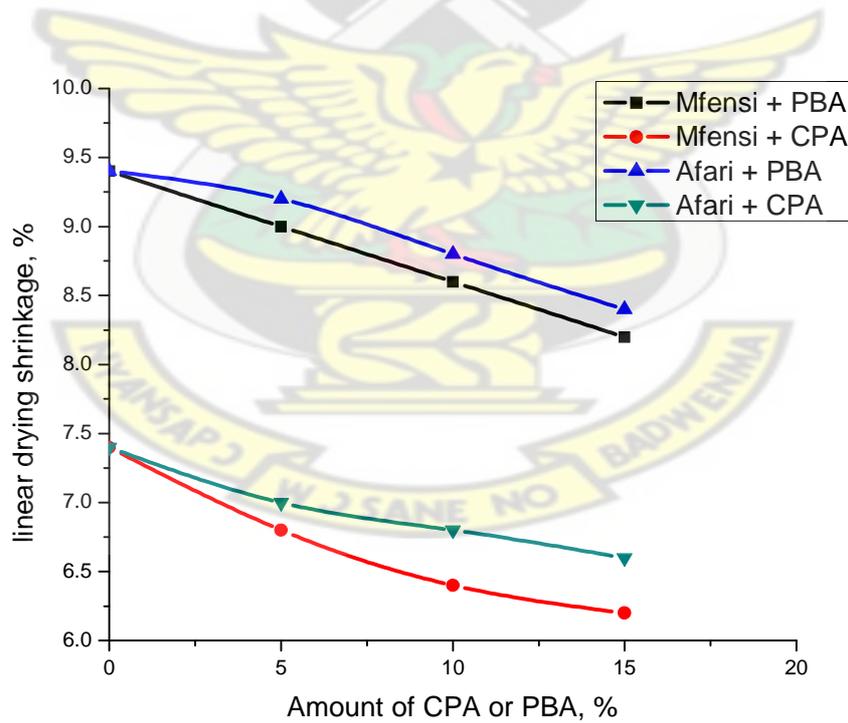


Figure 5.7 Percentage linear drying shrinkages of Afari and Mfensi clay test pieces with CPA and PBA plus no additions of lime

Figure 5.6 shows graphical representation of the results of percentage linear drying shrinkages of Afari and Mfensi clay test pieces with lime additions only presented in Table 4.15. From the graph, there was a linear % shrinkage decrease with increase in lime contents with respect to Afari and Mfensi clays. The highest decrease in shrinkage value was recorded with 15% addition of CaO.

Figure 5.7 is the graphical representation of the results of percentage linear drying shrinkages of Afari and Mfensi clays test pieces when CPA and PBA were used as additives but with no lime addition. It was noted that all the curves exhibited similar decreasing linear trend. In all cases, linear drying shrinkages decreased slightly with increase in CPA and PBA contents in both clays with no lime addition, registering an amount of 9.4% when no additives were employed for Afari clay or 7.4% for Mfensi clay to an amount of 8.2% at 15% CPA addition to Afari clay or 6.2% for the same amount of CPA addition to Mfensi clay. Linear drying shrinkage values of Afari clay test pieces are considerably higher than Mfensi clay test pieces. This is due to the fact that raw Afari clay shrinks more than Mfensi as indicated earlier. Results in the case of PBA additions were marginally higher than those of CPA. This shows that test pieces with PBA additions shrink a little more than that of CPA additions but the rate of shrinkages were not significantly high. The shrinkages on adding the CPA and PBA additives were much less than when no additives were added.

Similar results were obtained, when lime was added to the mixture in addition to CPA or PBA as presented in Figures 5.8 to 5.10.

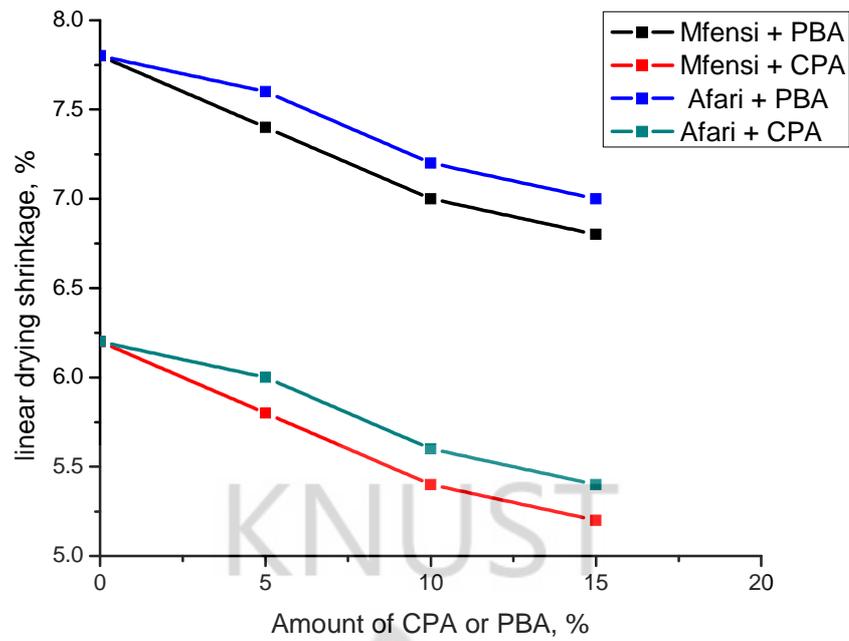


Figure 5.8 Percentage linear drying shrinkages of Afari and Mfensi clay test pieces with 5% lime plus percentage variations of CPA or PBA

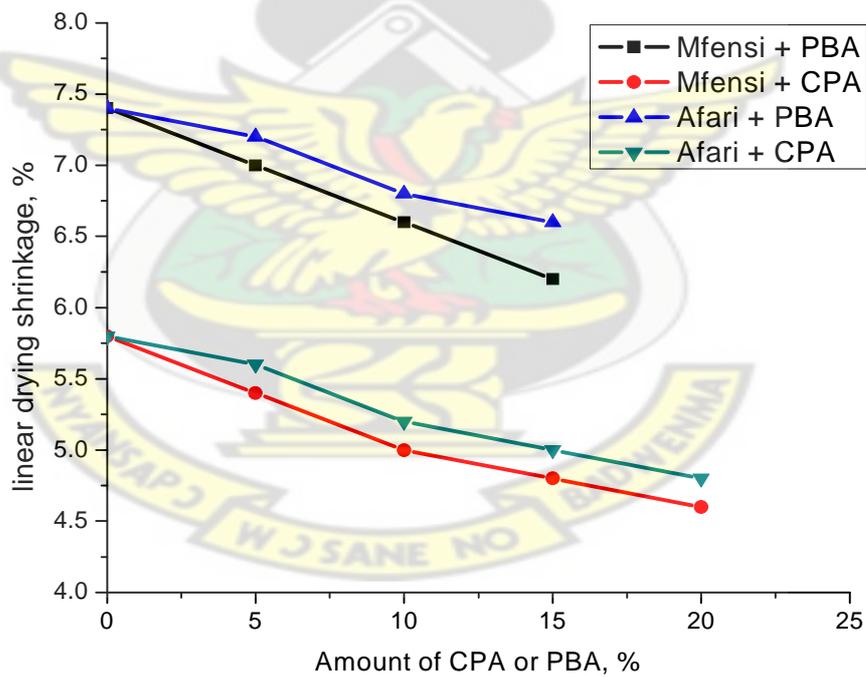


Figure 5.9 Percentage linear drying shrinkages of Afari and Mfensi clay test pieces with 10% lime plus percentage variations of CPA or PBA

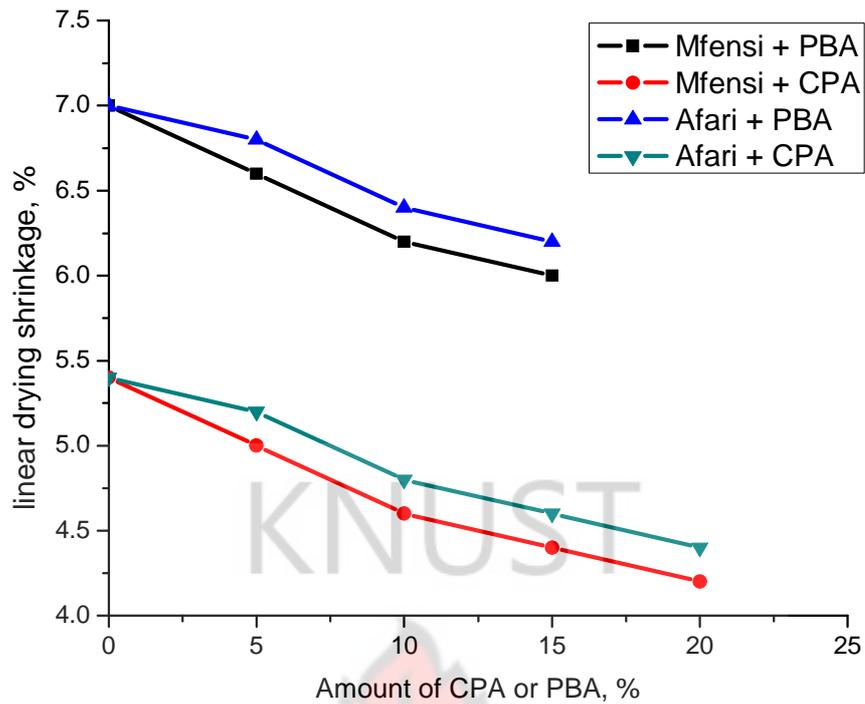


Figure 5.10 Percentage linear drying shrinkages of Afari and Mfensi clay test pieces with 15% lime plus percentage variations of CPA or PBA

The least linear drying shrinkage for Afari clay was obtained at 15% lime and 15% CPA addition, with a value of 6.0%. In the case of Mfensi clay the least linear drying shrinkage was obtained at the same additive additions as in the case of the Afari clay, with a value of 4.4%.

The reductions in shrinkage as a result of the addition of the stabilizers was due to the filling of inter voids by the additives and the possible formation of different phases in the voids as a result of phase changes and inter-particle reactions.

5.5.2 Percentage Volumetric Drying Shrinkage of Test Pieces (Clays + Lime + CPA or PBA)

Similar results were obtained for percentage volumetric shrinkage as in linear drying shrinkages. These have been presented in Figures 5.11 to 5.15. The reasons for the percentage volumetric drying shrinkages of Afari and Mfensi clays are the same as proposed in the case of linear drying shrinkages.

