KWAME NKRUMAH UNIVERSITY OF SCIENCE AND TECHNOLOGY

KUMASI, GHANA.

Durability of Locally-Produced Burnt Clay Bricks



A thesis submitted to

The Department of Materials Engineering,

Kwame Nkrumah University of Science and Technology

In Partial Fulfilment of the Requirements for the Degree of

Master of Science in Environmental Resources Management

Department of Materials Engineering

October, 2014

DECLARATION

"I hereby declare that this submission is my own work towards the MSc. 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".

Signature	Date
Adjei Hose Delali	NNUSI
(Student)	
Signature	. Date
Dr. Anthony Andrews	
(Supervisor)	
Signature	Date
Prof. Samuel Kwofie	
(Head of Department)	

DEDICATION

This work is dedicated to my lovely husband, Dr Timothy Kwabena Adjei, and my two beautiful Angels, Jehnissi Ayeyi Adjei and Yehoda Nyamekye Adjei. I sincerely appreciate your love and support. God bless you!



ACKNOWLEDGEMENT

I say a big thank you to the God of all the earth for granting me grace, for if it had not been the Lord on my side I will not have made it thus far. I am forever grateful to Him.

I wish to acknowledge the priceless guidance, advice and constructive contribution of my supervisor, Dr Anthony Andrews, without whom this work will not have been completed.

To my wonderful mum, Mrs Vivian Bansah, I wish to say mummy God bless you. Had it not been for your prayers and great help I will not have made it. To my one and only lovely sister, Mrs. Edem Korkor Appiah Dwomoh, I say thanks for urging me on to make it. To all my wonderful family and friends especially Rev. and Pastor Mrs. Reginald and Rita Adanuvo for being there as great pillars and mentors to me.

God bless you Director (BRRI), Ing. Dr. Eugene Atiemo, for giving me opportunity to come this far I truly respect and honour you. To Dr. Mrs. Ama Tagbor, Dr J.K. Boadi, Dr Akayuli and Mr Obeng I say a big thank you for your wonderful guidance. My sincere gratitude also goes to all my colleagues at BRRI especially Mr James Sarfo Ansah and Mr Kelly Boakye.

Lastly, I like to acknowledge the support received from the

- Danny, Mr Nelson, Mr Samuel Nketia, Mr Sampson and Mr Ampofo all of (BRRI)
- Mr Atti and Mr. Sam Anaman of Materials Engineering Department (KNUST)
- Mr Kwabena Antwi of Civil Engineering Department (KNUST)

ABSTRACT

Sustainable economic growth for every country and Ghana for that matter is dependent on infrastructural development, public development projects and the provision of affordable houses for the average populace. Ghana faces a huge housing deficit with its attendant environmental and health problems. Construction is costly due to importation of clinker for cement production. The use of locally-produced burnt clay bricks is an alternative. However, locally-produced burnt clay bricks are perceived not to be durable and of varying properties. Hence, the study investigated the durability of locally-produced burnt clay bricks. Properties of laboratory-produced burnt bricks from Mfensi, Mankranso and Nyamebekyre clays were compared with burnt bricks available on the market but produced from the same clay source. Burnt bricks produced in the laboratory were fired at 800, 900 and 1050°C to investigate the effect of firing temperature on brick durability. Burnt bricks were subjected to salt attack tests and durability assessed by measuring degradation in some physical and mechanical properties. Salt environments considered included sea water, 0.5 M NaCl and 0.5 M Na₂SO₄. The results show that burnt bricks fired at high temperatures are more durable and have better chances of survival in aggressive environments than bricks fired at low temperatures. Mfensi bricks fired at 1050°C had higher cold crushing strength in seawater and Na₂SO₄ but not in NaCl. Likewise Mankranso and Nyamebekyre bricks fired at 1050°C also performed very well in seawater and NaCl reducing in strength when exposed to Na_2SO_4 . The differences in durability in the environments studied are due to variation in the chemical composition of the clays which resulted in different properties of burnt bricks. Careful control of clay composition and firing temperature can produce durable burnt clay bricks with high durability, that remain unaltered in the process of their service life even in aggressive environments.

TABLE OF CONTENT

DECLARATION II
DEDICATIONIII
ACKNOWLEDGEMENTIV
ABSTRACTV
TABLE OF CONTENTVI
LIST OF FIGURESX
LIST OF TABLES
CHAPTER ONE
INTRODUCTION
1.1 BACKGROUND
1.2 Problem Statement
1.3 AIM AND OBJECTIVES4
1.4 Scope of Work
CHAPTER TWO
LITERATURE REVIEW
2.1 Introduction
2.2 CLAYS
2.3 BURNT CLAY BRICKS
2.3.1 Manufacture of burnt clay bricks6
2.4 DURABILITY AND SERVICEABILITY8

2.5 SALT ATTACK9
2.5.1 Mechanism of salt attack of burnt clay bricks11
2.6 FACTORS AFFECTING THE SALT ATTACK IN MASONRY MATERIALS15
2.6.1 Influence of raw material composition15
2.6.2 Influence of soluble salt17
2.6.3 Influence of microstructure20
2.6.4 Influence of moisture21
2.7 PROPERTIES OF BURNT CLAY BRICKS
2.7.1 Physical properties23
2.7.2 Mechanical properties25
CHAPTER THREE
METHODOLOGY
3.1 INTRODUCTION
3.2 MATERIALS AND MATERIAL PREPARATION
3.3 CHARACTERIZATION OF CLAY SAMPLES
3.3.1 Mineralogical composition
3.3.2 Chemical analysis
3.3.3 Particle size distribution
3.3.4 Specific gravity
3.3.5 Determination of Atterberg limits
3.4 Moulding, Drying and Firing
3.5 CHARACTERISATION OF FIRED BRICKS
3.5.1 Determination of linear firing shrinkage31
3.5.2 Determination of water absorption
3.5.3 Determination of apparent porosity

3.5.4 Determination of bulk density32
3.5.5 Determination of cold crushing strength
3.6 Salt Attack Test
3.7 Efflorescence Test
CHAPTER FOUR
RESULTS AND DISCUSSION
4.1 INTRODUCTION
4.2 CHEMICAL AND MINERALOGICAL COMPOSITIONS
4.3 ATTERBERG LIMITS, PARTICLE SIZE DISTRIBUTION AND SPECIFIC GRAVITY
4.4 PROPERTIES OF BURNT CLAY BRICK
4.4.1 Effect of firing temperature on bulk density41
4.4.2 Effect of firing temperature on apparent porosity
4.4.3 Effect of firing temperature on water absorption
4.4.4 Effect of firing temperature on cold crushing strength
4.5 DURABILITY OF BURNT CLAY BRICKS
4.5.1 Effect of chloride environment on apparent porosity and water absorption50
4.5.2 Effect of chloride environment on cold crushing strength
4.5.3 Effect of sulphate environment on apparent porosity and water absorption62
4.5.4 Effect of sulphate environment on cold crushing strength
4.6 Comparism of Durability of Burnt Clay Bricks in Chloride and Sulphate
ENVIRONMENTS
4.7 VISUAL INSPECTION
CHAPTER FIVE
CONCLUSION AND RECOMMENDATIONS

5.1 CONCLUSION	73
5.2 Recommendation	74
REFERENCES	75
APPENDIX A	88
PROPERTIES OF CLAY MATERIALS	88
APPENDIX B	89
PROPERTIES OF BURNT CLAY BRICKS	



LIST OF FIGURES

FIGURE 3.1: FLOW DIAGRAM SHOWING THE PROCESSES INVOLVED IN ASSESSING THE
DURABILITY OF LOCALLY-PRODUCED BURNT CLAY BRICKS
FIGURE 4.1: X-RAY DIFFRACTION ANALYSES OF CLAY SAMPLES SHOWING MAJOR
MINERALOGICAL PHASES (A) MFENSI (B) MANKRANSO AND (C) NYAMEBEKYRE
FIGURE 4.2: PARTICLE SIZE DISTRIBUTION OF CLAY SAMPLES
FIGURE 4.3: EFFECT OF FIRING TEMPERATURE ON THE BULK DENSITY OF BURNT BRICKS
PRODUCED FROM DIFFERENT CLAY MATERIALS
FIGURE 4.4: BULK DENSITY OF COMMERCIAL BURNT BRICKS PRODUCED FROM DIFFERENT CLAY
MATERIALS
FIGURE 4.5: EFFECT OF FIRING TEMPERATURE ON THE APPARENT POROSITY OF BURNT BRICKS
PRODUCED FROM DIFFERENT CLAY MATERIALS
FIGURE 4.6: APPARENT POROSITY OF COMMERCIAL BURNT BRICKS PRODUCED FROM DIFFERENT
CLAY MATERIALS
FIGURE 4.7. FEEECT OF EIDING TEMPEDATURE ON WATER ARSORDTION OF PURNT RRICKS
FIGURE 4.7. EFFECT OF FIRING TEMPERATURE ON WATER ABSORPTION OF BURNT BRICKS
PRODUCED FROM DIFFERENT CLAY MATERIALS
 FIGURE 4.7. EFFECT OF FIRING TEMPERATURE ON WATER ABSORPTION OF BURNT BRICKS PRODUCED FROM DIFFERENT CLAY MATERIALS

FIGURE 4.12: EFFECT OF EXPOSURE TIME ON THE WATER ABSORPTION OF BURNT BRICKS
PRODUCED FROM DIFFERENT CLAY MATERIALS IN SEAWATER
FIGURE 4.13: EFFECT OF EXPOSURE TIME ON THE APPARENT POROSITY OF BURNT BRICKS
PRODUCED FROM DIFFERENT CLAY MATERIALS IN 0.5 M NACL
FIGURE 4.14: EFFECT OF EXPOSURE TIME ON THE WATER ABSORPTION OF BURNT BRICKS
PRODUCED FROM DIFFERENT CLAY MATERIALS IN 0.5 M NACL
FIGURE 4.15: EFFECT OF EXPOSURE TIME ON THE COLD CRUSHING STRENGTH OF BURNT BRICKS
PRODUCED FROM DIFFERENT CLAY MATERIALS IN SEAWATER
FIGURE 4.16: EFFECT OF EXPOSURE TIME ON THE COLD CRUSHING STRENGTH OF BURNT BRICKS
PRODUCED FROM DIFFERENT CLAY MATERIALS IN 0.5 M NACL61
FIGURE 4.17: EFFECT OF EXPOSURE TIME ON THE APPARENT POROSITY OF BURNT BRICKS
PRODUCED FROM DIFFERENT CLAY MATERIALS IN $0.5 \text{ M} \text{ Na}_2 \text{SO}_4$
FIGURE 4.18: EFFECT OF EXPOSURE TIME ON THE WATER ABSORPTION OF BURNT BRICKS
PRODUCED FROM DIFFERENT CLAY MATERIALS IN 0.5 M NA ₂ SO ₄ 65
FIGURE 4.19: EFFECT OF EXPOSURE TIME ON THE COLD CRUSHING STRENGTH OF BURNT BRICKS
PRODUCED FROM DIFFERENT CLAY MATERIALS IN $0.5 \text{ M Na}_2 \text{SO}_4$
FIGURE 4.20: CHANGE IN STRENGTH OF BURNT BRICKS FIRED AT DIFFERENT TEMPERATURES
after 90 days <mark>exposure</mark> in aggressive environments. Negative values signify
INCREASE IN STRENGTH
Figure 4.21: Change in strength of burnt bricks produced at 1050° C after 90 days
EXPOSURE IN AGGRESSIVE ENVIRONMENTS. NEGATIVE VALUES SIGNIFY INCREASE IN
STRENGTH70
FIGURE 4.22: IMAGES OF BURNT BRICKS BEFORE (A) AND AFTER (B) EXPOSURE TO SEAWATER
SHOWING EFFLORESCENCE

LIST OF TABLES

TABLE 2.1: SALTS FOUND AS EFFLORESCENCE IN FCB SOURCE (SPRY, 1990) 13
TABLE 2.2: SALT CLASSES ACCORDING TO DAMAGING CAPACITY (SPRY, 1990) 19
TABLE 2.3: CLASSIFICATION OF SOLUBLE SALTS CONTENT (BS EN 771-1) 20
TABLE 2.4: WEIGHT LOSS AND POROSITY AFTER CRYSTALLIZATION TEST (NAVARRO AND
Doehne, 1999)23
TABLE 4.1: CHEMICAL COMPOSITION OF BURNT CLAY BRICKS SAMPLES (MK=MANKRANSO;
MF=Mfensi; NB=Nyamebekyre)
TABLE 4.2: ATTERBERG LIMITS OF MANKRANSO, MFENSI AND NYAMEBEKYRE CLAYS
TABLE 4.3: ANALYSES OF PARTICLE SIZE DISTRIBUTION
TABLE 4.4: EFFLORESCENCE CLASSIFICATION OF BURNT BRICKS AFTER 90 DAYS EXPOSURE IN
NACL, NA ₂ SO ₄ AND SEAWATER
TABLE A1: SPECIFIC GRAVITY, ATTERBERG LIMIT, (%) PARTICLE SIZE ANALYSIS (%) RESULTS OF CLAY SAMPLES INVESTIGATED
TABLE B1: PROPERTIES OF BURNT BRICKS PRODUCED IN THE LABORATORY 89
TABLE B2: PROPERTIES OF BURNT BRICKS AFTER 90 DAYS EXPOSURE IN SEAWATER
TABLE B3: PROPERTIES OF BURNT BRICKS AFTER 90 DAYS EXPOSURE IN 0.5 NACL 91
TABLE B4: PROPERTIES OF BURNT BRICKS AFTER 90 DAYS EXPOSURE IN $0.5 \text{ M Na}_2 \text{SO}_4$ 92

CHAPTER ONE

INTRODUCTION

1.1 Background

Worldwide, the use of cement for infrastructural development is key to the growth of many economies (Mehta and Monteiro, 2006). However, cement production is the second largest source of CO_2 generated worldwide. It contributes about 5-8% of global total CO_2 emissions, mainly from the use of fossil fuel for calcination (Scrivener and Kirk, 2007). One ton of cement production is responsible for one ton of CO_2 emission: half of the CO_2 is from the chemical process of clinker production and the rest due to the calcinations of limestone (Taylor *et al.*, 2006).