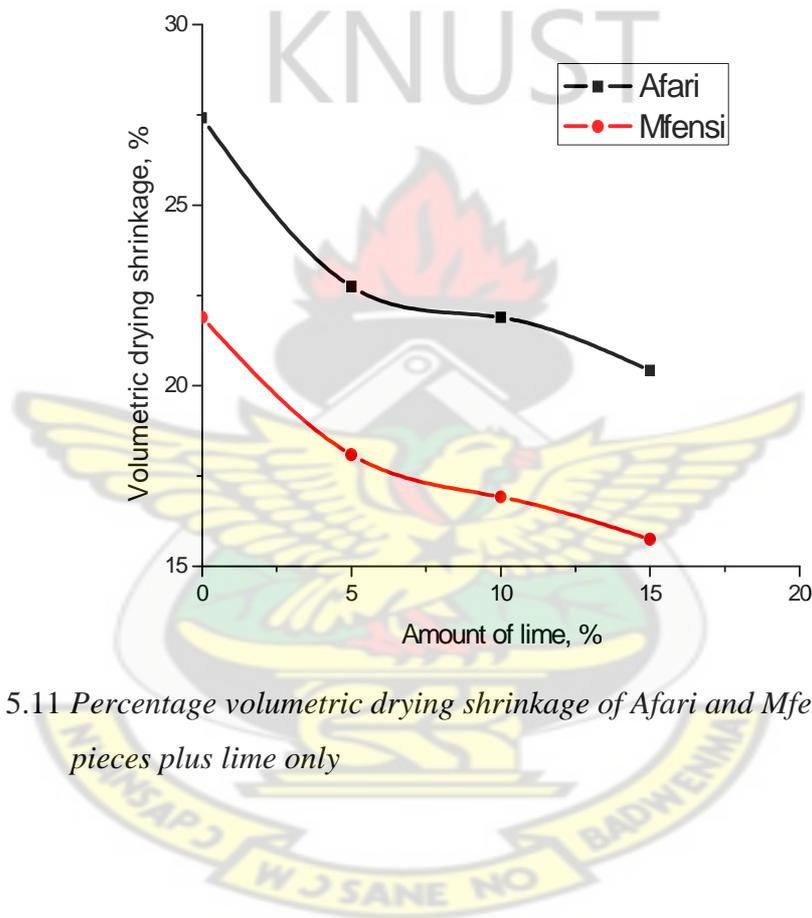


Figure 5.11 Percentage volumetric drying shrinkage of Afari and Mfensi clay test pieces plus lime only

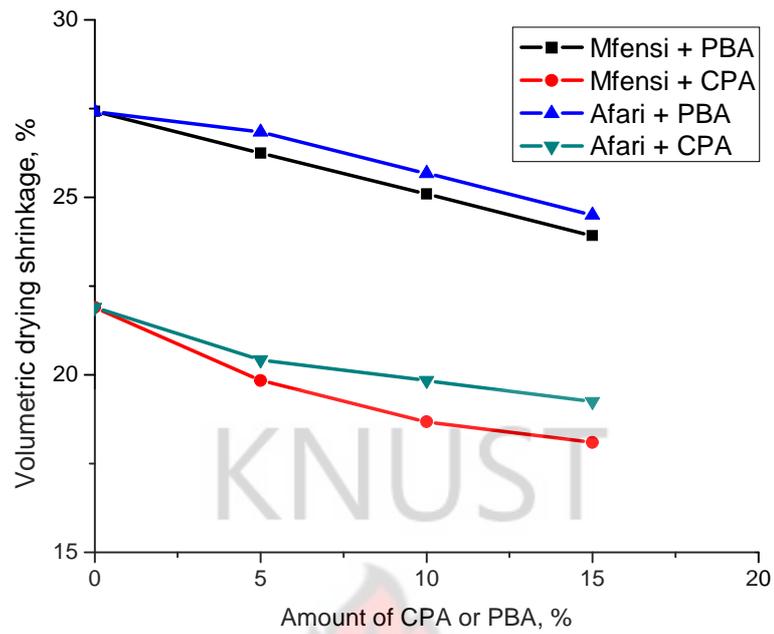


Figure 5.12 *Percentage volumetric drying shrinkages of Afari and Mfensi clay test pieces with CPA and PBA with no lime addition*

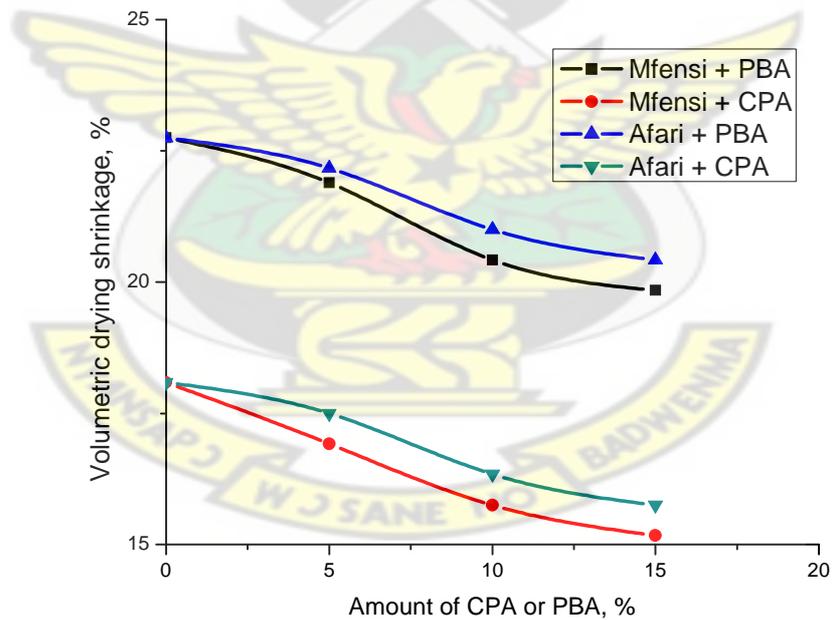


Figure 5.13 *Percentage volumetric drying shrinkage of Afari and Mfensi clay test pieces with 5% lime and percentage variations of CPA or PBA*

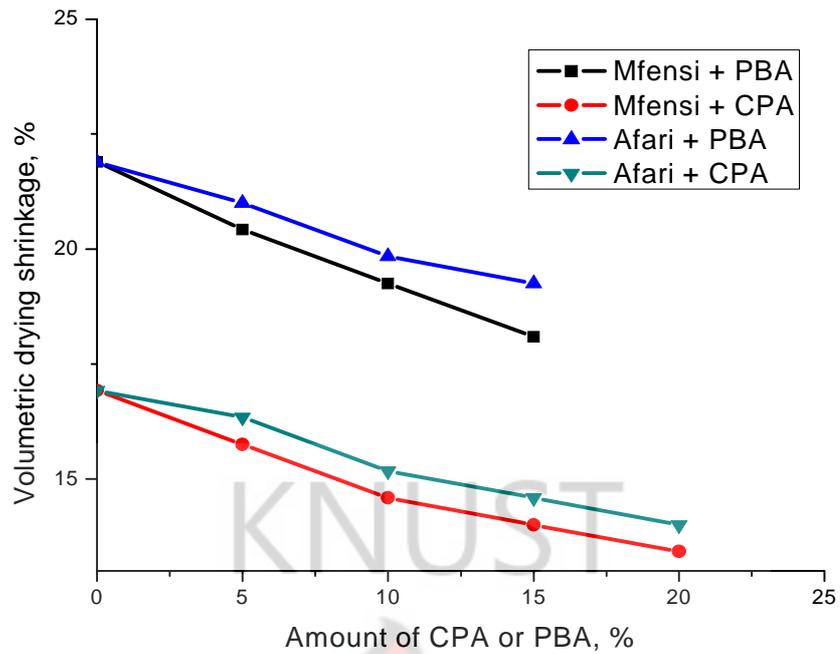


Figure 5.14 Percentage volumetric drying shrinkage of Afari and Mfensi clay test pieces with 10% lime and percentage variations of CPA or PBA

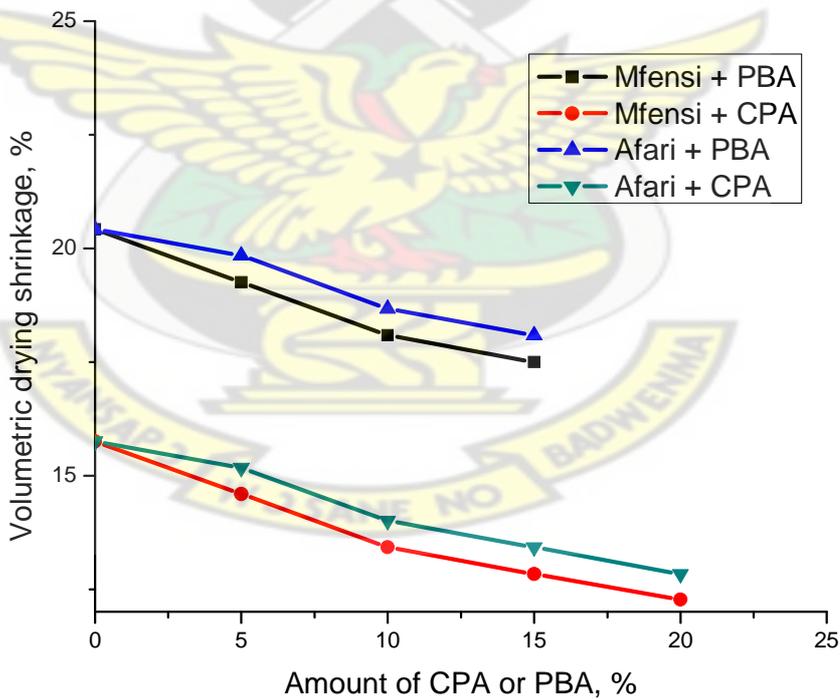
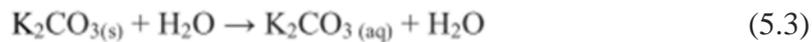
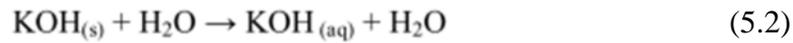
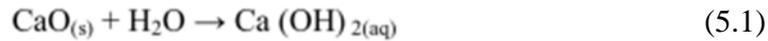
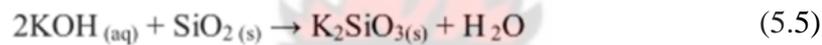
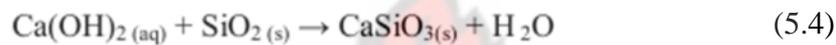


Figure 5.15 Percentage volumetric drying shrinkage of Afari and Mfensi clay test pieces with 15% lime and percentage variations of CPA or PBA

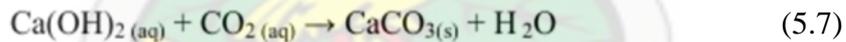
The test pieces with lime (CaO), CPA and PBA additives contained partially soluble CaO or soluble KOH, K₂CO₃ (Woode and Hammond, 2001) components, which on addition of water during the forming process would have dissolved to fill in the inter-particle voids:



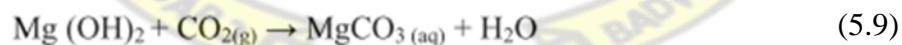
These would probably have entered into complex chemical reactions during curing to produce solid components in the voids, therefore filling the voids:



Also, Ca(OH)₂ could react with the CO₂ of the air to transform into CaCO₃:



Similarly, any free MgO in the ash could react as



CaCO₃ is relatively stable in a neutral or alkaline environment. Any CaCO₃ formed therefore also act as a binding or cementing agent between the clay particles. This would result in the further stabilization of the clay particles leading to an increase in compressive strength.

These reactions will continue depending on the reaction rates and the availability of components. Other complex reactions involving the clay minerals which will be discussed later, may also take place. As a result of the formation of these solid compounds in the voids, the matrix becomes less compressible and therefore less shrinkable. The formation of these compounds can be proven by phase analysis of the test pieces. The filling of the voids should play an important part on the structural stability of the material produced.

Comparing the results of Afari and Mfensi clay samples (all compositions) with respect to their linear and volumetric drying shrinkages as shown in Tables 4.14 to 4.22 and represented graphically in Figures 5.6 to 5.15; the following conclusions could be adduced: Both clays behave essentially the same in terms of linear drying shrinkages and volumetric shrinkage. They have decreasing trend as the additives are increased. This trend was observed with all the compositions. Afari clay has slightly higher percentage shrinkage than Mfensi as already discussed, probably because of the higher clay mineral content.

1. Linear drying shrinkages values of both Afari and Mfensi clay test pieces are almost one-third of their volumetric shrinkage values. This observation is attested by Worrall (1986) that linear shrinkage is very approximately one-third of volumetric shrinkage for an isotropic specimen, which is a body that shrinks equally in all directions.
2. With PBA additions, shrinkages are a little more than that of CPA additions but the differences in shrinkages are not significantly high. This may be as a result of the difference in the silica content in the ashes.

- Linear and volumetric drying shrinkage decreased with increase in lime or CPA or PBA only, lime with CPA and lime with PBA. This trend was observed with all the compositions.

5.6 Compressive Strength of Test Pieces (Clays + Lime + CPA or PBA)

Compressive strength test were performed on the dry Afari and Mfensi clay test pieces. The results of the compressive strength of Afari and Mfensi clay test pieces with respect to the addition of lime and cocoa pod husk ash (CPA), are shown in Tables 4.24- 4.28 and those in relation to the addition of lime and oil palm empty bunch ash (PBA) in Tables 4.39 - 4.32 have been graphically illustrated in Figures 5.16 - 5.23.

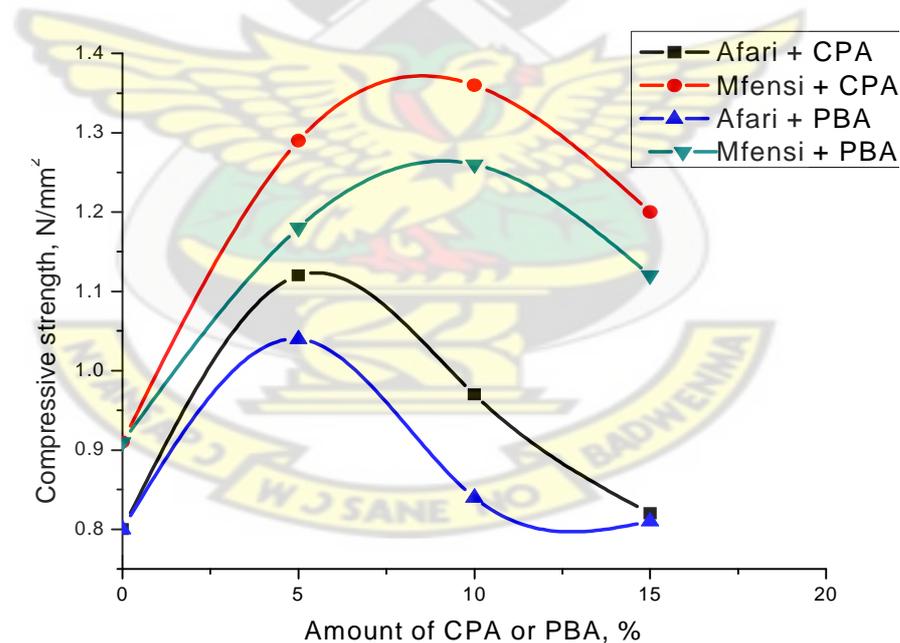


Figure 5.16 Compressive strength of Afari and Mfensi clays test pieces with 0% lime plus percentage variations of CPA or PBA

Figure 5.16 is the graphical illustration of results of compressive strength of Afari and Mfensi clay test pieces with 0% lime with varying amounts of CPA or PBA.

From this Figure, it could be seen that the compressive strength of Mfensi clay test pieces increased to a maximum of 1.36N/mm^2 and 1.26N/mm^2 at 10% CPA and 10% PBA respectively, after which the compressive strength fell when the CPA or PBA content was increased to 15%. In the case of Afari clay, the compressive strength of the test pieces also increased to maximum of 1.12 N/mm^2 and 1.04 N/mm^2 at 5% CPA and 5% PBA respectively, after which the value decreased. Thus, the compressive strength of Mfensi clay test pieces on adding CPA and PBA were significantly higher than those of the Afari clay test pieces. Even at 5% of CPA or PBA addition, the performance of the Mfensi clay was better, recording a difference of 0.17 N/mm^2 as against 0.14 N/mm^2 in the case of PBA. This means that Mfensi clay responded well to CPA and PBA than that of Afari clay.

The decline in the compressive strength values after 5% addition of CPA or PBA in the case of Afari clay is surprising. However, this could be due to the chemical composition of the Afari clay (Table 4.13).

Supposing all Al_2O_3 in Afari clay in Table 4.13 is in the form of kaolinite:

Their molecular weight are $\text{Al}_2\text{O}_3 = 102$ $2\text{SiO}_2 = 120$ $2\text{H}_2\text{O} = 36$

$102\text{ Al}_2\text{O}_3 = 26.7\%$ and $120\text{ 2SiO}_2 = x$

$$x = \frac{120}{102} \times 26.7$$

$$x = 31.41$$

Amount of SiO_2 left is = $43.88 - 31.41$

$$= 17.47$$

In the case of the Mfensi clay:

$(102)\text{ Al}_2\text{O}_3 = 23.44\%$ and $(120)\text{ 2SiO}_2 = x$

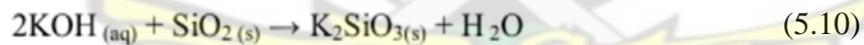
$$x = \frac{120}{102} \times 23.44$$

$$x = 27.58$$

$$\text{Amount of SiO}_2 \text{ left is} = 58.62 - 27.58$$

$$= 31.04$$

Using the chemical composition and assuming that all Al_2O_3 in the clay is in the form of kaolinite ($\text{Al}_2\text{O}_3 \cdot 2\text{SiO}_2 \cdot 2\text{H}_2\text{O}$), from the calculations above, the amount of silica bound to kaolinite in the Afari and Mfensi clays would be 31.41% and 27.58% respectively. This leaves an amount of 17.47% and 31.04% respectively for Afari and Mfensi clays as free silica. As proposed earlier, potassium hydroxyl of the ash reacts with free reactive silica of the clay to produce potassium silicate:



It is also proposed that not all silica in the clay or ash is reactive. When all reactive silica is reacted and excess KOH is present at the time of compressive strength measurements as a results of increased additions of the ash, all the KOH may not have been used up leading to a decline in the compressive strength.

There may also be a reaction involving potassium hydroxyl and the kaolinite, a reaction similar to that between caustic soda and kaolinite, as in the Bayer process for refining bauxite (Guihua, 1998)



Both potassium silicate and potassium aluminium silicate materials would act as cementitious materials in the void, binding the clay particles together and consequently stabilizing the clay and improving the compressive strength.

Compressive strength values were better when lime was added to the mixture in addition to CPA or PBA. The values increased for Mfensi clay to 2.50 N/mm², 4.85 N/mm², and 5.85 N/mm² respectively at 5%, 10% and 15% CPA additions (Figures 5.17 to 5.19). Thus the best results were obtained for 10% lime and 15% CPA additions.

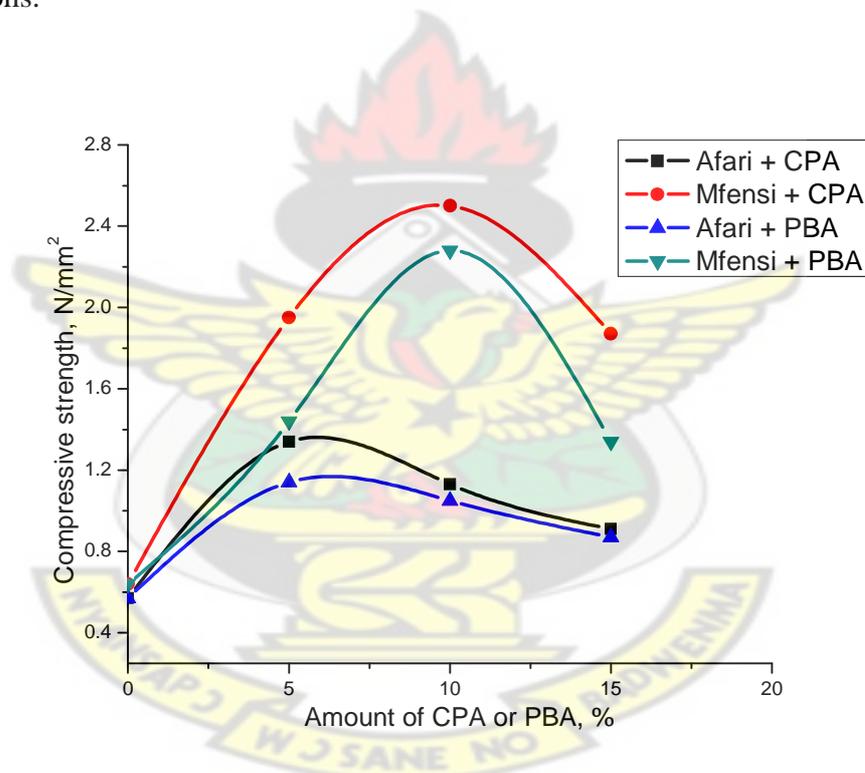


Figure 5.17 Compressive strength of Afari and Mfensi clays test pieces with 5% lime and percentage variations of CPA or PBA

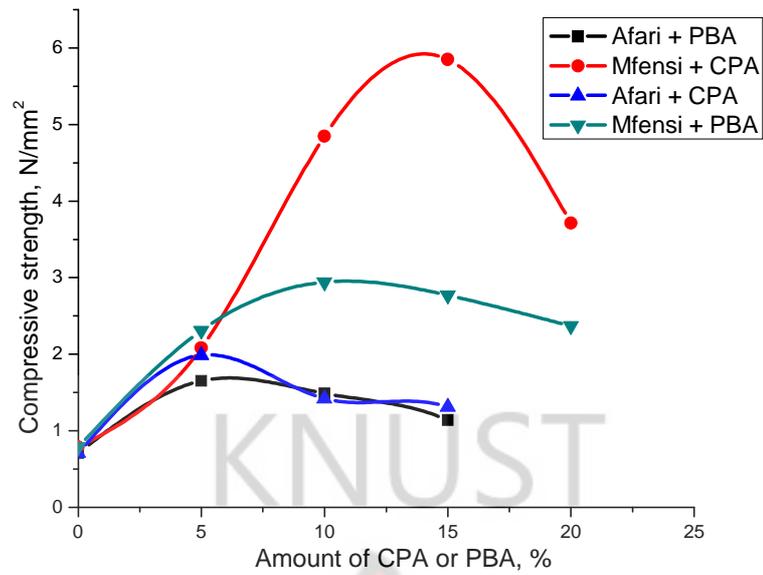


Figure 5.18 Compressive strength of Afari and Mfensi clays test pieces with 10% lime and percentage variations of CPA or PBA