In Ghana the use of cement in the construction industry is much extensive and more widespread. It is estimated that Ghana spends over US\$150 million per annum to import clinker, the main semi-finished raw material for cement manufacture (Ministry of Trade and Industry, 2010). This has increased the unit cost of a bag of Portland cement hence making construction in Ghana expensive. This has created a huge housing deficit of over 1,500,000 units per annum with its attendant environmental and health problems (Ministry of Works and Housing, 2005). To help reduce the housing deficit, the Building and Road Research Institute (BRRI) of the Council for Scientific and Industrial Research (CSIR) in Ghana has been conducting research into the development and promotion of locally-developed building materials. One of such materials is burnt clay bricks (Ayetey, 1977; Kesse, 1985).

To this end, extensive studies into the establishment of brick and tile factories and the training of artisans on brick production and construction were carried out (Amonoo Neizer, 1973; Ayetey, 1977; Kirkendale, 1975; Obeng, 1993). CSIR-BRRI has also over the years

pioneered the promotion and use of burnt clay bricks for construction of several structures. These include the fence walls of the Aboadze Thermal Plant at Aboadze near Takoradi, T. I Ahmadiyya and Kumasi Senior High schools, Kumasi Airport fence wall, Silicon Hotel at Kumasi and BRRI Guest House just to mention a few. Burnt clay bricks have been acclaimed to have several technical, economic and environmental advantages. They are durable and have good aesthetic appeal. Their use in construction also encourages sustainable economic gain through the reduction of clinker consumption and construction cost (Atiemo, 1998).

However, the use of burnt clay bricks for construction in Ghana is yet to gain a widespread acceptance on a similar scale in comparison with Portland cement products. The key reasons given for this low level of acceptance of burnt clay bricks by developers include societal perception and the lack of confidence in the technical durability of the materials (Baiden et al., 2014). BRRI for instance has received several verbal complains of deterioration of burnt clay bricks supplied to customers after its use. Developers expect burnt clay bricks to be strong, inexpensive and durable in aggressive environment (Winslow, 1988). For instance, in marine environment, bricks come under salt attack which causes efflorescence, scaling, crumbling, and cracking among others causing material damage (DeVekey, 2008; Bucea et al., 2005). According to Lubelli et al., (2004), the effect of sodium chloride (NaCl) is either direct or indirect. Direct damage is by crystallization of chloride salts that generates pressure to cause material damage. Indirect damage is due to the catalytic oxidation and hydrolysis of chloride. Halite is a stable phase in NaCl water system under room temperature. Sodium sulphate is also one of the common salts that also cause crystallization decay. Careful control of clay composition and firing temperature can produce durable burnt clay bricks that remain unaltered in the process of their service life even in aggressive environment.

1.2 Problem Statement

The durability or stability of masonry structures during usage can be affected by manufacturing process, material properties, and environmental conditions such as moisture and salt attack as well as maintenance culture (Surej *et al.*, 1998; Zsembery, 2001). The material properties may be threatened or lost as a result of interaction between the masonry material and the environment (Gravaglia *et al.*, 2000). One of such severe environments which can cause drastic deterioration of properties in masonry structures is marine environment.

Salt attack of burnt clay bricks occurs when soluble salts are absorbed into the porous structure of a brick material. The soluble salts are left behind after evaporation building up into crystals. Even at concentrations as low as 0.05 wt %, these salts can crystallize inside the brick material and produce subflorescence and efflorescence resulting in the build-up of crystallization pressure (Baronio *et al.*, 1985a). The effect of salt attack can be seen in diverse forms which include scaling, crumbling, softening, splits, cracks and granular disintegration which ultimately cause failure of the masonry material (Ibrahim, 2006; Baronio *et al.*, 1985). If damage to the microstructure of the material is allowed to continue it will lead to reduced compressive strength of the burnt clay bricks (Zsembery, 2001).

The wet-dry cycle as experienced in Ghana during alternating sunny and rainy periods makes masonry structures prone to salt attack (Heathcote, 1995; Carrie and Morel, 1975). Therefore studying the factors affecting durability of burnt clay bricks produced and used locally is vital. Durability properties include physical behaviour like porosity, pore size distribution, bulk density and mechanical strength. These are dependent on the types of raw material, the forming process and firing condition used in manufacturing. These when evaluated will inform proper selection of building materials in construction, ensure strength and performance during service life when subjected to aggressive environment.

1.3 Aim and Objectives

The aim of this work is to assess the durability of locally-produced burnt clay bricks in sulphate and chloride environments.

Specific objectives include the following;

- Determination of the chemical and mineralogical compositions of Mfensi, Nyamebekyre and Mankranso clays used in the production of burnt bricks
- Production and characterization of burnt clay bricks using Mfensi, Mankranso and Nyamebekyre
- Determination of the durability of burnt clay bricks in sulphate and chloride environments

1.4 Scope of Work

This study is in five chapters. Chapter One is the introduction which involves the background of the work, problem statement, aim and objectives of study. Chapter Two summarises the relevant literature in the area of study. Chapter Three describes the methodology used for the work. Bricks were produced from Mfensi, Nyamebekyre and Mankranso clays at varying firing temperatures and some properties measured. Burnt clay bricks were also obtained from BRRI, Vicalix and Rock and Tile Factories in the Ashanti region and some properties measured and compared with laboratory-produced bricks. Salt attack tests were then conducted on the fired bricks. The results and discussion of data are presented in Chapter Four where the durability of the bricks analysed. Chapter Five draws the conclusion to the study followed by some recommendations.

CHAPTER TWO

LITERATURE REVIEW

2.1 Introduction

This chapter summarizes the available literature on burnt clay bricks durability in aggressive media. The literature covers clays and burnt clay bricks in general, properties and production of burnt clay bricks, durability and the mechanisms of salt attack.

KNUST

2.2 Clays

Clay is the most widely used raw material in brick production. It is defined as a mixture of natural deposits of fine grained earthen material which contains clay minerals and is formed by the weathering of certain rocks. It is usually plastic and cohesive, shrinking when dry and expanding when wet. It gains strength with retention of shape on firing and with particle size range of 2µm and below (BSI, 1990).

Clay occurs abundantly in all the regions and districts of Ghana (Kesse, 1985). Clays differ mineralogically, chemically and physically in properties (Ayetey, 1977). It consists of minerals that are tiny crystalline and made of hydrous aluminium silicates, other metallic ions and some impurities. Holtz and Kovacs (1981), suggested that clays are either two layers (Kaolinite) or three layers (Montmorillonite) in which silicon and aluminium ions have tetrahedral coordination with respect to oxygen while aluminium, magnesium, iron and other ions have octahedral coordination with oxygen or hydroxyl ions.

Clays used in the manufacture of burnt bricks include kaolinite, montmorillonite, illite, micas, and chlorites which contain sufficient amounts of calcium carbonate (Zsembery, 2001). During the process of firing, sodium, iron and magnesium normally found in the clays act as

fluxes which melt to produce a glassy phase that act to bind the brick matrix together (Cultrone et al, 2004).

2.3 Burnt Clay Bricks

The raw material used over thousands of years in construction and building material has been clay which has either been baked in the sun or fired in the kiln (Bourgeois, 1987; Kostof, 1995). Burnt clay bricks are made by firing clay at high temperatures to stone hardness (Ahmed *et al.*, 2008). Clay brick is a very durable building material which has seen many civilizations appreciating its unique properties. The physical, chemical and mechanical properties of a burnt clay bricks are dependent on the raw materials and the processes of manufacture and all these ultimately vary the durability of the bricks (Binda *et al.*, 2000; Lopez-Arce *et al.*, 2003).

2.3.1 Manufacture of burnt clay bricks

The production of burnt clay bricks is in four stages namely winning, clay preparation, moulding, drying and firing.

Winning and clay preparation

Winning and clay preparation is the first step in the production of burnt clay bricks. The top soil containing stones, pebbles, gravel and roots are removed after clearing the trees and vegetation (Brownel, 1976). After removing the top layer of the earth, the soil mass is then manually excavated and accumulated, it is then moved to an open air storage area puddled, watered and rummaged in order to reduce soluble salts to a minimum and obtain a more homogeneous material (Brownel, 1976). The resulting mix must be plastic enough to facilitate moulding but not too plastic as that could result in warping, twisting or cracking

during the drying phase. Sand can then be added to reduce severe shrinkage (Weaver, 1997; Vekey, 1998). The admixed is then left over for weathering and subsequent processing. Vitruvius (1960) stated that the choice of raw material was essential to improve the performance and durability of burnt clay bricks. The digging operation is usually done before rains and the raw material selection is dependent on availability and proximity to the factory location (Álvarez de Buergo and Limón 1994).

Moulding

Moulding is a process of giving a required shape to the brick from the prepared brick earth. This brick is known as green brick (Brownell, 1976). Moulding may be carried out by hand or by machines.

Drying

Green bricks contain about 7–30% moisture depending upon the method of moulding. Drying removes moisture or water that only has hydrogen bonds joining it to clay particles. The drying process helps to control shrinkage, save fuel and time during burning. Ground burnt clay and sand is often added to the clay during mixing by some manufacturers. This reduces shrinkage since the drying shrinkage is dependent upon pore spaces within the clay and the mixing water. Many fine pores are created as the water evaporates increasing porosity so as to facilitate drying (Brownell, 1976). The moisture content is brought down to about 3% under exposed conditions within three to four days (Ibrahim, 2011). Thus, the strength of the green bricks is increased and the bricks can be handled safely.

In developing countries like Ghana, bricks are normally dried in natural open air. The drying process lasts from one to three weeks with hand moulded bricks (Ayetey, 1977). Bricks are

stack on raised ground and are protected from bad weather and direct sunlight. Gaps are left in adjacent layers of the stacks so as to allow free movement for the workers on raised ground.

Firing

The critical stage in the manufacture of burnt clay bricks is the firing stage; it determines the shape, colour and the durability of the burnt bricks. The clay after drying is allowed to dehydrate, the water which has been retained in the pores is driven off and the clay loses its plasticity. At temperatures of approximately 450° C the clay structures begins to break down due to the decomposition of the hydroxyl (OH) groups (McConville, 2005) and organic matter starts to burn off. After the reaction, an amorphous or glassy structure is formed. At 863°C calcium carbonate present in the raw material begins to decompose into calcium oxide and carbon dioxide. This reaction triggers molecular rearrangement causing shrinkage (McConville, 2005). Sulphur oxide and nitrous oxides are evolved between 950-1200°C. During this process a strong glassy matrix is created that surrounds the brick material. Cracking or bursting of the bricks occurs if heating is done rapidly. This is due to the formation of an impermeable vitrified outer skin preventing the loss of gases such as water vapour and CO₂ from the interior of the clay (Jordan *et al.*, 1999). However, scum is produced on the bricks surface if the clay contains alkali and heating is done slowly.

2.4 Durability and Serviceability

A material is said to be durable when it remains in its original form, structure and appearance for the expected lifetime without excessive or unexpected maintenance (Hendry and Khalaf 2001). Searls (1996) defines serviceability as the property of a material to require service in order to remain in its original form, structure and appearance it was intended to for its lifetime. Durability and serviceability refer to the material's ability to resist change from external environmental factors throughout the lifetime of the structure. These changes occur in the microstructure of the material causing damage to it. Collepardi (1990) found that changes in the microstructure of the burnt clay brick promoted sites for salt crystallization and these sites cause flaking and spalling. Researchers have over the years measured durability by the magnitude of stresses imposed during salt crystallization (Evans, 1958; Khaimov-Mal'kov, 1956; Knofel, 1987). Fracturing of the microstructure of the burnt clay brick by crystallization of water in colder regions also affect durability and serviceability (Powers and Prentice, 1956). It has also been reported that microbiological species can cause damage to the microstructure of burnt clay bricks affecting their durability (Koestler, 1996).

2.5 Salt Attack

Salt attack is a physical phenomenon that takes place when evaporation occurs just below the surface of a masonry material such as brick and mortar. Salt attack effects include efflorescence, scaling, cracking, crumbling, softening and salt crystals. It occurs as a result of a combination of factors that include the permeable masonry, presence of soluble salts and the process of evaporation. According to Buchwald and Kaps (2000), salt attack or decay on a material is caused by the presence of moisture and soluble salts in the pores. When evaporation has occurred the salts left behind grow within the pores of the bricks and the growth pressure deteriorates the bricks. This occurrence is however dependent on the physical properties of the brick (Espinosa *et al.*, 2008; Rijniers *et al.*, 2005). Deterioration occurs when evaporation takes place within the microstructure of the brick leaving salts to grow as crystals. Developing crystals exert pressure within the pores of the brick sufficient to cause deterioration (Evans, 1958). Material property such as porosity, pore size distribution

and crack orientation determine how salt solution travels. According to Meredith (1992), density and chemical bonding of the material determines the mechanical properties of the burnt clay bricks.

Sodium chloride and calcium sulphate are present in most masonry (Young 1995). However not all salts that exist in moisture cause damage with the exception of sodium sulphate and sodium chloride (Zembery, 2001). Sulphate according to Binda and Molina (1990) is the most destructive and frequently found salt type. Bucea et al. (2005) studied the effect of sodium sulphate and sodium chloride in the brick-mortar stack. The sulphate and chloride solution used were about 6.2% and 14% by weight volume (w/v). These were then exposed to solutions with seven days wet and seven days dry for each cycle. After one cycle, the salt appeared on the surface of the brick, and the mortars deteriorated, causing the binder to lose its cohesion. However, after seven cycles, the mortars became soft especially in sodium sulphate solution. This situation is mainly due to the crystallization of sodium sulphate and sodium chloride. This was parallel to the study carried out by Van Hees and Brocken (2004), who reported that sodium sulphate provides a more severe condition than sodium chloride. The brick masonry showed intense spalling and scaling.

Philips and Zembery (1982) also studied salt attack and resistance on fired clay bricks. The bricks were exposed for two hours to sodium sulphate and sodium chloride with concentrations of 14% (w/v). Bricks were then dried for 22 hours at 110° C with cycle number ranging from 1 to 80. The study revealed that sodium sulphate caused failure in a few cycles whereas many specimens survived a large number of sodium chloride cycles. Lee et al, (2008) and Santhanam *et al.*, (2002) also studied the effects of sodium and magnesium sulphates by curing specimens in solution up to 15 months. It was observed that after 15

months the specimens deteriorated due sulphate attack causing surface damage and reduction in compressive strength.

2.5.1 Mechanism of salt attack of burnt clay bricks

Many processes cause changes to occur to the physical and chemical properties of burnt clay bricks but the most common cause of deterioration is salt attack (Ottosen *et al.*, 2007; Rorig-Dalgaard *et al.*, 2012). Salt attack on masonry materials such as burnt clay bricks occurs in various forms which include efflorescence, sub florescence, scaling, cracking, crumbling, and softening. The various mechanisms of salt attack commonly found in burnt clay bricks are briefly discussed.

Salt Crystallization

Salt crystallization theory is the most widespread explanation of salt decay (Evans, 1970; Bortz, 1990; Fahey, 1986; Fernandez *et al.*, 2007; Binda and Baronio, 1984; Sperling, 1980). Salt crystallization is the main cause of deterioration of building material characterized by cracking, local scaling etc. Knofel *et al.* (1987) summarizes the theories that describe salt decay based on salt crystallization. According to the crystallization theory, decay is caused by the pressure from crystallizing salts in a thin zone near the surface of the material with different salts crystallizing at different humidity (Arnold, 1976). Fitzner and Snethlage (1982) indicated that crystals grow from the coarse pores into small adjoining pores exerting stress on the pore walls. A number of factors affect salt crystallization which includes the type of salt, the concentration of the salt solution, the rate of drying, the number of cycles in which the burnt clay brick has been wet and dried (Bruemner, 2002). Lewin (1982) proposed that the site of crystallization is determined by a dynamic balance between the rate of escape of water contained in the material and the rate of supply of solution to that site. He stated that if the rate of escape (that is evaporation) was slower than the rate of replenishment then salt crystallization will take place. According to Fitzner and Snethlage (1982) during crystallization, crystals grow from the coarse pores into the adjoining pores. Puhringer *et al.* (2007) observed that these crystals have their shapes varying due to varying relative humidity which exert stress on the pore walls leading to an inner rupture of the material. The stresses that are created in the microstructure of the burnt clay bricks during salt crystallization are not uniform. Therefore crack growth is due to the ability of the microstructure to dissipate stresses that were applied due to the process of crystallization.

Efflorescence and Subflorescence

Efflorescence is defined as the presence of salt crystals on the surface of burnt clay bricks (Bowman, 1986). Efflorescence indicates the presence of sub florescence in the microstructure of the burnt clay brick affecting durability and serviceability. Sub florescence is the growth of salt crystals beneath the surface and within the microstructure (Binda and Baronio, 2006; Spry, 1990). Beneventte *et al.* (2004) stated that efflorescence is produced in the porous media of stone if salt crystallization occurs on surface, whereas salt subflorescence produces more decay. Efflorescence depends on the soluble salt content as well as the wetting and drying conditions; it does not only cause deterioration but creates an aesthetic problem.

The main salt types known to be efflorescent include vanadium oxide and soluble alkali and alkaline earth metals, carbonates, sulphates, chlorides and nitrates. Vanadium oxide is present in the raw material of many burnt clay bricks. They appear as an orange stain when the efflorescence contains vanadium oxide (V_2O_5). When other salts crystallize within the microstructure of burnt clay bricks containing vanadium salts larger cracks and particles can exfoliate (Charola, 198; Knofel, 1987). Table 2.1 indicates the main types of salts that are efflorescence.

Chemical Composition	Chemical Name	Mineral Name
CaCO ₃	Calcium carbonate	Calcite, Aragonite
MgCO ₃	Magnesium carbonate	Dolomite
Na ₂ CO ₃	Sodium carbonate	Soda ash
Na ₂ CO ₃ .H ₂ O	Sodium carbonate monohydrate	Thermonatrite
Na ₂ CO _{3.} 10 H ₂ O	Sodium carbonate decahydrate	Natron (Natrite)
CaSO ₄	Calcium sulphate	Anhydrite
CaSO ₄ .2H ₂ O	Hydrated calcium sulphate	Gypsum
CaCl ₂	Calcium chloride	Hydrophillite
CaCl ₂ .nH ₂ O	Calcium chloride hydrate	Antarcticite
MgSO ₄	Magnesium sulphate	-
MgSO _{4.} H ₂ O	Magnesium sulphate monohydrate	Kieserite
MgSO _{4.} 7H ₂ O	Magnesium sulphate heptahydrate	Epsomite
MgCl _{2.} 6H ₂ O	Magnesium chloride hexahydrate	Bischofite
Na ₂ SO ₄	Sodium sulphate	Thernardite
$Na_2SO_4.10H_2O$	Sodium sulphate decahydrate	Mirabillite
KCl	Potassium Chloride	Sylvite
NaCl	Sodium Chloride	Halite
KNO ₃	Potassium nitrate	Nitre

Table 2.1: Salts found as efflorescence in FCB source (Spry, 1990)

Chloride Attack

In brick masonry, the most common chlorides are halite (NaCl), sylvite (KCl), and antareticite (CaCl₂.6H₂O) usually found in coastal areas but also present in brick as additives. Chlorides are soluble and hygroscopic, quickly dissolving during condensation and then penetrates deep into the masonry material. In coastal, dry land and urban environment, sodium chloride which is a common salt causes damage to most building materials. The main sources of sodium chloride are sea spray, from rising damp, carried out by the wind or due to flooding. According to Lubelli *et al.* (2004), the damage sodium chloride causes on masonry materials can be classified into two which are direct and indirect.

Direct damage by sodium chloride is due to crystallization or thermal expansion mechanism. Thermal expansion mechanism in materials with sodium chloride contamination is very vital because differences in thermal expansion of pure sodium chloride on bricks cause internal stresses in the material (Benavente *et al.*, 2004). Larsen and Nielson (1990) conducted a test on the influence of sodium chloride on thermal expansion and hygroscopic shrinkage of both modern and medieval bricks. It was reported that the thermal expansion in case of sodium chloride contaminated bricks is proportional to the salt content. The sodium chloride caused shrinkage of about 70 times higher than the non-contaminated bricks. Additionally, 2% by weight of sodium chloride in a brick increases thermal expansion by 16%. Halite is a stable phase in sodium chloride - water system. It penetrates the porous brick or masonry when carried by sea spray in solution. The salt crystallizes when the masonry dries up. This generates pressure within the brick or masonry causing powdering of the material.

Sulphate Attack

In comparison with other salts, sulphates are less soluble and less mobile. When introduced into the internal pores network of bricks can cause great damage due to the size and aggressiveness of the crystals. They become hydrated salts on the pore walls of the bricks when they are precipitated out as water evaporates. In low humidity environments, the anhydrous salts do not dissolve but hydrate and increase in volume causing pressure to build within the walls of the pores. There must be an increase in temperature for sulphates to hydrate. However, the hydration process must be slow to allow large crystals to grow (Benavente *et al.*, 2006). Larbi (2004) indicated that the sulphate attack to brick and hardened mortar joints occurs when sulphates in solution react with tricalcium aluminate in Portland cement to form ettringite. Cement based building material undergo damage resulting in cracking, expansion, decomposition etc. This expansion causes local stresses in the brick or brick work (Veniele *et al.*, 2003). This usually occurs where there are wet or saturated conditions with the presence of soluble sulphate such as sodium and potassium sulphates.

2.6 Factors Affecting the Salt Attack in Masonry Materials

Several factors influence salt attack which includes raw material composition, soluble salts, microstructural properties, mortar mixes, moisture, temperature and humidity. These must be present for salt decay to take place (De Vekey, 2008).

2.6.1 Influence of raw material composition

The earth has several natural abundant minerals; however, clay is one of the most abundant. In Ghana, the selection of clay for the manufacture of bricks is primarily based on local availability (Kesse, 1985). The clay type used is very vital because suggested chemical composition of the clay allows identification of possible deficiencies. The presence of organic matter, lime nodules, harmful soluble salts and other impurities might influence the durability of the brick (Robinson and Borchelt 1994). Soluble salts and other impurities frequently found in old clay brick fabrics are one of the most important factors of brick decay (Baronio *et al.*, 1985b; Brocken and Nijland, 2004). Chemical composition can also provide information about firing temperature and degree of vitrification (Cultrone *et al.*, 2000), which is relevant for the manufacturing of new replacement bricks (Elert *et al.*, 2003; Cardiano *et al.*, 2004; López-Arce *et al.*, 2003). Majority of the soluble salts originate from within the raw material like calcium carbonates and sulphates. It is therefore imperative to determine the chemical and mineralogical compositions of raw clays before making a selection for burnt bricks manufacture (Moropoulou *et al.*, 1993; Cultrone *et al.*, 2004; Pauri *et al.*, 1994).

Moderate amounts of carbonates within clay have been noted to act as flux which reduces shrinkage and anisotropic behaviour and increases compressive strength (Peters and Iberg, 1978; Cultrone *et al.*, 2001). Additionally the presence of carbonates in clay influence porosity evolution during firing resulting also in irreversible chemical and physical transformations (Binda and Baronio, 2006). For calcareous clays, the control of firing temperature is less critical because their morphology remains unchanged over a wide range of temperatures (Tite and Maniatis, 1975). The presence of carbonates in clay influence porosity evolution during firing resulting also in irreversible chemical and physical transformations (Binda and Baronio, 2006). For most clays, at temperatures in clay influence porosity evolution during firing resulting also in irreversible chemical and physical transformations (Binda and Baronio, 2006). For most clays, at temperatures below 600°C, chemically bonded water is lost resulting in a destruction of the crystal lattice. At about 800°C, calcite is transformed into lime (CaO) and by 900°C amorphous silica and alumina is formed. Calcium carbonate dissociation also occurs with the removal of CO₂ and the formation of CaO. This reaction is accompanied by an increase in porosity. In the presence of water, calcium oxide is converted into portlandite (Ca (OH) ₂). This becomes CaCO₃ in the presence of atmospheric

carbon dioxide. These reactions result in an increase in volume and cause the formation of fissures, a phenomenon known as "lime blowing" resulting in further increases in porosity (Laird and Worcester, 1956). The transformation of dolomite also contributes to the porosity increase. The decomposition products of dolomite include lime and periclase (MgO), which in the presence of water are transformed into portlandite and brucite (Mg (OH) ₂). The latter in the presence of carbon dioxide may then become hydromagnesite (Mg₅ (CO₃)4(OH) $_2$ ·4H₂O) (Cultrone *et al.*, 2001).

KNUST

2.6.2 Influence of soluble salt

Soluble salts do occur naturally in the material body of burnt clay bricks. However, it can also be derived from an external source. In burnt clay bricks, soluble salts are developed by the reaction between sulphur oxides formed during firing and minerals present in the brick (Edgell, 2005). High levels of soluble salts present in masonry materials cause the crystallization of salt to occur underneath. The sources of water soluble salts in bricks are either intrinsic or extrinsic. That is they are either present in the masonry material or absorbed from the atmosphere or ground water during service life. Alkali and alkaline earth sulphates are intrinsic sources of soluble salts introduced to the bricks as clay is being fired resulting from the oxidation of sulphides present in the clay (Jordan, 2001). These nitrates and sulphates of alkali and alkaline earth metals form salts with carbonates as shown in Table 2.2. Calcium carbonate reacts with soluble alkali ions from within the burnt clay bricks to produce other alkali carbonates (Harrison, 1986).

Extrinsic salts are transported into the bricks from its environment. Gypsum is drawn from the surrounding mortar and concrete. Sodium chloride is the commonest soluble salt introduced to the brick. The sources of salts may be one or a combination of the following

(Young, 1995).