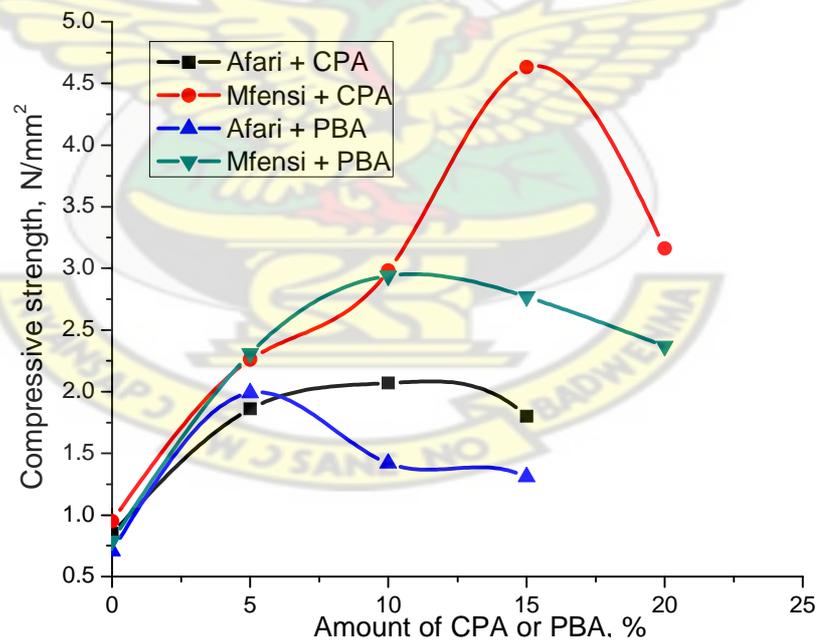


Figure 5.19 Compressive strength of Afari and Mfensi clays test pieces with 15% lime and percentage variations of CPA or PBA

Similar trend was observed when PBA was used as additive. Only in this case the compressive strength values were relatively lower, registering values of 2.28 N/mm²

at 5% PBA and 2.94 N/mm² at 10% PBA, dropping to 2.84 N/mm² at 15% PBA additions all at 10% lime (Figures 5.17 to 5.19).

Compressive strength versus lime additions at various CPA or PBA additions are shown in Figures 5.20 to 5.22 respectively. These show the effect of lime additions to the development of strength. The best result for the Mfensi clay was obtained at 10% lime and 15% CPA addition. However, in the case of PBA additions, the best result was achieved at 10% lime and 10% PBA additions which might be of importance for cost consideration.

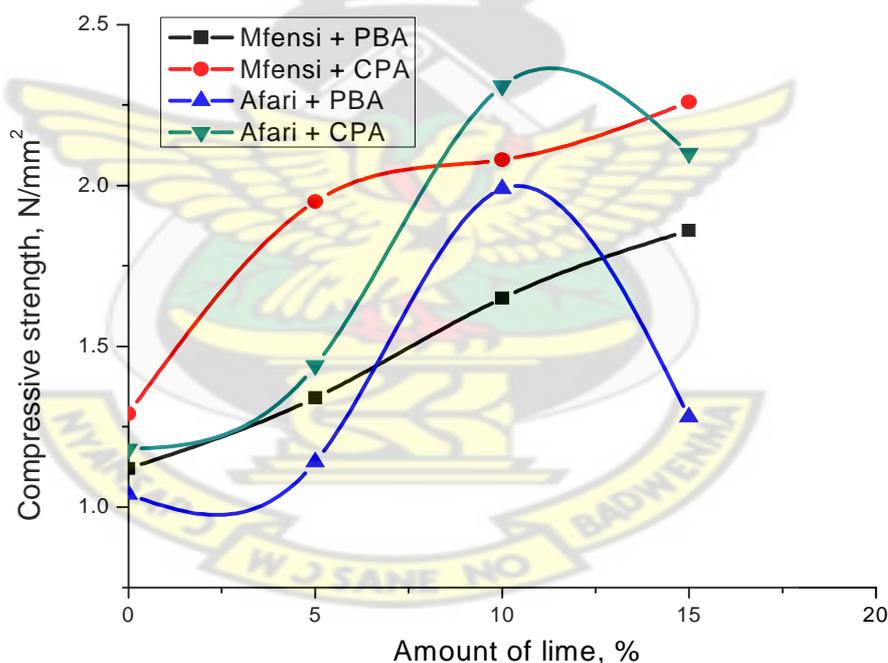


Figure 5.20 Compressive strength of Afari and Mfensi clays test pieces with 5% CPA or PBA and percentage variations of lime

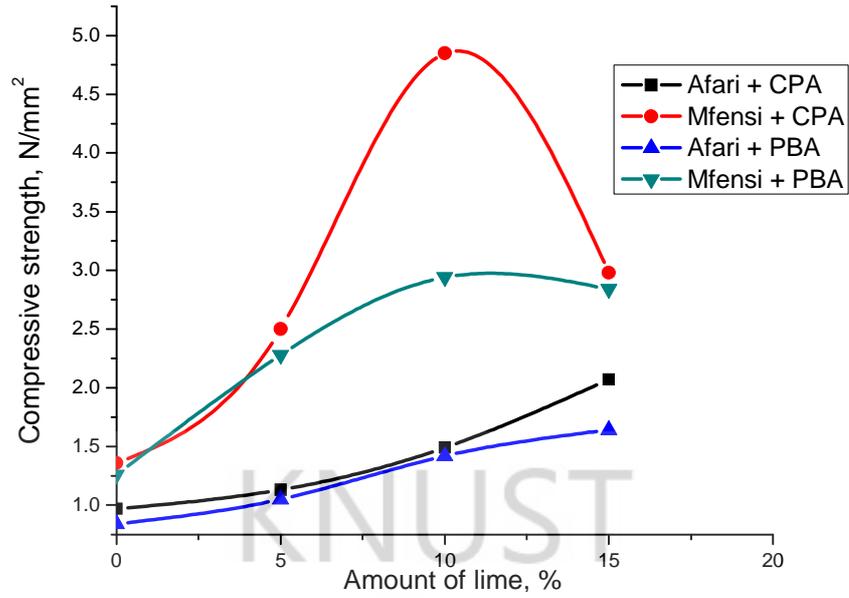


Figure 5.21 Compressive strength of Afari and Mfensi clays test pieces with 10% CPA or PBA and percentage variations of lime

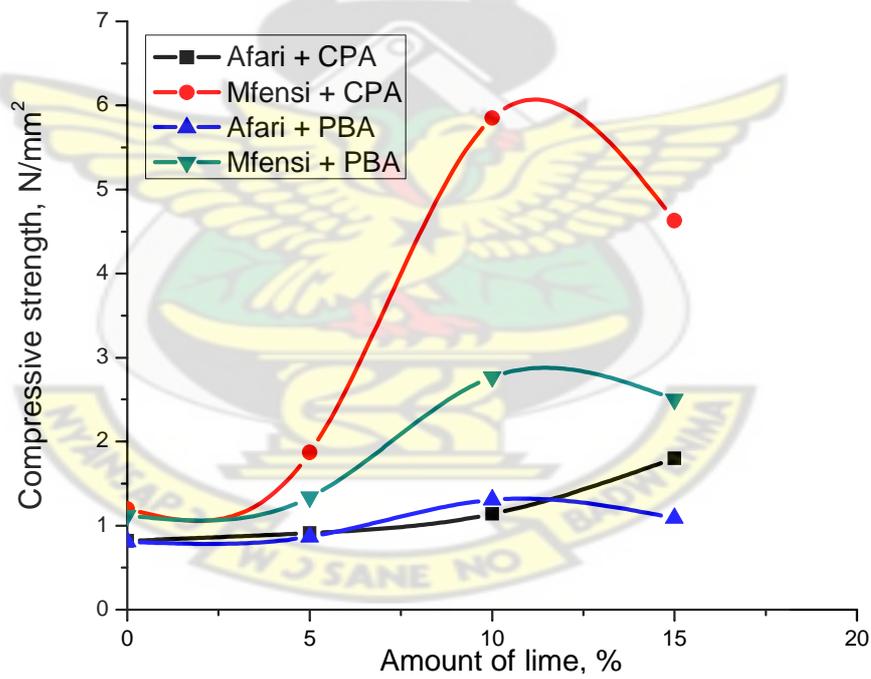


Figure 5.22 Compressive strength of Afari and Mfensi clays test pieces with 15% CPA or PBA and percentage variations of lime

The compressive strength values for the Afari clay were much less than those for the Mfensi clay and the best results were obtained at about 5% CPA or PBA additions. The compressive strength values varied between 1.34 N/mm² at 5% lime, 1.65 N/mm² at 10% lime and 1.86 N/mm² at 15% lime additions for 5% CPA usage, increasing to 2.07 N/mm² at 15% lime and 10% CPA additions. The compressive strength values were lower for PBA additions than experienced in the case of Mfensi clay.

Figure 5.17 to 5.22 also showed that the compressive strength values decreased as the amount of additives (lime, CPA and PBA) were increased beyond specific values (2.07 and 5.85 N/mm²). Additionally, the performances of the Afari clay were much lower than that of the Mfensi clay.

In critical examination and comparing of the results of compressive strength of Afari and Mfensi clay test pieces with all compositions in Tables 4.24 - 4.32, which are graphically represented in Figures 5.16 - 5.22, the following deductions could be made:

1. Generally, there was much improvement in the compressive strength of both clays when the additives (lime with CPA or PBA) were added. Thus the compressive strength of both clays increased to a maximum, after which the strength fell with further increase in the amount of additives (lime with CPA or PBA).
2. In comparison with the test pieces of both clays, Mfensi clay test pieces obtained relatively higher compressive strengths than Afari clay test pieces with lime plus variations of CPA and PBA respectively.

5.7 Wet Compressive Strength of Test Pieces after Soaking for 28 Days (Clays + Lime + CPA or PBA)

Wet compressive strength test were performed on the Afari and Mfensi clay test pieces immediately after soaking for 28 days in water. Data on the wet compressive strength of the Afari and Mfensi clay test pieces at various amount of lime and cocoa pod husk ash (CPA) additions after 28 days of soaking in water tabulated in Tables 4.33 - 4.40 and those of lime and PBA additions presented in Tables 4.41 - 4.48 have been graphically illustrated in Figures 5.24 - 5.26.