- Saline soils and groundwater
- Sea spray
- Air-borne salt
- Air pollutants
- Biological, such as pigeon poop, microorganism, leaking sewers
- Salt naturally occurring in stone, brick clay, or mortar sand
- Salt water used for puddling brick clay or mixing mortar
- Salts used for de-icing roads in cold climates
- Inappropriate cleaning compounds

Some authors have also suggested differences in the rate at which salts damage burnt clay bricks during crystal growth and expansion within its pore structure. Salts within the brick, hydrate and make contact with the brick wall causing damage to it (Bortz, 1993; Boucher, 1987; Spry, 1990). According to Spry, (1990) the most damaging salts are those that hydrate. The types of salts present in a burnt clay brick are vital. However the degree of salt attack may change as a result of the formation of more damaging salts. Salts can be divided into four classes based on their damaging ability as shown in Table 2.2.

Salt Class	Damaging Degree	Types of Salts	
Class A	Least Damaging	Low solubility salts	
		Examples: CaCO ₃ , CSO ₄	
Class B	Moderately	Stable Salts	
	Damaging	Examples: NaCl, NNO ₃ , KCl, KNO ₃ , K ₂ SO ₄ , K ₂ CO ₃	
Class C	Very Damaging	Efflorescent Hydrous Salts	
		Examples: Na ₂ SO ₄ .nH ₂ O, MgSO ₄ .nH ₂ O, Na ₂ CO ₃ .	
		nH ₂ O	
Class D Extremely Damage		Deliquescent Hydrous Salts	
		Examples: CaCl ₂ .nH ₂ O, MgCl ₂ .nH ₂ O, Ca	
	(NO ₃) ₂ .nH ₂ O, Mg (NO ₃) ₂ .nH ₂ O.		

Table 2.2: Salt classes according to damaging capacity (Spry, 1990)

BS EN 771-1 classifies three categories of soluble salt contents in fired clay bricks, namely, S0, S1, and S2, as presented in Table 2.3. Category S0 comprises bricks not subject to any limit on specified soluble salt. It is intended for use in situations where the total protection against water penetration is provided. However, category S1 gives a limit for bricks on soluble salt, including sodium, potassium, and magnesium contents. In category S2, bricks have a lower limit than those in S1. In contrast, BS 3921:1985 limits the soluble salt content of fired clay brick unit into two categories. The first category is Low (L) class with restrictions on the ions of magnesium, potassium, and sodium as well as on the total amount of sulphate. The second category is the Normal (N) class with limits on the amount of total amount of sulphate.

Soluble ion	BS 39	21: 1985	BS	-EN 771-1	
Soluble Ion	Low (L) (%)	Normal (N) %	S0(%)	S1 (%)	S2 (%)
Sodium	0.030			0.170	0.060
Potassium	0.030	0.25	No		
Magnesium	0.030		requirement	0.080	0.030
Sulphate	0.500	1.60	Nil	Nil	Nil

Table 2.3:	Classification	of soluble salts	content (BS EN 771-1)
------------	----------------	------------------	-----------------------

2.6.3 Influence of microstructure

Most masonry building materials, such as fired-clay and calcium silicate bricks, are permeable containing voids or pores. Permeable structures allow water and water vapour to penetrate. Benavente *et al.* (2006) classified the main pore structure parameters of burnt clay bricks into three: porosity, pore size distribution, and pore shape. Crystallization of salts greatly depends on these parameters. Porosity is defined as the ratio of the volume of voids to the total volume of bricks and is expressed as a percentage. According to Benevente *et al.* (2006), bricks that have high porosity and a large percentage of pores measuring less than 1-2.5 micrometer in radius have a tendency to decay. Weathering agents are able to flow in such a way that it affects the durability of the brick when its pores are connected. Large pore size results in very low crystallization pressure since the rate of crystallization depends on the pore size according to equation [2.1] (Scherer, 2004).

$$DDE (\mu m) = \Sigma \left[Dv \frac{(ri)}{(ri)} \right] Pconc$$
[2.1]

Where,

Dv = pore size distribution

 $r_i = pore size$

 P_{conc} = connected porosity

Durability dimensional estimator (DDE)

Porosity is also directly related to the mineralogical composition of the raw material, as clay bricks manufactured with a high sand fraction have a tendency to be extremely porous and permeable (Benavente *et al.*, 2006). Firing temperature also affects the pore size and porosity of the bricks. High firing temperatures undergo great changes in pore size and porosity to become more vitreous with high degree of durability (Cultrone *et al.*, 2004).

2.6.4 Influence of moisture

Moisture is the main source of deterioration of masonry building materials including bricks. Moisture serves an important role as a medium of transport (Espinosa *et al.*, 2008). It introduces salts into the material and helps move them within the matrix of the material. Water penetration gives rise to problems such as moisture penetration, rising damp, efflorescence on external walls, stains, fungi or algae growth, concrete corrosion and loss of thermal insulation. Moisture when in contact with the salts either on or within the matrix of the bricks over a period causes dissolution. According to Young, (1995) capillary action or suction of water through small pores causes damp or moisture to occur in a permeable material. Moisture being an agent for salt attack in fired clay bricks cause's deterioration leading to a reduction in structural performance (Gurevich, 2005). The presence of moisture in masonry such as bricks will lead to a decrease in strength, growth of fungus and degradation of aesthetic value resulting in an increase in maintenance cost (Selvarajah and Johnston, 1995).

2.6.5 Influence of relative humidity and temperature

According to Binda and Baronio, (2006), cycles of temperature and humidity play very crucial roles in salt crystallization. The crystallization of sodium sulphate from water solution is influenced by cycles of temperature and humidity conditions. For temperatures between 1.42°C and 32.4°C, it crystallizes decahydrate as monoclinic prisms. However, where there is temperature increase beyond 32.4°C, it crystallizes an anhydrous phase (stable phase). Furthermore, the anhydrous sulphate also could crystallize into unstable phase (Na₂SO₄.7H₂O) if the temperature is below 24.4°C and in humid environment transformed into Na₂SO₄.10H₂O. When relative humidity is near 100%, Na₂SO₄.10H₂O does not dehydrate. Sodium sulphate can absorb moisture in liquid or gaseous form and become Na₂SO₄.10 H₂O. Therefore due to the variations in temperature and humidity as well as changes in the crystalline phase, fatigue phenomenon is caused in the brick which then causes it to fail.

A study carried out by Navarro and Doehne (1999) showed that sodium sulphate and sodium chloride evaporate at high relative humidity at a low rate and faster at low relative humidity. However, under the same conditions of temperature and relative humidity, sodium chloride evaporates faster than sodium sulphate. This gradually reduces after some days as the pores get filled with precipitated halite crystal. The results of the average weight loss and porosity values for macro scale experiment at 30 days are summarized in Table 2.4. According to their experimental results, sodium chloride crystallization caused very little damage while sodium sulphate crystallization caused significant damage at low and high relative humidity.

Salt	RH (%)	Wt. Loss (%)	Porosity with salt (%)	Porosity without salt (%)
NaCl	60	0.68	8.8	19.3
	35	2.67	10.3	21.9
Na ₂ SO ₄	60	7.06	20.2	20.5
	35	21.43	21.4	20.8

Table 2.4: Weight loss and porosity after crystallization test (Navarro and Doehne, 1999)

KNUST

2.7 Properties of Burnt Clay Bricks

2.7.1 Physical properties

In the evaluation of strength and durability, properties relating to the quality of raw clay and the manufacturing process must be evaluated.

Porosity

Porosity is defined as the ratio of the volume of voids spaces (pores and cracks) to the total volume of bricks and expressed as a percentage (Fernandes *et al.*, 2006). This property has influence on the chemical reactivity, mechanical strength, durability and the brick quality in general hence, a vital parameter. The quality of the raw material, the presence of additives or impurities, the amount of water and the firing temperature all influence the size and distribution of pores.

Bricks that are porous with a high percentage of pores measuring less than 1-2.5 μ m in radius have a tendency to decay because salt crystallization is highly dependent on pore structure parameters (Benavente *et al.*, 2006). Old clay bricks usually have high porosity values of between 15 and 40 vol% (Esbert *et al.*, 1991). 70–80% of the pores had a diameter size of 70–250 μ m, independently of the type and origin of the clay (Papayianni and Stefanidou

2000). An increase in the firing temperature will result in an increase the proportion of large pores (3–15 μ m) (Mamillan, 1979; Cultrone *et al.*, 2004). This allows connectivity between pores to be reduced, whereas the amount of small pores diminishes. Large pores are not easily attacked by soluble salts and hence have a good effect on brick durability.

Cultrone *et al.* (2004) and Elert *et al.* (2003) reported that the presence of carbonates in the raw clay influence porosity evolution during firing. Firing produces mineralogical, textural and physical changes that depend on many factors that influence porosity. At temperatures of 800 to 1,000°C, calcite is transformed into lime (CaO). This reaction causes an increase in porosity with small pore sizes of 1 μ m. Smaller pore sizes affect the quality of bricks, they have increased ability to absorb and retain water. Winslow *et al.* (1988) drew similar conclusions for bricks with a pore size smaller to 1.5 μ m. In the presence of water, calcium oxide is converted into portlandite (Ca (OH) ₂). This becomes CaCO₃ in the presence of atmospheric carbon dioxide. These reactions according to Laird and Worcester, (1956) result in an increase in volume causing fissures to be created, a phenomenon known as "lime blowing" resulting in further increases in porosity. The transformation of dolomite also contributes to the porosity increase.

Bulk density

Bulk density is a useful property of brick durability. When the bulk density of brick decreases, its strength decreases and water absorption increases. Increase in water absorption of bricks, results in the bricks exhibiting larger pore sizes and hence low bulk density. According to Nwobodo and Davies, (2000), bulk density provides a general indication of brick quality.
Water absorption

Another relevant parameter is water absorption which is a measure of available pore space and is expressed as a percentage of the dry brick weight. It is affected by properties of clay, method of manufacturing and degree of firing. Water absorption capacity of the brick affects the surface finishing of the brick-laid wall (Cultrone *et al.*, 2004). Water absorption determines the capacity of fluid to be stored and to circulate within the brick. This increases deterioration and reduces mechanical strength. In countries where temperatures fall below 0°C, the water inside the pores can freeze leading to surface delaminations, disintegration or cracking. Deterioration occurs on the surface of the brick rendering it unappealing aesthetically. The volume increase caused by the crystallization of the salts can cause severe damage. The water is sucked by the pores as a result of capillary tension along the walls of the pores. López-Arce *et al.*, (2003), pointed out that tension is stronger in small pores than in large ones.

2.7.2 Mechanical properties

In order to assess the safety of a brick masonry structure, the mechanical property is a very relevant parameter. All masonries are made of heterogeneous materials whether brick, mortar or mortar–interface with their compressive strength dependent on the strength of their component. Bricks used in the construction of columns, walls, arches and vaults are subjected to compressive stresses and hence should possess reasonable strength in compression and low strength in tension.

Compressive strength

Compressive strength is influenced by the production process and the raw material characteristics. Compressive strength evolution correlates to textural and microstructural

changes in the bricks, including increasing vitrification and reductions in porosity both resulting in an increase in the mechanical strength (Bucea *et al.*, 2005). In the American Society for Testing Materials (ASTM) specifications for solid bricks (ASTM C62-00), the minimum compressive strength (kg/cm²) is correlated with weathering resistance, and three different grades are specified: bricks resistant to severe weathering — 211 kg/cm²; bricks resistant to moderate weathering — 176 kg/cm²; and bricks resistant to negligible weathering — 106 kg/cm². Most studies indicate low values for compressive strength and a large dispersion of the values, with coefficients of variation ranging between 25 and 55%; but unusual strengths, higher than 50 MPa, were reported by Pauri *et al.* (1994).



CHAPTER THREE

METHODOLOGY

3.1 Introduction

This chapter gives an outline of the specific experimental procedure used for the production of burnt clay bricks from Mankranso, Mfensi and Nyamebekyre clays. The methods used in characterising the clays and fired bricks are described into details. A flow diagram describing the process of production and characterisation of burnt clay bricks is shown in Figure 3.1.



Figure 3.1: Flow diagram showing the processes involved in assessing the durability of locally-produced burnt clay bricks

3.2 Materials and Material Preparation

Six burnt clay bricks samples were obtained from three different factories namely BRRI, Vicalix and Rock Brick and Tile Factories. Mfensi, Mankranso and Nyamebekyre clays were obtained from their respective villages all in the Ashanti Region of Ghana. The clays were air dried for 24 hours before processing. The bigger lumps were crushed into smaller particle sizes. The clay samples were assigned sample names MK, MF and NK representing Mankranso, Mfensi and Nyamebekyre clays, respectively. A total of 450 bricks were moulded after clay has been mixed with water, tempered and thoroughly worked into a plastic state.

3.3 Characterization of Clay Samples

3.3.1 Mineralogical composition

X-ray diffraction (XRD) analysis is the most common technique used to determine the mineralogical composition of masonry material. This technique is also attractive and efficient because it requires only a small amount of material or sample which is about 2 gram. Samples were gently ground and passed through a 100 μ m sieve. Samples were then compressed into labelled pellets and placed in the X-ray diffractometer (Siemens D5000) using Cu K α radiation. Samples were scanned from 10 – 50° (20) at step size of 0.01°. The voltage and current of the X-ray tube were 40 kV and 40 mA, respectively. The results of the mineralogical compositions are presented in Chapter Four.