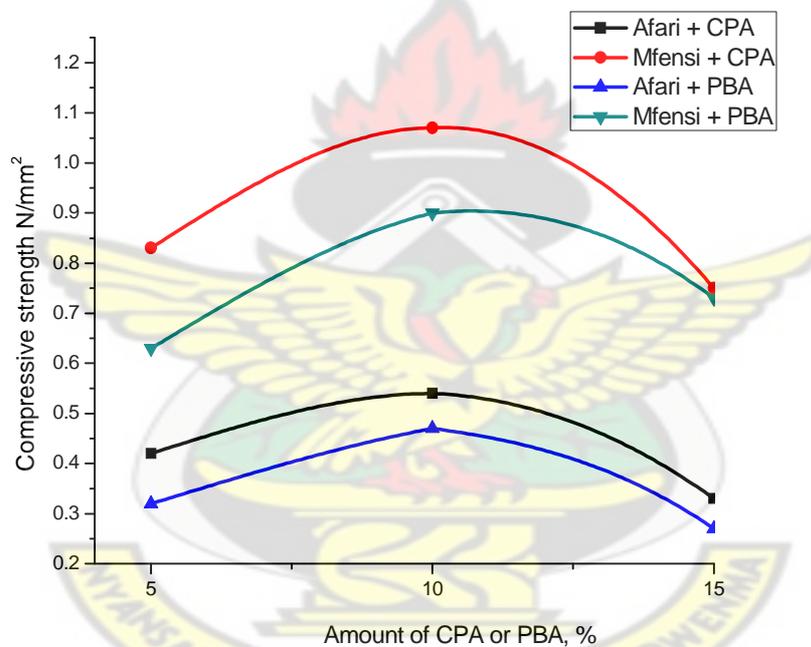


Figure 5.23 Wet compressive strength of Afari and Mfensi clay test pieces with 5% lime and variations of CPA or PBA

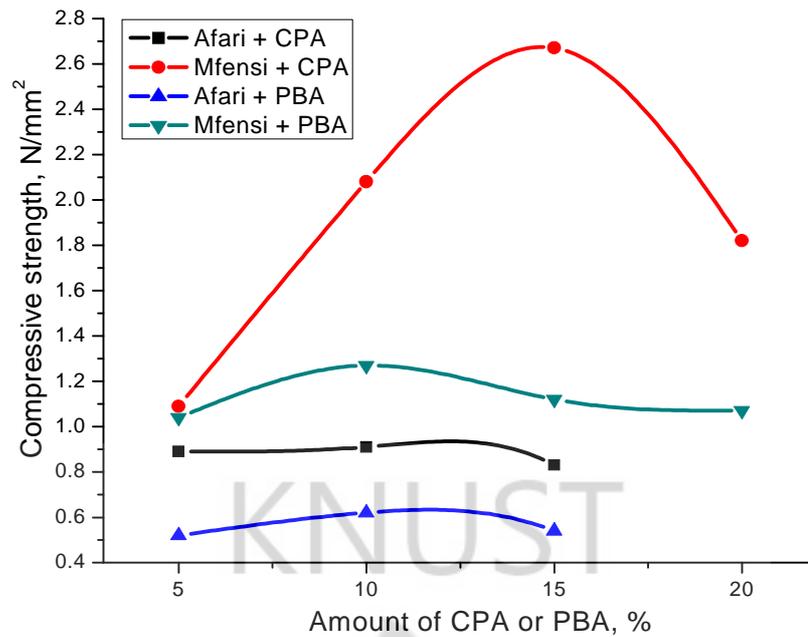


Figure 5.24 Wet compressive strength of Afari and Mfensi clay test pieces with 10% lime and variations of CPA or PBA

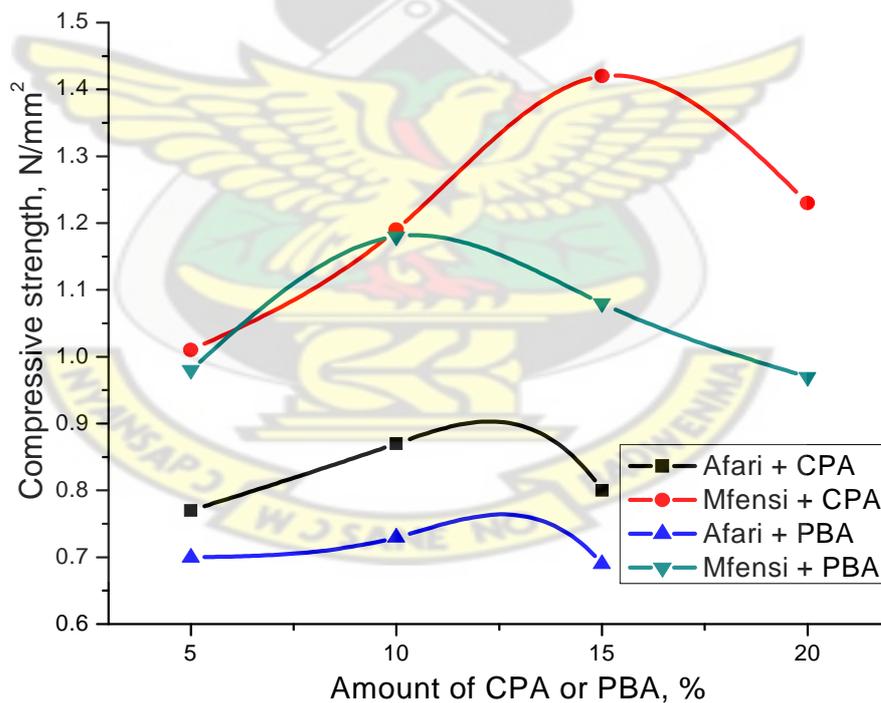


Figure 5.25 Wet compressive strength of Afari and Mfensi clays test pieces with 15% lime and percentage variations of CPA or PBA

Figure 5.24 represents results of wet compressive strength of Afari and Mfensi clay test pieces with 5% lime plus varying amounts of CPA and PBA and soaked for 28

days in water. No values were obtained for the 5% lime plus 0% additions of CPA or PBA, as the edges flaked off and test pieces disintegrated in all such cases.

In all cases, the compressive strength exhibited similar trends as was in the case of non-wetted test pieces. Additionally, the compressive strength of the wet test pieces were much lower than the corresponding non-wetted ones. The highest compressive strength value of 2.67 N/mm^2 was obtained for the Mfensi clay at 10% lime and 15% CPA additions and the lowest value of 0.27 N/mm^2 was recorded with the Afari clay at 5% lime and 15% PBA addition. The decrease in compressive strength generally varied between 53% and 63% with lime and CPA or PBA additions.

In critical observation and comparison between the results of dry compressive strength and wet compressive strength of both clays test pieces in all compositions, the following conclusions could be made:

1. Afari and Mfensi clay test pieces with no additives disintegrated in the water within the period of an hour. Afari and Mfensi clay test pieces with the ashes (CPA/PBA) as the only additives also disintegrated in about a week of soaking in water. Wet compressive strength test could not be performed on these test pieces.
2. Afari and Mfensi clay test pieces with lime as the only additive were able to maintain their shapes in water for 28 days period of soaking without disintegrating, but some damages were noticed at the edges and some surfaces of the test pieces. Thus, the edges of the test pieces were flaking off hence no wet compressive strength tests were performed on these test pieces.

3. Although there is a drastic reduction in wet compressive strength as compared to the dry compressive of all the compositions of both Afari and Mfensi clays test pieces, wet compressive strength of Mfensi clay test pieces is higher than Afari.

5.8 Water Absorption of Test Pieces (Clays + Lime + CPA or PBA)

Water absorption tests were also performed on Afari and Mfensi clays test pieces during and immediately after 28 days of soaking in water. Data on the percentage water absorption of Afari and Mfensi clay test pieces with various additions of lime and cocoa pod husk ash (CPA) during and after 28 days of soaking in water tabulated in Tables 4.33 - 4.40, and those of lime and PBA additions presented in Tables 4.41 - 4.48, have been illustrated in Figure 5.26 - 5.28.

Figure 5.26 represents results of percentage water absorption of Afari and Mfensi clay test pieces with 5% lime plus varying amounts of CPA and PBA and soaked for 28 days in water. No values were obtained for the 5% lime plus 0% additions of CPA or PBA, as the edges flaked off and test pieces disintegrated in all such cases. Similar trends also happened in Figure 5.27 and 5.28 with 10% and 15% lime plus 0% additions of CPA or PBA.

In all cases, similar trends exhibited as the water absorption decrease with an increase in CPA or PBA additions. Additionally, percentage water absorption of Afari wet test pieces were higher than the Mfensi clay test pieces. The highest water absorption value of 36.50% was obtained for the Afari wet test pieces at 5% lime and

5% PBA addition and the lowest value of 17.78% was recorded with the Mfensi clay at 15% lime and 20% CPA addition as shown in Figures 5.26 and 5.28.

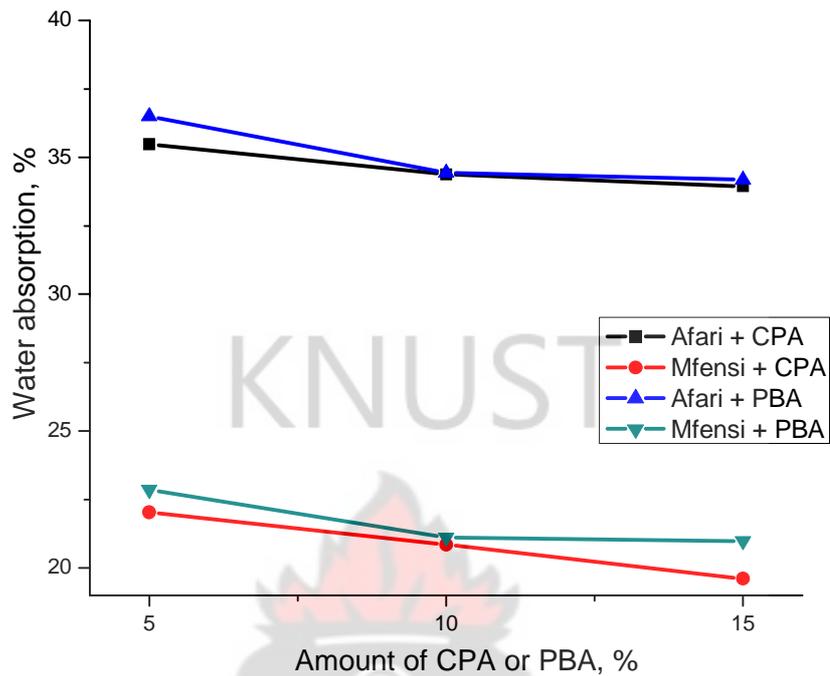


Figure 5.26 Water absorption % of Afari and Mfensi clays test pieces with 5% lime and % variations of CPA or PBA

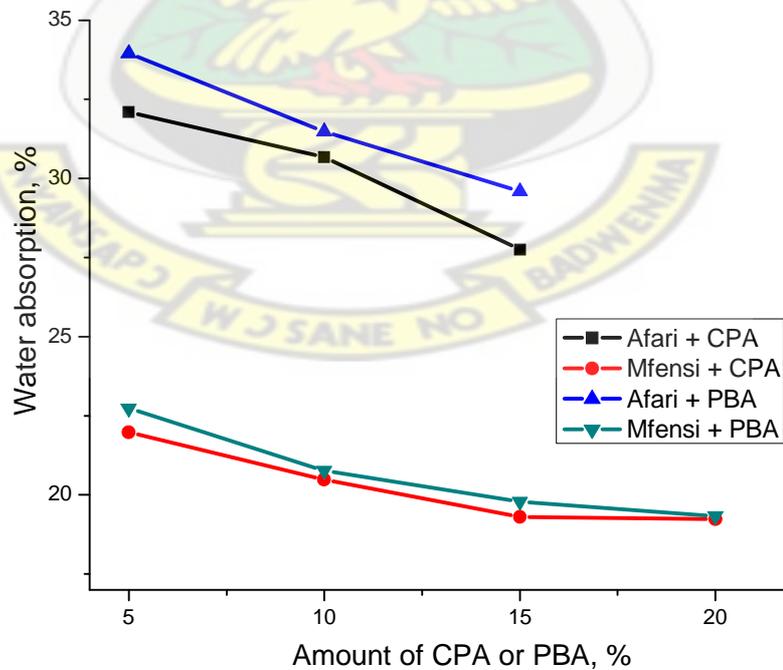


Figure 5.27 Percentages of water absorption of Afari and Mfensi clays test pieces with 10% lime and percentage variations of CPA or PBA

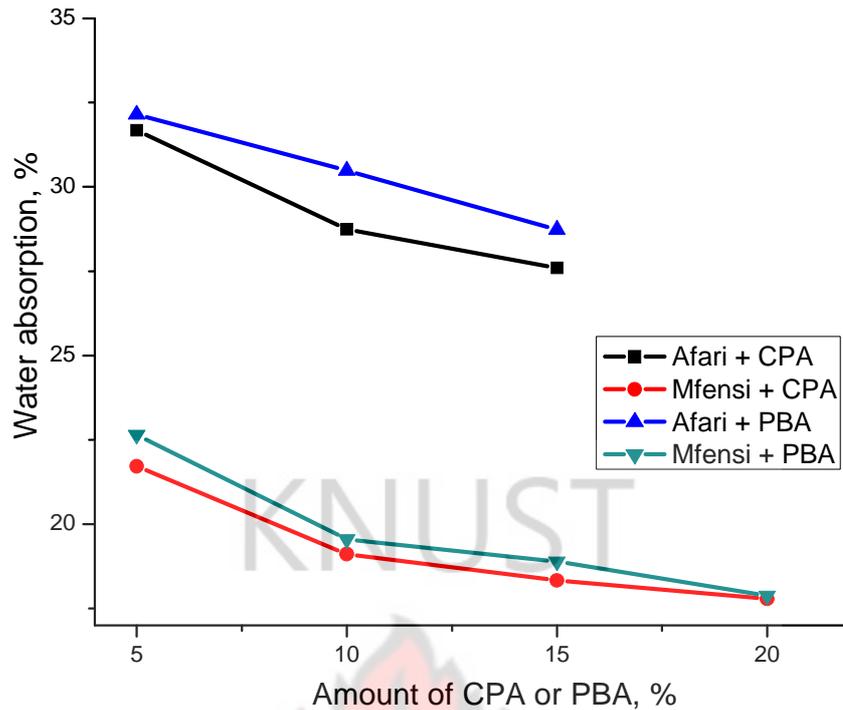


Figure 5.28 Percentages of water absorption of Afari and Mfensi clays test pieces with 15% lime and percentage variations of CPA or PBA

In summary, a comparison of the results of percentage water absorption of Afari and Mfensi clays test pieces with varying amounts of the additives (lime, CPA or PBA and lime plus CPA or PBA) in all compositions showed the following:

1. Both Afari and Mfensi clay test pieces were at or close to full saturation of soaking after seven days. Thus the weight of the test pieces after seven days of soaking were almost the same as the weight after 14 days, 21 days and 28 days respectively.
2. Afari and Mfensi clay test pieces with no additives disintegrated in the water within the period of an hour. Afari and Mfensi clay test pieces with the ashes (CPA/PBA) as the only additives also disintegrated in about a week of soaking in water. Water absorption test could not be performed on these test pieces.

3. Afari and Mfensi clay test pieces with lime as the only additive were able to maintain their shapes in water for 28 days period of soaking without disintegrating, but some damages were noticed at edges and some surfaces of the test pieces.
4. Water absorptions in both clays reduced as the amount of additives were increased. The decrease in water absorption over time was significantly low.
5. The water absorption values of treated Afari clay test pieces were higher between 27 - 36% when compared with treated Mfensi clay test pieces which were in the range of 17 - 22%. Hence Afari clay test pieces absorb more water than Mfensi clay test pieces.

5.9 Proof of Hypothesis

In proving the hypothesis, the under listed questions arose from the discussions and in answering them the subsequent sub headings were derived. These include:

1. What is responsible for strength development?
2. Why is performance of clay + lime + CPA/PBA better than clay + lime?
3. Why is performance of clay + CPA better than that of PBA?
4. Why is there a dip in performance (compressive strength) at increase in lime and CPA or PBA additions beyond specific values?

5.9.1 Strength Development in Clays, Lime and CPA or PBA Matrix

It is important to understand clay particles, lime and CPA or PBA interaction in arriving at the answer to questions one (1). During the discussion of results, it was proposed that various interactions or reactions between the additives were responsible for the development of the resultant strength properties of the test pieces.

The work of Little (1999), indicate that both cation exchange between lime additive and clay surface cations resulting in strong flocculated structure, and long-term pozzolanic reactions between hydroxyl ions released from the lime and silicate and alumina sheets of the clay contribute to the formation of calcium silicate hydrate and calcium aluminate hydrate that cement the particle together.

Hayden (1975) and McDowell (1986) have also suggested that the carbonation of lime by the diffusion of carbon dioxide from air, leading to the formation of calcium carbonate helps in cementing the particles together.

Davidson et al (1959) have suggested that the addition of sodium hydroxyl in lime stabilization activates the stabilization process when the sodium hydroxyl reacts with the siliceous material of the clay to form sodium silicate, which in turn reacts with the calcium hydroxyl to form calcium silicate and sodium hydroxyl. The calcium silicate then cements the clay particles together. This suggestion did not include the involvement of aluminous materials and sodium hydroxyl is relatively expensive chemical, which when used in large quantities will be at considerable cost. In the present study, sodium hydroxyl has been replaced by potassium hydroxyl from the CPA and PBA ashes.

Ingles work (1968, 1970, 1972) indicates that when sodium hydroxyl is used (in the absence of lime), the aluminium minerals such as kaolinite react to form sodium silicate and sodium aluminate. The sodium aluminate proceeds to precipitate insoluble aluminium oxide hydrate which gives the soil considerable durability. Gogo's work (1985) confirmed the results obtained by Ingles, but suggested that the

sodium hydroxyl be substituted with local materials for the development of durable and cheap building materials.

In bauxite processing, the reaction between aluminous and siliceous materials and sodium hydroxyl known as desilication process (Worrall, 1986) leads to the formation of sodium aluminium hydrosilicate. In a downstream process (causticisation) in the presence of calcium hydroxyl, the sodium aluminium hydrosilicate is transformed into calcium aluminium hydrosilicate.

The diffractograms of samples of selected test pieces are presented in Figs. 5.29 – 5.32.

X-ray diffraction patterns of selected samples of treated test pieces of Afari and Mfensi clays are presented in Figures 5.29 to 5.32.

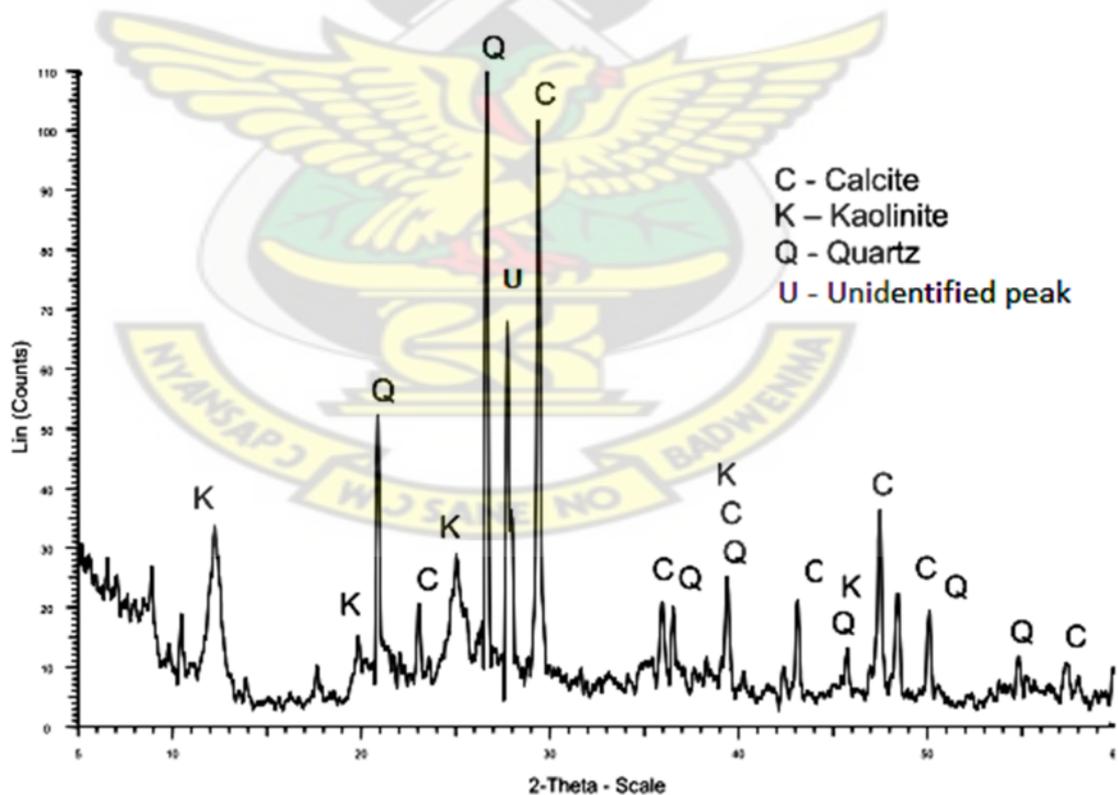


Figure 5.29 X-ray pattern diffractogram of the treated Afari clay with 15% CPA and 10% lime (A14)

Figure 5.29 is the x-ray patterns of treated Afari clay with 15% CPA and 10% lime representing the sample with the highest compressive strength of all treated Afari clay test pieces. The diffractogram indicate the presence of quartz (hexagonal lattice structure), kaolinite (triclinic and monoclinic lattice structures), calcite (rhombo hexagonal lattice structure) and an unidentified peak considered to be from the CPA.

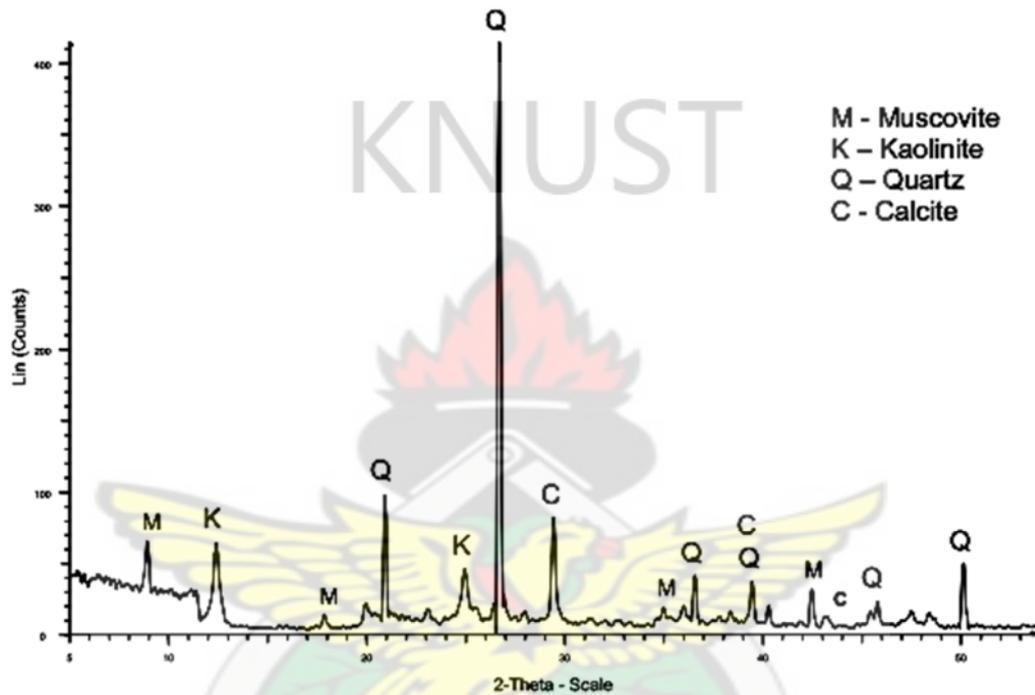


Figure 5.30 X-ray pattern diffractogram of the treated Mfensi clay with 10% lime and CPA 10% (M10)

Figure 5.30 shows the diffractogram of the treated Mfensi clay with 10% CPA and 10% lime (M10). The phases identified include quartz (hexagonal lattice structure) kaolinite (monoclinic lattice structure) muscovite (monoclinic lattice structure) and calcite (rhombo hexagonal lattice structure).