3.3.2 Chemical analysis

The chemical analysis of the clay samples was determined using the X-ray fluorescence equipment (Spectro X-lab 2000). 4g of each sample was mixed with 0.09g of wax and then milled for 3 minutes to produce a homogenous mixture. The mixture was poured into a disc

and placed under a press pellet machine. The pellet machine produced a tab which was placed in a container. The container and its content were fixed in the Spectro X-lab 2000 instrument to determine the chemical composition of the samples. The results of the chemical analysis are presented in Chapter Four.

3.3.3 Particle size distribution

The particle size distribution of the clay samples were determined by the hydrometer method of sedimentation as specified by British Standard BS 1377:90. 200g of the samples were dried in an oven at 105°C for 4 hours. The dried samples were then quartered and 50g of each sample was transferred into a 600 ml brass container. 100 ml of a dispersant solution, made from 7g of sodium metahexaphosphate $(NaPO_3)_6$ and 33g of sodium oxalate $(Na_2C_2O_4)$ dissolved in 1 litre of distilled water, was added to each sample and made up to 250 ml with distilled water. The suspensions were agitated with a mechanised stirrer for 15 minutes and each sample was later transferred to a 1 litre measuring cylinder. The contents were made up to 1 litre with distilled water and left to stand undisturbed for 24 hours to effect the decoagulation of the various particles. The cylinder was agitated manually by holding the measuring cylinder containing the suspension between the palms and turning it upside-down for a minute to disperse the particles and placed on a bench. The timer was immediately switched on. The hydrometer readings were first taken after 30 seconds and then after 1, 2 and 4 minutes and specific intervals for 8 hours and at 24 hours. After the hydrometer readings, the samples were washed through a 75 μ m sieve and the material retained, if any, was dried at 105°C for 24 hours. The dried samples were passed through 0.6 mm, 0.4 mm, 0.2 mm, 150 µm and 75 µm standard sieves and the material retained on each sieve recorded.

3.3.4 Specific gravity

The specific gravity of the clay samples was determined as specified by the British Standard BS 1377:90. A 50 ml density bottle with the stopper was dried in an oven and weighed (m_1) . 25g of the clay sample was oven-dried at 105°C for 24 hours. The sample was transferred into the density bottle and the bottle with its contents and the stopper weighed again (m_2) . Then the sample in the bottle was covered with kerosene of known specific gravity. With the stopper removed, the container was placed in a vacuum desiccator, and the air gradually evacuated. When no air was seen to be released, the bottle was removed from the desiccator and filled with de-aired kerosene. The stopper was again inserted and the bottle immersed in a water bath until a constant temperature of 25°C was attained. The bottle was then wiped dry and weighed (m_3) . The bottle was afterwards emptied of its contents, cleaned and completely filled with kerosene, stoppered and reweighed (m_4) .

The specific gravity (G_s) of the sample was calculated as:

$$G_S = \frac{G_L(m_2 - m_1)}{(m_4 - m_1) - (m_3 - m_2)}$$

where G_L = specific gravity of kerosene.

3.3.5 Determination of Atterberg limits

Liquid and plastic limit tests were determined for all the clays from which the plasticity indices (PI) were calculated. Clay samples were sieved using 425 μ m sieve size and the undersize used for the tests. Tests were conducted according to ASTM D 4318. The results of this test are presented in Chapter Four.

3.4 Moulding, Drying and Firing

A predetermined weight of air-dried clay was mixed with sufficient amount of water and kept at room temperature. It was then dry pressed into a mould of dimensions 60 x 60 x 50 mm.

[3.1]

Specimens were initially dried under room temperature for 24 hours then oven dried at 105°C for 48 hours. Each specimen was marked and weighed before firing in an electric furnace. Dried bricks were fired in furnace at 800, 900 and 1050°C, respectively for 1 hour.

3.5 Characterisation of Fired Bricks

The burnt clay bricks were characterized by determining their, apparent porosity, water of absorption, bulk density and cold crushing strength.

3.5.1 Determination of linear firing shrinkage

The shrinkage properties of the fired bricks was measured by taking the dimensions of three (3) sides of the green and the fired bricks using a venier caliper. Green bricks' dimensions were taken after air drying. The average linear shrinkage of each side was computed as a percentage of the original green dimension. A standard deviation was then deduced.

$$Ls = \frac{Lg - Lf}{Lg} \times 100$$

Where;

Lg is the green length of the brick (length before firing)

Lf is the final length of the brick (length after firing)

3.5.2 Determination of water absorption

Durability of bricks can be judged by water absorption test (IS 3495 (Part-2): 1992) Fired bricks were weighed using a sensitive balance and kept in water for 24 hours. Bricks were weighed again after 24 hours to determine the percent water absorption. The samples were dried in a ventilated oven at a temperature of 105° C to 115° C till they attained substantial constant masses. They were cooled to room temperature and their weights obtained as (M₁).

[3.2]

The dried samples were then immersed completely in clean water at a temperature of $27+2^{\circ}C$ for 24 hours. Each sample was removed, wiped out of any traces of water with damp cloth and weighed three minutes after it had been removed from water (M₂).

Water absorption % mass, after 24 hours immersion in cold water is given by the formula;

$$W = \frac{M_2 - M_1}{M_1} \times 100$$
 [3.3]



3.5.3 Determination of apparent porosity

The apparent porosity was determined in accordance with ASTM C 20-80. The fired bricks were dried in an oven at a temperature of 105 °C for 12 hours. The dry weight in air (W_{da}) of each specimen was measured. The specimen was suspended in a vessel of boiling distilled water for 20 minutes and allowed to cool to room temperature. The weight soaked in water (W_{sw}) was measured. The specimen was then removed from the water and the surfaces gently cleaned with a damp cloth and weighed again in air to determine the saturated weight (W_{sa}). The apparent porosity, AP, of each brick was calculated using the following relation:

$$AP (\%) = \frac{volume \ of \ water \ abbsorbed \ after \ boiling}{Bulk \ voulme \ (volume \ displaced)} \times 100$$
$$AP (\%) = \frac{Wsa - Wda}{Wsa - Wsw} \times 100$$
[3.4]

3.5.4 Determination of bulk density

The test specimens were dried at 110°C for 12 hours and their weight measured and recorded. The bricks were allowed to cool and then immersed in a beaker of water. Bubbles were observed as the pores in the specimens were filled with water. Their soaked weights were measured and recorded. They were then suspended in a beaker one after the other using a sling and their respective suspended weights were measured and recorded. Bulk densities of the samples were calculated using the formula:

[3.5]

Bulk Density =
$$\frac{D}{(W-S)} \left(\frac{g}{cm^3}\right)$$

Where:

D = Weight of dried specimen

- S =Weight of dried specimen suspended in water,
- W = Weight of soaked specimen suspended in air.

3.5.5 Determination of cold crushing strength

The cold crushing strength of fired bricks is usually related to other properties, such as porosity and firing temperature, which are key parameters for durability (Cultrone *et al.*, 2000). These properties can also markedly affect the mechanical resistance of bricks (Cultrone *et al.*, 2004). The crushing affords a basis for comparing the quality of bricks. Five bricks each were taken for the cold crushing strength tests. The samples were placed in the compression testing machine positioned between the stationary and movable plates of the machine with load applied at a uniform rate of 14 N/m² per minute till failure. The load to failure, was registered on a gauge, was recorded. The compressive strength was determined by taking the ratio of the average load to the cross sectional area as;

$$CCS (MPa) = \frac{Average load (N)}{Cross sectional area (mm2)}$$
[3.6]

3.6 Salt Attack Test

Salt attack test was carried out on the fired bricks. The bricks were exposed by soaking for 7, 15, 30, 60 and 90 days in 0.5 M NaCl, 0.5 M Na₂SO₄ and seawater. Solutions were prepared from their salt crystals using distilled water. Samples were removed at the end of exposure periods and then oven dried for 22 hours at 110°C. Deterioration as well as the amount of damage was assessed by comparing the compressive strengths, apparent porosities, bulk densities and absorption before and after exposure tests. Visual inspection was also carried out.

3.7 Efflorescence Test

The ends of the brick were kept in a 150 mm diameter glass dish containing 25 mm depth of water at room temperature (20° – 30° C). After 7 days, most of the water was absorbed or evaporated. The specimen were then dried in an oven for 24 hours and compared by observing the top as well as all four faces of each specimen. The efflorescence test was carried out according to ASTM C67-02c (2002) part 11). Presence of efflorescence, which is non-quantitative, was classified as follows according to IS 3495-1 to 4 (1992) part 3 scheme.

- 1. Nil when the deposit of efflorescence is imperceptible.
- Slight when the deposit of efflorescence does not cover more than 10 per cent of the exposed area of the brick.
- Moderate when the deposit of efflorescence is more than 10 per cent but less than 50% of the exposed area of the brick.
- Heavy when the deposit of efflorescence is more than 50 per cent but the deposits do not powder or flake away the brick surface.
- 5. Serious when the deposits are heavy and powder or flake away the brick surface.

The specifications limit the efflorescence to be not more than moderate (10-50%) up to class 12.5 and not more than slight (< 10 per cent) for higher classes.



CHAPTER FOUR

RESULTS AND DISCUSSION

4.1 Introduction

The fired bricks from the different clays were characterized to acquire results that are relevant to this project. Fired bricks were characterized based on their bulk density, apparent porosity, water absorption and resistance to aggressive environments. The results from the various tests are illustrated in figures and tables in this chapter and the appendices.

4.2 Chemical and Mineralogical Compositions

The chemical composition of clay samples used in the study is presented in Table 4.1. The clays were mainly composed of SiO₂ and Al₂O₃. The SiO₂ content in Mfensi clay was the highest (69.8%) followed by Nyamebekyre (67.5%) and Mankranso (60.3%) clays, respectively. Al₂O₃ was highest in Mankranso (18.2%) followed by Mfensi (15.7%) and Nyamebekyre (15.3%), respectively whilst organic matter content of the Mfensi clay was slightly higher than that of the others. The XRD analyses of the clay samples are shown in Figure 4.1. In all the clay samples, quartz was identified as the major mineralogical phase with minor fractions of kaolinite. The kaolinite fraction appears to be less in Nyamebekyre compared to Mfensi and Mankranso clays. This is in agreement with the high amounts of SiO₂ found in the various clays studied.

Compound	MK	ME	ND
Compound	INIK	IVIF	ND
SiO ₂	60.3	69.8	67.5
Al ₂ O ₃	18.2	15.7	15.3
Fe ₂ O ₃	9.1	4.6	4.2
CaO	1.2	0.2	0.5
MgO	ND	0.1	0.1
SO ₃	0.1	0.02	0.04
K ₂ O	1.0	0.9	1.1
MnO	0.03	0.2	0.02
Na ₂ O	1.1	0.9	0.9
TiO ₂	0.8	0.6	0.8
LOI	4.5	5.3	4.8

Table 4.1: Chemical composition of burnt clay bricks samples (MK=Mankranso;



MF=Mfensi; NB=Nyamebekyre)



Figure 4.1: X-ray diffraction analyses of clay samples showing major mineralogical phases (a) Mfensi (b) Mankranso and (c) Nyamebekyre

4.3 Atterberg Limits, Particle Size Distribution and Specific Gravity

Table 4.2 shows the results of the Atterberg limits of Mankranso, Mfensi and Nyamebekyre clays. The plasticity indices for the three clays investigated fell within the recommended 10-60% for ceramic clays (Nnuka and Enejor, 2001). For low shrinkage property the plasticity index (PI) should be within 10-20% (BS 1377-7:1990). The plastic limits for the various clays were 22.4%, 34.4% and 15.3% for Mankranso, Mfensi and Nyamebekyre clays, respectively. The difference in liquid and plastic limits gives the plasticity index value. From the results Mfensi clay showed the highest plasticity index of 34.5%.

Clay type	Liquid Limit (LL)	Plastic Limit (PL)	Plasticity Index (PI)
Mankranso	38.9	22.4	16.5
Mfensi	68.9	34.4	34.5
Nyamebekyre	28.4	15.3	13.1

Table 4.2: Atterberg limits of Mankranso, Mfensi and Nyamebekyre clays

Figure 4.2 shows the particle size analysis of the clay powders. The analysis of the granulometric curves revealed that the average size particles of Nyamebekyre was the highest followed by Mankranso and Mfensi, respectively. The particle size distribution of clay is important for strength development during firing which subsequently impacts on the durability of the burnt clay bricks. Independently from other manufacturing processes, it can be said that raw materials with uniform particle size distribution can give good compactness which results in low porosity (Elert *et al.*, 2003). Table 4.3 shows the analyses of the particle size distribution of the various clays. It could be seen that Mfensi clay had the highest clay content followed by Mankronso and Nyamebekyre clays, respectively. Thus Mfensi clay had small particle sizes and hence will enhance inter-particle packing and reduce inter-particle void. This will minimize intrusion of water and hence improve brick durability (Weng *et al.*, 2003)

The specific gravities of the various clays were determined using British Standard BS 1377:90. Nyambekyre clay recorded highest specific gravity (2.77 g/cm³) followed by Mankranso (2.64 g/cm³) and Mfensi clay (2.40 g/cm³), respectively. Thus Mfensi clay could be used to produce relatively lightweight burnt bricks.