Figure 5.31 is the x-ray patterns of treated Mfensi clay with 10% CPA and 15% lime (M11). The phases observed are quartz, kaolinite, muscovite and calcite.

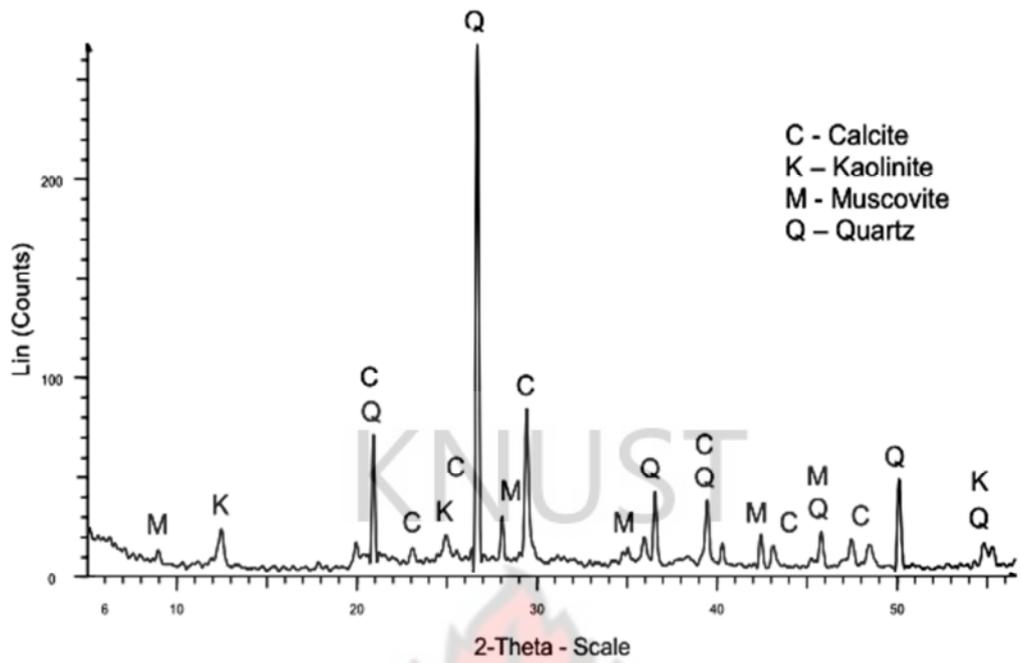


Figure 5.31 X-ray pattern diffractogram of the treated Mfensi clay with 10% lime and 15% CPA (M11)

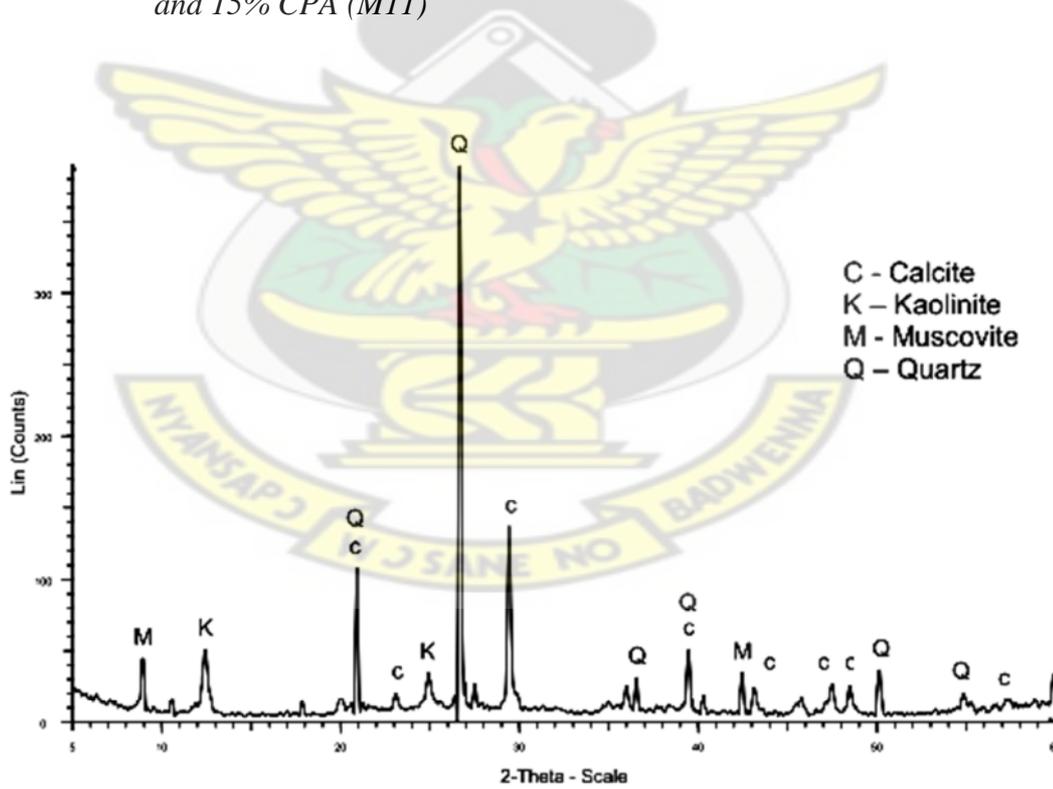


Figure 5.32 X-ray pattern diffractogram of the treated Mfensi clay with 10% lime and 20% CPA (M16)

Figure 5.32 shows XRD pattern of the treated Mfensi clay with 10% CPA and 20% lime (M16). The diffractogram indicates the presence of quartz, kaolinite, muscovite and calcite. The dominant peaks are those of quartz (hexagonal lattice structure) and calcite (rhombo hexagonal lattice structure). Muscovite (monoclinic lattice structure) and kaolinite (monoclinic lattice structure) were also identified.

From the above observations, the development of strength and durability is therefore due to the following:

- (i) The addition of lime, results in interactions between the lime and clay particles as suggested by Little (1999). Figs 5.29 – 5.32 all show the presence of calcite as a cementitious material as suggested by Hayden (1975), McDowell (1986) and Davidson et al (1959). Similar observations were reported by Chaunsali and Peethamparan (2010). Also present are residual quartz and kaolinite.
- (ii) By adding CPA or PBA, the components especially potassium hydroxyl took part in reactions with components of the clay and with the surface of the clay particles producing cementitious materials to cement the clay particles together.

Montmorillonite and albite phases in the raw Afari clay disappeared in the treated Afari clay with additives of lime and CPA confirming a reaction between the clay components and the additives.

In general, there was a reduction in the peak intensity of the kaolinite and muscovite peaks in the treated Afari and Mfensi clays, as can be seen by the peak heights of the peaks in the treated Afari and Mfensi clays. This is

particularly so for the test piece of 75% Mfensi clay plus 10% lime and 15% CPA additions as compared to the raw Afari and Mfensi clays. This could be attributed to reactions between the additives and the phases. A similar behaviour was reported by Al-Rawas (2002) and Solanki and Zaman (2012).

A comparison of the peak heights of selected phase (PH_p) to that of quartz at $2\theta = \dots$ (PH_q) is presented in Table 5.2 where:

$$PHR = \frac{PH_p}{PH_q} \quad (5.12)$$

and PHR is the ratio of PH_p to PH_q

Table 5.2: The relative peak heights of XRD patterns in Figures 5.4, 5.5, 5.29 to 5.32

Identified phase/test piece	Peak Height Ratio (PHR)					
	A0	M0	A14	M10	M11	M16
Kaolinite at $2\theta = 12.5$	0.132	0.222	0.318	0.171	0.093	0.128
Calcite at $2\theta = 29.5$	N/A	N/A	0.909	0.195	0.333	0.359
Muscovite at $2\theta = 9$	N/A	0.333	N/A	0.171	0.111	0.115

In comparing the peak heights (PHR) of the treated Mfensi clays (M10, M11 and M16), the data shows that the M11 test piece had the lowest value of PHR, indicating that the relative amount of kaolinite in the test piece had reduced considerably. The compressive strength of this test piece was highest (Fig. 5.18) This could also be attributed to reaction between the additives and the phases as stated above.

5.9.2 A comparison of the performances of Clay + Lime + CPA/PBA and Clay + Lime

The difference in the performance of the clay + lime + CPA/ PBA to clay + lime may be due to the following:

1. This may be due to the reactivity of the components as K_2O in the CPA/PBA is more reactive as compare to CaO .
2. As reported by AustStab Technical Note (2002), lime will react effectively with any pozzolanas (materials containing reactive silica and alumina) that are present in the clay in an alkaline environment ($pH > 7$). With the presence of CPA or PBA resulting in a more alkaline environment will help the lime to perform more effectively in the cementitious reaction by producing calcium silicate hydrates (CSH) and calcium aluminate hydrate (CAH). Similar report was reported by Little (1999).

5.9.3 Comparison of performance of Clay + CPA and Clay + PBA

The marginal difference in the performance of the clay + CPA/ PBA may be due to the difference in their chemical compositions as summarised in Table 5.3.

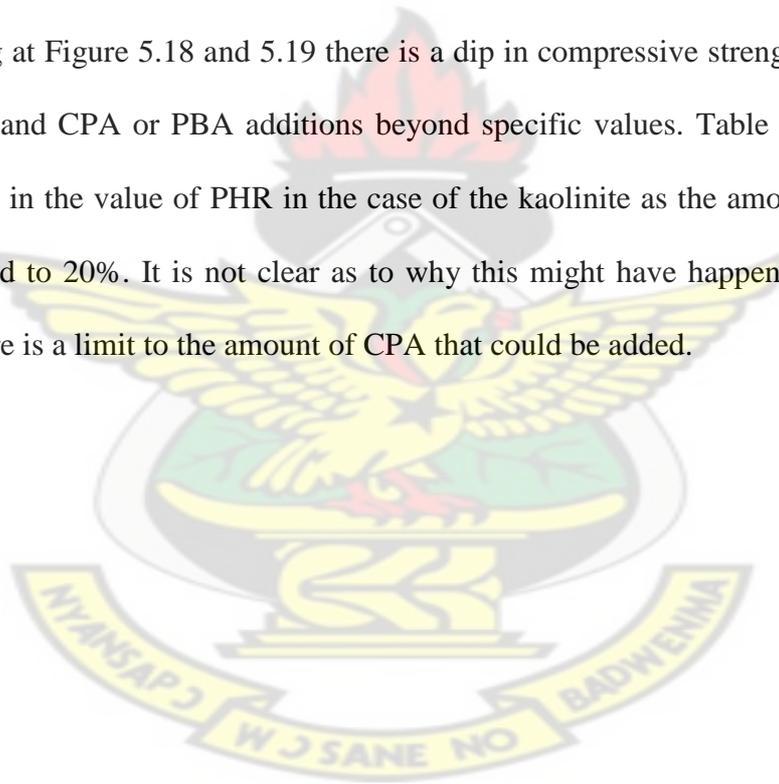
Table 5.3 The major difference in CPA and PBA

Element	Composition, %	
	CPA	PBA
SiO_2	8.05	22.43
Al_2O_3	2.28	1.54
K_2O	37.39	36.39
CaO	8.43	5.21
MgO	5.16	7.83
Na_2O	0.44	2.23
LOI %	32.00	16.50

A major difference is in the amount of silica in both ashes. It is possible that much of the silica of the PBA is un-reactive or bound to other components of the ash and therefore do not take part in the cementitious reactions. It is also possible that much of the potassium in the PBA is bound to other components as well as loss on ignition (LOI) is only 16.50%, about half of that of CPA and therefore not available for the cementitious reactions.