Figure 4.2: Particle size distribution of clay samples

Type	Composition (%)				
SP Store	Clay	Silt	Sand	Gravel	
Nyamebekyre	21.0	36.0	41.0	2.0	
Mfensi	46.2	34.8	19.0	0	
Mankranso	41.0	40.0	18.8	0.2	

Table 4.3: Analyses of particle size distribution

4.4 Properties of Burnt Clay Brick

Before subjecting to salt attack test, some properties of the burnt clay bricks produced commercially and in the laboratory were measured and compared. These properties have been discussed under this section

4.4.1 Effect of firing temperature on bulk density

Figures 4.3 and 4.4 show the influence of firing temperature on the bulk densities of laboratory and commercial burnt clay bricks, respectively. The bulk densities of laboratoryproduced samples decreased slightly from 800°C to 900°C and increased at 1050°C. On the one hand, Mfensi bricks produced in the laboratory had the highest bulk densities at the various firing temperature. This could be due to the high amounts of finer particles which resulted in high inter-particle packing. On the other hand, commercial bricks produced from Mankranso had the highest bulk density. It is interesting to note that the bulk densities of laboratory-produced bricks were higher than commercially-produced bricks for all brick types. This could be due to lack of compactness in the process of forming which creates voids in the bricks extruded thereby reducing their bulk density. The commercial bricks were fired at temperatures between 900 and 1050°C. However, the specific firing temperature is not known since the kilns used do not have built-in thermocouples for temperature readings. According to Weng et al. (2003) and Somayaji (1995), bulk density of burnt clay bricks is dependent on the specific gravity, the method of manufacture and degree of burning which usually exceeds 1.6 g/cm³. Increasing firing temperature results in a corresponding increase in the bulk density of bricks. At lower temperatures, bricks exhibit larger pore sizes which results in lower density and a corresponding increase in water absorption which is not desirable for brick durability (Weng et al., 2003). Increase in bulk density is the result of increased number of fine particle sizes which also affects plasticity.



Figure 4.3: Effect of firing temperature on the bulk density of burnt bricks produced from

different clay materials





4.4.2 Effect of firing temperature on apparent porosity

Figure 4.5 shows the effect of firing temperature on the apparent porosity of burnt bricks produced from the various clays. Generally, burnt bricks produced from Mfensi clay had the highest apparent porosity at the various firing temperatures. For instance, at 800°C, the apparent porosity of Mfensi burnt bricks was 50%, whilst those of Mankranso and Nyamebekyre were 27% and 22%, respectively. It was noted that apparent porosity decreased with increasing firing temperature for all investigated clays. The decrease was more significant in Mfensi burnt bricks than those of Mankranso and Nyamebekyre. This could be due to the high organic matter content in the Mfensi clay. The organic matter content as indicated in the chemical composition (LOI) of Mfensi clay was higher (5.3%) than that of Mankranso (4.5%) and Nyamebekyre (4.8%). The organic matter increased vitrification which resulted in closure of small pores and the development of atomic bonding between particles by solid state diffusion. Vitrification refers to the process of converting a material into glassy amorphous solid free from crystalline structure and occurs at the glass transition temperature just below the melting point. This is followed by grain growth which creates a dense structure thereby increasing the technical quality and durability of such bricks (Barsoum, 1997; Warren 1992). Increasing firing temperature results in full solid state sintering of individual clay particles, reducing porosities present within the microstructure (Johari et al., 2010). This is due to the formation of glass phase which fills the pores inside the body of the bricks resulting in reduction of pore ratio (Junse, 1994).

The apparent porosity of the commercial bricks produced from the different clay types is shown in Figure 4.6. Mfensi burnt bricks had the highest apparent porosity followed by Mankranso and Nyamebekyre, respectively. The apparent porosities were comparable to laboratory bricks fired at 1050°C. Higher apparent porosity causes greater water absorption which is not desirable. This is because, the lower the negative influence of water on the bricks the better the quality of bricks and consequently, the higher the durability (Scherer, 2004).



Figure 4.5: Effect of firing temperature on the apparent porosity of burnt bricks produced

from different clay materials





materials

4.4.3 Effect of firing temperature on water absorption

Figure 4.7 shows the effect of firing temperature on the water absorption of burnt bricks produced from the different clay types. Mfensi burnt bricks had the highest water absorption at the different firing temperatures followed by Mankranso and Nyamebekyre burnt bricks, respectively. It is also observed that the water absorption decreased with increasing firing temperature. Studies carried out by Cultrone *et al.*, (2004) showed that vitrification begins above 900°C with formation of glassy phase. This decreases the total pore size and consequently water absorption (Basegio *et al.*, 2002; Karman, 2006).

Figure 4.8 shows the water absorption of commercial burnt bricks produced from different clay types. It is observed that Mfensi burnt bricks had highest water absorption followed by Mankranso and Nyamebekyre, respectively similar to that observed in laboratory-produced bricks. However, the water absorption in commercially-produced bricks was higher than those produced in the laboratory.





Figure 4.7: Effect of firing temperature on water absorption of burnt bricks produced from

different clay materials





materials

4.4.4 Effect of firing temperature on cold crushing strength

Figure 4.9 shows the effect of firing temperature on the cold crushing strength of burnt bricks produced from different clay types. Strength of Mfensi burnt bricks increased with increasing firing temperature with best strength at 1050°C. On the other hand, Mankranso and Nyamebekyre burnt bricks recorded optimal strength at 900°C. The variation could be due to differences in fluxes and organic matter contents. Fluxes have the tendency to reduce sintering temperatures (i.e liquid phase sintering) and could decompose at high temperatures reducing strength of bricks. During liquid phase sintering, the reduction of pores becomes more significant as the compacted structure starts to increase in strength.

Figure 4.10 shows the cold crushing strength of commercial burnt bricks produced from different clay types. Again it is observed that Mfensi burnt bricks had the highest cold crushing strength followed by Mankranso and Nyamebekyre, respectively. Generally, cold crushing strength values of laboratory-produced bricks were higher than those produced commercially. The relatively low strength values could be due to variations in firing temperatures.





Figure 4.9: Effect of firing temperature on cold crushing strength of burnt bricks produced

from different clay materials





materials

Based on the above results, and for the fact that the properties of the commercial bricks fell within the properties of the laboratory-produced bricks, the exposure tests were carried out on the laboratory-produced bricks. It is worth mentioning however that, some of the laboratory-produced bricks had better properties than the commercial bricks.

4.5 Durability of Burnt Clay Bricks

Manmade structures, irrespective of the construction material used, deteriorate with time. However, one can determine and control the rate of deterioration. For burnt bricks, major factors that influence the durability include:

- 1. Brick characteristic strength which determines load carrying ability of walls built with the bricks. If the strength of bricks is below the stresses exerted on the blocks by the wall, the wall in question will collapse.
- 2. Water absorption (weakens the bricks and affects strength)
- 3. Attack by chemically aggressive environments (causes degradation in properties)
- 4. Erosion of bricks caused by impacting raindrops (affects aesthetics)

Discussion of the erosion of burnt bricks is outside the scope of this study. The degree of attack by aggressive environments will be influenced by the water absorption ability. The strength could be weakened if water is allowed to permeate into the bricks. Consequently, the durability of the burnt clay bricks have been tested based on the water absorption behaviour and strength after exposure to aggressive environments.

4.5.1 Effect of chloride environment on apparent porosity and water absorption

Figure 4.11 shows the effect of exposure time on the apparent porosity of burnt bricks produced from different clay materials in seawater. Burnt bricks fired at different temperatures have been compared. Whereas Mfensi burnt bricks fired at 800°C recorded a reduction in apparent porosity (31.6% to 24.7%) after 90 days exposure in seawater, the apparent porosity of Mankranso (26.8% to 29.5%) and Nyamebekyre (22.3% to 29.5%) burnt bricks increased marginally. Similarly, a decrease in apparent porosity of about 27.1% was observed in Mfensi burnt bricks fired at 900°C after 90 days exposure in seawater. Again, Mankranso (20.96% to 30.05%) and Nyamebekyre (19.96% to 22.05%) burnt bricks recorded an increase in apparent porosity values. However, at 1050°C, the apparent porosity values for Mankranso and Nyamebekyre burnt bricks remained fairly constant whilst Mfensi burnt bricks recorded a marginal increase in apparent porosity after 90 days exposure.

Apparent porosity is a measure of the volume of the open pores, into which a liquid can penetrate, as a percentage of the total volume. A low apparent porosity is desirable since it would prevent easy penetration and growth of chloride crystals. One of the ways to reduce apparent porosity is by increasing the firing temperature of burnt bricks (Rye, 1976). At higher temperatures smaller pores are filled by melt during vitrification (Delbrouck *et al.*, 1993; Orts *et al.*, 1993). It is observed that bricks fired at low temperatures provided little resistance to the chloride attack by increasing the apparent porosities of burnt bricks. For instance, Mankranso burnt bricks fired at 900°C had highest percentage increase in apparent porosity of about 50.5% after exposure period. On the other hand, Mankranso burnt bricks fired at 1050°C had an increase in porosity of about 0.5% after exposure period. Thus increasing firing temperature reduced apparent porosity.









different clay materials in seawater

Figure 4.12 shows the effect of exposure time on the water absorption of burnt bricks produced from different clay materials in seawater. Bricks produced at different temperatures have been compared. Mfensi burnt bricks fired at 800°C experienced an initial increase in water absorption from 14.1% to 40.7% after 7 days then declined to 14.9% after 90 days exposure. Further increase in firing temperature to 900°C saw further decrease of about 19.2% in water absorption in Mfensi burnt bricks. On the other hand, Mankranso and Nyamebekyre burnt bricks at 800°C experienced slight variations in water absorption values with an increase from 14.1% to 15.3% and 13% to 15.8%, respectively over the 90 days of exposure. At 900°C, water absorption value increased by 29.3% for Mankranso and Nyamebekyre decreased by 6.1%. At 1050°C, Mfensi and Nyamebekyre bricks increased by 16.2% and 2.1%, respectively whilst Mankranso burnt bricks decreased over the 90 days exposure representing 7% reduction in water absorption.

The initial increase in water absorption values is due to sea salt crystal growth within the pores of the bricks causing superficial material loss as well as internal micro-cracks. This increases the volume of the voids and also produces additional ones for more incoming solution as the exposure time increased (Scherer, 2004). At the end of the 90 days exposure to seawater Mankranso bricks fired at 900°C had highest percentage increase of 29.3% in water absorption with Nyamebekyre bricks fired at 1050°C having the highest percentage decrease of 26.3% in water absorption. Generally, bricks fired at 1050°C had lower percentage increase in water absorption due to the presence of smaller pores which reduces deterioration as a result of chloride crystal growth within the pores of the bricks.



Figure 4.12: Effect of exposure time on the water absorption of burnt bricks produced from

different clay materials in seawater

Figure 4.13 shows the effect of exposure time on the apparent porosity of burnt bricks produced from different clay materials in 0.5 M NaCl. Similar behaviour of burnt bricks could be observed as in seawater environment. At 800°C, Mankranso and Nyamebekyre burnt bricks recorded an increase in apparent porosity values by 17% and 4.2%, respectively. On the other hand, Mfensi burnt bricks experienced 43% reduction in apparent porosity after 90 days exposure period. As temperature increased to 900°C, the apparent porosity values of Mfensi and Nyamebekyre burnt bricks decreased whilst Mankranso increased after exposure period. Further increase in firing temperature to 1050°C resulted in a slight variation in apparent porosity values of Mankranso, Nyamebekyre and Mfensi burnt bricks. Similar reasons provided for the behaviour in seawater could also be provided in 0.5 M NaCl. Increasing firing temperature reduced the apparent porosities in the burnt bricks (Cultrone *et al.*, 2000). Thus burnt bricks fired at 1050°C had marginal differences in apparent porosity values compared to bricks fired at 800 and 900°C.





Figure 4.13: Effect of exposure time on the apparent porosity of burnt bricks produced from different clay materials in 0.5 M NaCl

Figure 4.14 shows the effect of exposure time on water absorption of burnt bricks produced from different clay materials in 0.5 M NaCl. Bricks produced at different temperatures have been compared. At low firing temperature (800°C), there was marginal percentage increase of 5.7% and 0.4% in the water absorption of Mankranso and Nyamebekyre bricks, respectively after the exposure period. Mfensi bricks experienced a decrease of 24.9% in water absorption value over the exposure period. At 900°C, Mankranso experienced an increase of 26.4% whilst Mfensi and Nyamebekyre recorded reductions of 2.1% and 66.9%, respectively in their water absorption values. At 1050°C, decreases of 19.8%, 2% and 20.9% were recorded for Mfensi, Mankranso and Nyamebekyre bricks, respectively.

Water absorption values increased gradually after an initial reduction and this can be attributed to chloride crystal growth within the pore spaces of the bricks. However, bricks fired at 1050°C experienced variation in water absorption. This is because the rate of physical damage by salt crystallization does not depend on only pore size but also a function of several parameters such as moisture supersaturation, magnitude of repulsive forces between salts, rates of elements supply and water evaporation (Scherer, 2004; Fonseca *et al.*, 2013). At the end of the 90 days exposure to NaCl, Mankranso bricks fired at 900°C had highest water absorption of 26.4% with Nyamebekyre bricks fired at 900°C having the highest reduction in water absorption of 66.9%. Burnt bricks fired at 1050°C had water absorption values decreasing with increasing exposure time as a result of the presence of smaller pores.