5.9.4 Dip in the Compressive Strength at increase in lime and CPA or PBA additions beyond specific values

Looking at Figure 5.18 and 5.19 there is a dip in compressive strength with increase in lime and CPA or PBA additions beyond specific values. Table 5.2 indicated an increase in the value of PHR in the case of the kaolinite as the amount of CPA was increased to 20%. It is not clear as to why this might have happened, but it shows that there is a limit to the amount of CPA that could be added.



5.11 Observations on the Durability of Test Pieces

Some of the test pieces of both clays were kept in the open for two years to observe the impact of the open environment on the test pieces. Figures 5.33 – 5.45 are the pictorial presentation of some of these test pieces exposed to the weather for qualitative analysis (durability test).



Figure 5.33 *Test pieces made with Afari clay and CPA after 2 or 3 rainfalls*



Figure 5.34 *Test pieces made with Mfensi clay and CPA after 2 or 3 rainfalls*

Figures 5.33 and 5.34 presents the Afari and Mfensi clays test pieces with CPA as the only additive which were kept in the open for natural weathering. The test pieces disintegrated after two to three times of rainfall.



Figure 5.35 Test pieces made with Afari clay and 10% and 15% lime exposed to the weather for two years

Afari clay test pieces with 10% and 15% lime as the only additive (Figure 5.35) which were kept in the open for natural weathering were able to maintain their shapes to the weather and did not disintegrate after a number of rainfalls. The surfaces and the edges however, seemed to be flaking off.



Figure 5.36 Test pieces made with Afari clay with 10% lime plus 5%, 10% and 15% CPA exposed to the weather for two years

Afari clay test pieces with additives of 10% lime plus 5%, 10% and 15% CPA respectively kept in the open for natural weathering are presented in Figure 5.36 also maintained their shape in the weather after two years period in the open. There was only slight change in colour.



Figure 5.37 Test pieces made with Afari clay with 15% lime plus 5%, 10% and 15% CPA exposed to the weather for two years

Also, Afari clay test pieces with additives of 15% lime plus 5%, 10% and 15% CPA respectively (Figure 5.37) kept in the open for natural weathering for two years maintained their shape in the weather without any corrosion or erosion.



Figure 5.38 Test pieces made with Afari clay with 15% lime plus 5%, 10% and 15% PBA exposed to the weather for two years

Afari clay test pieces with additives of 15% lime plus 5%, 10% and 15% PBA respectively (Figure 5.38) were only slightly damaged at the edges.

Similar observations were made of test pieces made with Mfensi clays (Figures 5.39 – 5.45).



Figure 5.39 Test pieces made with Mfensi clay plus only 5%, 10% and 15% lime exposed to the weather for two years. (Test piece with 15% lime addition flaked off at the edges)



Figure 5.40 Test pieces made with Mfensi clay with 5% lime plus 5% and 10% CPA after two years exposure to the weather for two years. (Maintained shape)



Figure 5.41 Test pieces made with Mfensi clay with 10% lime plus 5%, 10% and 15% CPA after two years exposure for two years. (Maintained shape)



Figure 5.42 Test pieces made with Mfensi clay with 15% lime plus 5% and 10% CPA after two years exposure for two years. (Maintained shape)



Figure 5.43 Test pieces made with Mfensi clay with 5% lime plus 5%, 10% and 15% PBA after two years exposure for two years. (Maintained shape)



Figure 5.44 Test pieces made with Mfensi clay with 10% lime plus 5%, 10% and 15% PBA after two years exposure for two years. (Maintained shape)



Figure 5.45 Test pieces made with Mfensi clay with 15% lime plus 5%, 10% and 15% PBA after two years exposure for two years. (Maintained shape)

Generally, Afari and Mfensi clays test pieces treated with lime and CPA or PBA appeared to be of good quality and were able to maintain their shape during the period of being in the weather without distortions. There was only slight change in colour. The surfaces were free from cracks. It can be concluded that Mfensi clay responded well when treated with lime and CPA.

5.12 Economic Benefits

Economically, the following are the benefits in the production of the stabilized clay bricks:

1. Clay is readily available to the rural communities.
2. Less fuel is needed; since the cocoa pod husks and oil palm empty bunches are themselves biofuel.
3. Cocoa pod husks and Palm empty bunches are readily available especially in the rural communities mostly thrown away as waste products.

4. The processes of producing these clay bricks is simple, therefore production cost will be reduced.

A comparison of the stabilized bricks, burnt bricks and sandcrete blocks is presented in Table 5.4.

Table 5.4 A comparison of stabilized bricks with burnt bricks and sandcrete blocks

	Stabilized bricks	Burnt bricks	Sandcrete blocks
Material used, availability and cost	Cocoa pod husks and Palm empty bunches are readily available especially in the rural communities mostly thrown away as waste products at no cost.	Clays are available but the fuel (wood) for clamp firing is not readily available and expensive.	Materials used in cement production are imported which due to high energy needed to produce the clinker.
Fuel	Less fuel is needed, cocoa pod and palm bunches are themselves biofuel.	Fuel is needed	High energy need to produce the clinker
Environmental benefits	Atmospheric pollution is minimal.	Energy waste coupled with atmospheric pollution during firing	Clinker production has impact on environment, dusting during cement manufacture.

CHAPTER SIX

SUMMARY, CONCLUSIONS AND RECOMMENDATION

6.1 Summary

The purpose of this study was to identify and investigate the use of local substitutes that can be used to produce chemically stabilized clay that would be more durable than unstabilized clay for rural housing. Mfensi and Afari clays both found in the Atwima Nwabiagya District in the Ashanti Region of Ghana were used. The local materials investigated included cocoa pod husk ash, oil palm empty bunch ash and lime used in different proportions in order to obtain a product that can be used as a preferably stable construction material. The scope of the study includes relevant literature that has direct or indirect bearing on the effective realization and achievement of the objectives.

The first objective of the research was to obtain and characterize Afari and Mfensi clays using geotechnical methods (particle size distribution, Atterberg limits test – liquid limit, plastic limit and plasticity index, linear and volumetric drying shrinkages), and chemical and mineralogical analyses by x-ray fluorescence and x-ray diffraction methods respectively. The results revealed that these two clays exhibited properties such as sufficient plasticity for satisfactory shaping, do not shrink excessively on drying and contain kaolinite and quartz as the main phases which may influence the development of relevant matrix for stabilization.

The second objective was to investigate the possible use of cocoa pod husk ash, oil palm empty bunch ash and lime as local stabilizers. This was achieved by first performing chemical and mineralogical analyses on the ashes (CPA and PBA). From

the results of the chemical composition of the ashes (CPA and PBA) in Table 4.14, it was observed that both ashes have relatively high amount of potassium oxide (K_2O) (cocoa pod husk ash - 37.39% and oil palm empty bunch ash - 36.39%) which were the main components in the ashes. These are the expected alkali in both ashes as chemical stabilizers to react with the clays to form a cementitious matrix. There is also an appreciable amount of calcium oxide (CaO) in cocoa pod husk ash (8.43%) and oil palm empty bunch ash (5.21%). The PBA contains high concentration of silica (22.43%), which may produce a different characteristic in the matrix, than CPA.

The last but not the least objective of the study was to determine the stabilization response of the stabilized clay in terms of strength, stability under moist environment, durability on exposure to various weather conditions. This was achieved by conducting tests including percentage linear and volumetric drying shrinkages, dry and wet compressive strength and water absorption on the treated test pieces.

6.2 Conclusions

From the observations, critical examinations, and analyses and comparing of the results obtained during the investigation the following conclusions have been drawn:

1. That there are locally available and affordable substances such as lime, cocoa pod and oil palm empty bunch ashes can be used to stabilize clays to improve structural properties such as the compressive strength, shrinkage and water absorption. The performance of the clays to these additives would differ depending on their composition.

2. Dry compressive strength and wet compressive strength of both clays when treated with the chemical stabilizers could be improved. The dry compressive strength of Mfensi clay increased from 0.91N/mm^2 at zero additive application to 5.85N/mm^2 , whilst the wet compressive strength varied from 0 to 2.67N/mm^2 when soaked in water for 28 days. Those of Afari clay could be improved from 0.80N/mm^2 when no additives were applied to 2.07N/mm^2 and from 0N/mm^2 to 0.91N/mm^2 when soaked in water for 28 days.
3. Improvements could be obtained in the linear and volumetric drying shrinkages or water absorption of the Mfensi clay with lime with CPA additives which could be significant for the durability of the stabilized clay. The linear and volumetric drying shrinkages reduced from 7.4% and 21.89% to 4.2% and 12.27% for Mfensi clay and from 9.4% and 27.42% to 6.0% and 17.5% for Afari clay respectively. Water absorption also reduced to 17.78% and 27.59% for Mfensi and Afari clay respectively.
4. In comparing the two clays for their stabilization responses to the chemical additives (lime, cocoa pod husk ash and oil palm empty bunch ash), Mfensi clay responded better than Afari clay in terms of compressive strength, linear and volumetric drying shrinkages, water absorption and durability test.
5. Among the three additives tested (lime, cocoa pod husk ash, oil palm empty bunch ash, lime plus cocoa pod husk ash and lime plus oil palm empty bunch ash), lime plus cocoa pod husk ash showed an encouraging results in terms of compressive strength, linear and volumetric drying shrinkages, water absorption and durability test.

6.3 Recommendation

From the viewpoint of compressive strength, linear and volumetric drying shrinkages, water absorption and durability test, addition of 10% lime and 10–15% cocoa pod husk ash is recommended as an optimum amount of chemical additives for mass production.

6.4 Agendum for Further Research

In view of the results found in the study and with respect to future research on chemical treatment of clays, the following can be considered for further research in the clay stabilization:

1. Further research could be conducted on the effect of heat on the cementitious actions and strength of the test pieces at low temperature (300°C - 600°C).
2. To have good compaction, further improvement in strength and ensure easy de-moulding of bricks, the use of a mechanical press for moulding of test pieces should be considered.
3. Further research could be conducted to investigate the use of other waste such as plantain peel ash and saw dust ash as chemical additives for clay stabilization since both additives may contain high amount of potash (Onyegbado, Iyagba, and Ofor, (2002).

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APPENDIX

The following publications were derived from the project:

1. Amoanyi R., Kwawukume P. S., Momade F. Y. (2012) Improving the strength properties of Afari and Mfensi clays by chemical stabilization. *International Journal of Engineering Research in Africa (JERA)* Vol. 8 pp 1-15.
2. Physical Characterization of Mfensi and Afari clay deposits in determining their suitability for clay stabilization *Journal of Science and Technology, KNUST Kumasi.* (JUST) Accepted for Review, 2011