Figure 4.14: Effect of exposure time on the water absorption of burnt bricks produced from different clay materials in 0.5 M NaCl

4.5.2 Effect of chloride environment on cold crushing strength

CMCCASHA

Figure 4.15 show the effect of exposure time on the cold crushing strength of burnt bricks produced from different clay materials in seawater. Bricks produced at different temperatures have been compared. The cold crushing strength of bricks fired at 800°C decreased by 40.6%, 34.4% and 49.5% for Mfensi, Mankranso and Nyamebekyre, respectively after exposure. The strength of bricks fired at 900°C also declined experiencing decreases of 8.6%, 28.9%, and 25.8% for Mfensi, Nyamebekyre and Mankranso bricks, respectively. At 1050°C, the cold crushing strength increased for all brick types with Mfensi, Mankranso and Nyamebekyre bricks recording 10.4%, 10.4% and 3.1%, respectively. Thus the strength values of bricks fired at 800 and 900°C declined whilst strength values of bricks fired at 1050°C increased. Additionally, burnt bricks exposed to seawater environment initially gained strength but prolong exposure resulted in a significant loss of strength. The initial gain could be due to partial filling of the pores by chloride crystals which causes an increase in compressive strength. This is consistent with studies done by Fonseca *et al.* (2013). However, a significant decrease was noted after prolong exposure. The effect of the salts had a clearly negative influence on the strength properties of the clay materials (Fonseca *et al.*, 2013).



Figure 4.15: Effect of exposure time on the cold crushing strength of burnt bricks produced from different clay materials in seawater

Figure 4.16 shows the effect of exposure time on cold crushing strength of burnt bricks produced from different clay materials in 0.5 M NaCl. Bricks fired at different temperatures have been compared. The cold crushing strength of burnt bricks from Nyamebekyre and Mankranso clay fired at 800°C showed a decrease of 25.9% and 34.6%, respectively at the end of the 90 days exposure period. The strength of Mfensi burnt bricks decreased by 29.7%. At 900°C, the strength of Mfensi, Mankranso and Nyamebekyre burnt bricks decreased by 31.0%, 35.0% and 61.8%, respectively. At 1050°C, an increase in strength values were observed for Mankranso and Nyamebekyre bricks whilst slight decrease was recorded for Mfensi bricks. The observed trend was a decline in strength of bricks exposed to NaCl environment. At the end of the 90 days exposure to NaCl, Nyamebekyre bricks fired at 900°C had highest reduction of 61.8% in cold crushing strength. These findings were consistent with those exposed to seawater.




Figure 4.16: Effect of exposure time on the cold crushing strength of burnt bricks produced

from different clay materials in 0.5 M NaCl

4.5.3 Effect of sulphate environment on apparent porosity and water absorption

Figure 4.17 shows the effect of exposure time on apparent porosity of burnt bricks produced from different clay materials in 0.5 M Na₂SO₄. Bricks produced at different temperatures have been compared. At 800°C, the apparent porosity of all the brick types decreased after the exposure period; Mfensi bricks decrease from 31.6% to 20.3%, Mankranso bricks decreased marginally from 26.8% to 26.7%, and Nyamebekyre bricks decreased from 22.3% to 20.3%. At 900°C, apparent porosities of Mfensi and Nyamebekyre bricks decreased by 43% and 24.4%, respectively whilst Mankranso bricks increased by 17.7% after 90 days exposure. Further increase in firing temperature to 1050°C increased the apparent porosities of Mfensi and Nyamebekyre bricks decreased the apparent porosities of Mfensi and 15.4%, respectively whilst Mankranso bricks decreased the apparent porosities of market by 3.7%. The decrease in apparent porosity values could be due to the partial filling of the pores and micro cracks by sulphate crystals (La Iglesia *et al.*, 1997).





Figure 4.17: Effect of exposure time on the apparent porosity of burnt bricks produced from different clay materials in 0.5 M Na₂SO₄

Figure 4.18 shows the effect of exposure time on the water absorption of burnt bricks produced from different clay materials in 0.5 M Na₂SO₄. Bricks produced at different temperatures have been compared. At 800°C, the water absorption for Mfensi bricks decreased by 30.4% whilst Nyamebekyre and Mankranso increased by 0.12% and 5.6%, respectively at the end of the 90 days exposure period. At 900°C, the water absorption of Mfensi and Nyamebekyre bricks decreased by 19.9% and 29.5%, respectively whilst Mankranso bricks increased by 9.0% after 90 days. At 1050°C, the water absorption of Mfensi and Mankranso bricks decreased by 15% and 9%, respectively while Nyambekyre bricks increased by 17.5% after 90 days of exposure.

The increase in water absorption values is due to the progressive disaggregation of the smaller pore walls as a result of pressure generated by the crystallization of sulphate salts. This allowed easy penetration of solution into the pore system increasing water absorption. The penetration and the residence of salts in the materials depend mainly on their pore structure (Benavente *et al.*, 2003). Studies carried out by Cultrone *et al.*, (2004) showed that abundant smaller pores exist within burnt clay bricks fired below 900°C. At 900°C and above when vitrification begins, the material becomes rigid. This favours breakage due to pressure generated by salt crystallization (Benavente *et al.*, 2003). This enhances greater penetration of sulphate solution accounting for the behaviour of bricks fired at 1050°C.





different clay materials in 0.5 M Na₂SO₄

4.5.4 Effect of sulphate environment on cold crushing strength

Figure 4.19 shows the effect of exposure time on the cold crushing strength of burnt bricks produced from different clay materials in 0.5 M Na₂SO₄. Bricks produced at different temperatures have been compared. At 800°C, the cold crushing strength of Mfensi, Mankranso and Nyamebekyre bricks decreased by 29.7%, 61.3% and 52.5%, respectively after 90 days of exposure period. Similar behaviour was observed in bricks fired at 900°C. The strength decreased by 31%, 36.9% and 39.9% in Mfensi, Mankranso and Nyamebekyre, respectively after 90 days exposure period. However, at 1050°C, the strength of Mfensi and Nyamebekyre bricks increased by 9.2% and 4.2%, respectively whilst Mankranso decreased by 4.3%.

The manufacturing processes such as moulding, higher firing temperatures and reductions in porosity bring about an increase in cold crushing strength. At firing temperatures of 800°C and 900°C, the strength values decreased after 7 days exposure period. This could be explained by initial superficial material loss and internal micro-cracks. Several factors could influence physical damage by salt crystallization. This includes moisture supersaturation, magnitude of the repulsive forces between the salts and the confining pore walls, rates of elements supply, water evaporation and the pore size (Scherer, 2004). It was observed that bricks fired at 800°C had highest percentage decrease in cold crushing strength whilst bricks fired at 1050°C exhibited greater resistance to deterioration.



Figure 4.19: Effect of exposure time on the cold crushing strength of burnt bricks produced

from different clay materials in 0.5 M Na₂SO₄

4.6 Comparism of Durability of Burnt Clay Bricks in Chloride and Sulphate Environments

Figure 4.20 compares the change in strength of burnt bricks fired at different temperatures after 90 days exposure in aggressive environments. Mfensi burnt clay bricks fired at 1050° C increased in strength in seawater and Na₂SO₄ by 10.4% and 35.4%, respectively. On the other hand, Mfensi bricks fired at 800 and 900°C had reduction in strength in all investigated environments with Na₂SO₄ having a more damaging effect. Nevertheless, the performances of bricks fired at 900°C were better than bricks fired at 800°C.

Mankranso burnt clay bricks fired at 1050°C also increased in strength in sea water and NaCl media by 18.2% and 14.0%, respectively. Bricks fired at 800 and 900°C had reduction in strength values in all environments with more damaging effect in Na₂SO₄. The results show that burnt bricks fired at high temperatures are more durable and have better chances of survival in aggressive environments than bricks fired at low temperatures. Nyamebekyre burnt clay bricks also showed similar behaviour with bricks fired at 1050°C demonstrating high durability in seawater and NaCl media. It can therefore be concluded that brunt bricks fired at high temperatures have high durability in aggressive environments.





Figure 4.20: Change in strength of burnt bricks fired at different temperatures after 90 days

exposure in aggressive environments. Negative values signify increase in strength

Figure 4.21 shows the change in strength of burnt bricks produced at 1050°C after 90 days exposure in different environments. Mfensi clay performed well in seawater and Na₂SO₄ environments but not NaCl. Likewise Mankranso and Nyamebekyre burnt bricks performed well in seawater and NaCl but not Na₂SO₄.



Figure 4.21: Change in strength of burnt bricks produced at 1050°C after 90 days exposure in aggressive environments. Negative values signify increase in strength

4.7 Visual Inspection

After curing samples in the various solutions for 90 days efflorescence test was carried out and visual observations made. Through observation, efflorescence and salt deposition were identified. Efflorescence caused samples to disintegrate especially at the edges. Images of efflorescence samples are shown in Figure 22. Efflorescence depends on several factors which include temperature, the supersaturation of the solution and the behaviour of fluids inside the pores (Rodríguez-Navarro et al., 1996).



Figure 4.22: Images of burnt bricks before (a) and after (b) exposure to seawater showing

efflorescence

Table 4.4 shows the efflorescence classification of burnt bricks after exposure in the various aggressive environments. The classification is based on IS 3495-1 scheme. The efflorescence test shows that bricks fired at 1050°C performed well in selected environments. This is in agreement with earlier findings under sections 4.5 and 4.6.

Table 4.4: Efflorescence classification of burnt bricks after 90 days exposure in NaCl,

NaCl									
Clay type	800°C	900°C	1050°C						
Mfensi	Serious	Heavy	Moderate						
Mankranso	Serious	Serious	Heavy						
Nyamebekyre	Heavy	Heavy	Moderate						
	Na	2SO ₄	7						
Clay type	800°C	900°C	1050°C						
Mfensi	Serious	Serious	Moderate						
Mankranso	Serious	Serious	Heavy						
Nyamebekyre	Serious	Heavy	Moderate						
	Sea	water							
Clay type	800°C	900°C	1050°C						
Mfensi	Serious	Heavy	Moderate						
Mankranso	Serious	Serious	Heavy						
Nyamebekyre	Serious	Serious	Moderate						

Na₂SO₄ and seawater

CHAPTER FIVE

CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

The durability of Mfensi, Mankranso and Nyamebekyre clays fired at 800°C, 900°C and 1050°C have been investigated. Properties of burnt clay bricks produced in the laboratory were compared with burnt bricks commercially available on the market. Salt attack tests were carried out on burnt bricks by curing in seawater, sodium chloride (0.5 M NaCl) and sodium sulphate (0.5 M Na₂SO₄) solutions for 7, 15, 30, 60 and 90 days after which some properties were measured. The following conclusions were drawn based on the results:

- The chemical and mineralogical composition of the clays tested show high presence of quartz (SiO₂). Mfensi clay had the highest plasticity index (34.5%) followed by Mankranso (16.7%) and Nyamebekyre (13.1%), respectively. Mfensi clay was more clayey with smaller particle size as compared to Mankranso and Nyamebekyre.
- The cold crushing strength values of laboratory-produced burnt bricks were higher than that produced commercially. Variations in other properties were also observed, with laboratory-produced bricks having better properties than commercially available bricks. It was observed that increasing the firing temperature improves the properties of the burnt bricks.
- Generally, the results show that burnt bricks fired at high temperatures are more durable and have better chances of survival in aggressive environments than bricks fired at low temperatures. Mfensi clay had higher SiO₂ confirmed by its high quartz content when fired at 1050°C were durable in seawater and Na₂SO₄ but not in NaCl environment. Mankranso and Nyamebekyre bricks fired at 1050°C also performed very well in seawater and Na₂SO₄ media. The differences in durability

in the environments studied are due to variation in the chemical composition of the clays which resulted in different properties of burnt bricks. This also resulted in differences in salt attack mechanisms.

5.2 Recommendation

- In the selection of bunt clay bricks as a building material that will ensure durability, the manufacturing process plays a key role. For construction in aggressive environment, especially in areas of chloride attack, burnt clay bricks should be fired above 800°C preferably 1050°C to ensure brick durability.
- In the process of brick manufacture, modification of clay composition should be considered by blending clay types to obtain bricks that can withstand both chloride and sulphate attack.
- This study highlights tremendous lack of locally relevant research on brick durability. To ultimately confirm the above conclusions made in this study and to build locally relevant data on bricks in Ghana, further research should be carried out on this very vital and local construction material.

CMJCARS

REFERENCES

Álvarez De Buergo M., Limón T.G. (1994) Restauración de Edificios Monumentales, Estudio de materiales y técnicas instrumentals, Centro de Estudios Experimentación de Obras Públicas Madrid

American Society for Testing and Materials (1982), Annual Book of ASTM Standards, Part 17: Refractories, Glass, Ceramic Materials, Carbon and Graphite Products

American Society for Testing and Materials (2000), C62-00 Standard Specification for Building Brick (Solid Masonry Units Made from Clay or Shale), West Conshohocken, PA, USA

American Society for Testing and Materials (2000), C62-02c Method of Tests of Burnt Clay Building Bricks, Determination of Efflorescence, West Conshohocken, PA, USA

Amonoo-Neizer K. (1973) Asokwa Brick Project, products of bricks by hand moulding Techniques, Special Report SR/1/73, BRRI, Kumasi, Ghana. p.13

Arnold A. (1976) Behaviour of some soluble salts in stone deterioration, in Proceedings of 2nd International Symposium on the Deterioration of Building Stone, Athens (Greece), p. 27-36

Atiemo E. (1998) Clay as pozzolana for building purposes, *Journal of Building and Road research*, 2 (1&2), p.10 Australian Standard (1997) ASC4465.10 Test for determining Resistance to Salt Attack

Ayetey J. K. (1977) Clays and their evaluation for bricks manufacture; Ghana clay report, BRRI current note 11, p.42

Baronio G. Binda L. (1985a) Physico-mechanical characteristics and durability of bricks from some monuments in Milan, Masonry International, 4, p.29–35

Baronio G. Binda L. Charola A.E. (1985b) Deterioration of bricks with and without perforations due to salt crystallization. In: 7th international brick masonry conference, Melbourne, p.267–276

Basego T. Berutti F. Bernardes A. Bergmann C. P. (2002) Environmental and technical aspects of the utilization of tannery sludge as a raw material for clay products, J Euro Ceramics Soc, 22, p.2251-2259

Benavente D. Linares-Fernandez L. Cultrone G. Sebastian E. (2006) Influence of microstructure on the resistance to salt crystallization damage in brick, Journal of Materials and Structures, 39, p.105–113

Benevente D. Garcia del Cura M. A. Garica-Guinea J. Sanchez-Moral S. S. Ordonez S. (2004) Role of pore structure in salt crystallisation in unsaturated porous stone. Journal of Crystal Growth, 260, p532–544

Binda L. Baronio G. (2006) The durability of masonry in aggressive environments and techniques for its conservation and protection. In: Durability of Materials and Structures in Building and Civil Engineering, Yu, C. W., & Bull, J. W. (Eds.), CRC Press, USA, p.184-240

Binda L. Molina C. (1990) Building Materials Durability: Semi-Markov Approach, Journal of Materials in Civil Engineering, 2 (4), p.223-239

Binda L. Saisi A. Tiraboschi C. (2000) Investigation procedures for the diagnosis of historic masonries, Construction and Building Materials, 14, p.199-233

Bortz S. A. Marusin L. S. Monk C. B. Jr. (1990) A critical review of masonry durability standards. Proceedings of the 5th North American Masonry Conference, p.1523 -1536

Bourgeois J. L. (1987) The History of the Great Mosques of Djenné." African Arts, 20 (3) p.5463

British Standard Institution (1985) Specification for clay bricks, London (BS3921: 1985)

British Standard Institution (1985) Specification for precast concrete blocks, BS 2028,BSI, London.p.44

British Standard Institution (1990) Standard methods for test for soils or civil engineering purposes, B.S. 1377, B.S.I., London, p.62

Brocken H. Nijland T. (2004) White efflorescence on brick masonry: towards prediction of efflo-rescence risk, In: 13th international brick/block masonry conference, Amsterdam

Brownell, W. E. (1976) Structural clay products, New York, 1st Edition Springer-Verlag, p.1-5

Bruemner A. (2002) The origin and effect of cryptoflorescence of fired clay bricks, PhD Thesis, University of Leeds, United Kingdom

Bucea L. Sirivivatnanom V. Khatri R. (2005) Building materials deterioration due to salts attack laboratory experimental program, Internal Technical Report. CSIRO Manufacturing and Infrastructure Technology, CMIT, p.165

Buchwald A. Kaps C. (2000) The ion mobility of deteriorating salts in masonry materials of different moisture content, Materials for Building and Structures, Euromat 99, 6, p.157-162

Cardiano P. Ioppolo S. Stefano C. Pettignano A. Sergi S. Piraino P. (2004) Study and characterization of the ancient bricks of monastery of "San Filippo di Fragalà" in Frazzanò (Sicily), Ana-lytica Chimica Acta, 519 (1), p.103–111

Carrie C. Morel D. (1975) Salissures des façades, Eyrolles, Paris

Charola A. E. Lazzarini, L. (1986) Deterioration of brick masonry caused by acid rain, Am. Chem. Soc., p.250–258 Collepardi M. (1990) Matter. Struct. 23, p.81-102

Cultrone G. De La Torre M. J. Sebastian E. M. Cazalla O. Rodriguez-Navarro C. (2000) Behavior of brick samples in aggressive environments, Water Air and Soil Pollution, 119, p.191–207

Cultrone G. Sebastián E. Elert K. de la Torre M. J. Cazalla O. Rodriguez–Navarro C. (2004) Influence of mineralogy and firing temperature on the porosity of bricks, J Euro. Ceram. Soc., 24, p.547-564

Cultrone, G. Rodriguez-Navarro C. Sebastián Pardo E. Cazalla O. de la Torre López M. J. (2001) Carbonate and silicate phase reactions during ceramic firing, European Journal of Mineralogy, 13, p.621–634

Cultrone, G. Sebastian E. Cazalla O. de la Torre López M. J. (1998) Physical, mineralogical and textural features of ceramic clays from Granada Province (Spain), in: C.S.F. Gomes (Ed.), Proceedings of the Second Mediterranean Clay Meeting, Aveiro, Portugal, 16–19 September, p.298–303

Delbrouck O. Janssen J. Ottenburgs R. Van Oyen P. Viaene W. (1993) Evolution of porosity in extruded stoneware as a function of firing temperature, Applied Clay Science, 8, p.187– 192 DeVekey R. C. (2006) The durability of masonry mortar, stone and ancillary components, In: Durability of material and structures in building and civil engineering, Scotland, United Kingdom, p.246 – 267

Edgell G. (2005) Material Testing; The testing of ceramics in construction; Whittles Publishing. Scotland. p.17 – 42

Elert K. Cultrone, G. (2003) Durability of bricks used in the conservation of historic buildings –influence of composition and microstructure, Journal of Cultural Heritage, 4(2), p.91-99

EN10545-3:1995 - Ceramic tiles - Part 3: Determination of water absorption, apparent porosity, apparent relative density and bulk density. CEN

Esbert R. M. Montoto M. Ordaz J. (1991) Mater. Construcción, 41(221), p.61-73

Espinoza R. M. Franke L. Deckelmann G. (2008) Phase change of salts in porous materials: crystalization hydration and deliquescence, Journal of Construction and Building Materials, 22, p.1758-1773

Evans J. L. White J. (1958) Further studies of the thermal decomposition of clays. Brit. Ceram. T., 57(298), p.1969-1970

Fahey B. D. (1986) A comparative laboratory study of salt crystallisation and salt hydration as potential weathering agents in deserts, Geogrfiska Annaler, 68A, p.107-111

Fernandes F. Lourenco P. B. (2007) Evaluation of the compressive strength of ancient clay bricks using micro-drilling, Journal of Materials in Civil Engineering, 19(9), p.791- 800

Fitzner B. Snethlage R. (1982) Einfluss der Porenradien-verteilung auf das Verwitterungsverhalten ausgewahlter Sandsteine, Bautenschutz Bausanierung, 3 p.97-103

Gravaglia E. Lubelli B. Binda L. (2000) Comparison between two different probabilistic approaches in the modelling of the masonry wall deterioration, 12th IBMeC, Madrid-Spain

Gurevich M. (2005) Water penetration through exterior walls: weep holes provide the best protection against serious problem, Masonry Construction. New York

Heathcote K. A. (1995) Constr. Building Mater., 9, p.185–189

Hendry A. W. Khalaf F. M. (2001) Masonry wall construction London

Ibrahim H. H. Hodhod H. A. Youssy M. A. R. (2006) Durability, drying shrinkage and physical properties of mortars used in restoration of historical buildings in Egypt, *1st International Structural Speciality Conference, Calgary, Alberta , Canada*

Ibrahim Mohd Haziman B Wan (2011) Engineering properties and microstructure of brickwork under aggressive environment, Research Paper

Jordan J. W. (2001) Factors in the selection of mortar for conservation of historic masonry, 6th Australasian Masonry Conference, Adelaide, Australia

Jordan M. M. Boix A. T. Sanfeliu C. de la Fuenta, (1999) Firing transformation of cretaceous clays used in the manufacturing of ceramic tiles, App Clay Sci, 14, p.225-234

Kesse G. O. (1985) The mineral and rock resources of Ghana. AA Rotterdam, p.437-439

Kirkandale G. A. (1975) A laboratory manual for testing clays for use in the production of building products, Special report No. 6, Journal of Building and Road Research, 6., B.R.R.I., Kumasi, p.1

Knofel D. K. Hoffman D. Snethlage R. (1987) Physicochemical weathering reactions as a formulary for time lapsing ageing tests, Mater. Struct., 20, p.127-145

Kostof S. (1995) A History of Architecture – Settings and Rituals, Oxford University Press, p.46, 50

Laird R. T. Worcester M. (1956) The inhibiting of lime blowing, Transaction of the British Ceramic Society, 55, p.545–563

Lee S. T. Swamy R. N. Kim S. S. Park Y. G. (2008) Durability of mortars made with recycles fine aggregates exposed to sulphate solutions, J Materials in Civil Engineering, 20(1), p.63-70

Lewin S. Z. (1982) The mechanism of masonry decay through crystallization. In: Conservation of Historic Stone Buildings and Monuments, National Acad. Press, Washington, D.C., p.120-144

López-Arce P. Garcia-Guinea J. Gracia M. Obis J. (2003) Bricks in historical buildings of Toledo City: Characterization and restoration, Materials Characterization, 50, p.59–68

Lubelli B. van Hees R. P. J. Groo J. W. P. (2004) Construction and Building Materials, 18, p.119–124

Mamillan M. (1979) Méthodes d'essais au gel des pierres, Problems Raised by Frost Action. In: 6th international congress of the fondation française d'Etudes Nordiques, Le Havre, p.225–238

McConville C. J. Lee W. E. (2005) Microstructural development on firing illite and smectite compared with that in kaolinite, J. Am. Ceram. Soc., 88, p.2267-2277

Mehta P. K. Monteiro P. J. M. (2006) Concrete—Microstructure, Properties, and Materials. A New York, NY: McGraw Hill

Ministry of Finance (2007) Budget statement and economic policy of the government of Ghana for the 2007 financial year, Accra, p.8

Ministry of Trade and Industry (2005)

Ministry of trade and Industry (2010)

Ministry of Works and Housing (2005)

Moropoulou A. Christaras B. Lavas G. Penelis G. Zias N. Biscontin G. Kollias E. Paisios A. Theoulakis P. Bisbikou K. Bakolas A. Theodoraki A. (1993) Weathering phenomena on the Hagia Sophia Basilica, Konstantinople. In: Brebbia CA (ed) Structural repair and maintenance of historical buildings III. WIT Press Publications, Southampton, UK, p.47–66

Navarro, C. R. Doehne E. (1999) Salt weathering: influence of evaporation rate, supersaturation and crystallization pattern, Earth Surf. Process. Landforms, 24, p.191–209

Nwobodo C. S. Davies T. J. (2000) The effect of apparent porosity on the modulus of rupture of alumina-chromia refractory matrix, A Paper Presented at FUTO 2000, Annual Conference of NAMMES. p.8

Obeng K. (1993) Study of properties of some Ghanaian clays used for the production of bricks, Journal of Building and Road Research, 1&2. B.R.R.I, Kumasi, p.12-14

Orts M. J. Escardino A. Amoro´s J. L. Negre, F. (1993) Microstructural changes during firing of stoneware floor tiles, Applied Clay Science, 8, p.193–205

Ottosen L. M, Pedersen A. J. Inge R. (2007) Salt-related problems in brick masonry and electro kinetic removal of salts, Journal of Building Appraisal, 3(3), p.181–194

Papayianni I. Stefanidou M. (2000) Characteristics of bricks of Byzantine period. In: 12th interna-tional brick/block masonry conference, Madrid, p.1729–1736

Pauri M. Stazi A. Mastrosanti F. D'Orazio M. (1994) The decay of ancient building masonry, a case study. In: 10th international brick/block masonry conference, Calgary, p.1295–1304

Peters T. Iberg R. (1978) Mineralogical changes during firing of calcium-rich brick clays, Ceramic Bulletin, 57(5), p.503–509

Philips D. N. Zsembery S. (1982) Assessment of the salt attack resistance of fired clay bricks, Clay Brick and Paver Institute (CBPI). Research Paper 8

Rijineers L. A. Pel L. Huinink H. P. Kopinga K. (2005) Salt crystallization as damage mechanism in porous building materials - A nuclear magnetic resonance study, Journal of Magnetic Resonanace Imaging, 23, p.273-276

Robinson G. Borchelt J. (1994) Characterization of bricks and their resistance to deterioration mechanisms, In: 10th international brick/block masonry conference, Calgary, p.1295–1304

Rörig-Dalgaard I. Ottosen L. M. (2012) Diffusion and electro migration in clay bricks influenced by differences in the pore system resulting from firing, Journal of Construction Building Materials, 27(1), p.390-397

Rye O. S. (1976) Arch. Phys. Anthrop. in Oceania11, p.106–137

Scherer G. W. (2004) Stress from crystallization of salt. Cement and Concrete Research, 34(9), p.1613-1624

Scrivener K. L. Kirk P. R. J. (2007) Innovation in use and research on cementitious material, In: 12th International congress of chemistry of cement, Montreal, Canada

Sperling C. H. B. Cooke R. U. (1980) Salt weathering in arid environments II. Laboratory Studies, Papers in Geography No. 9

Spry A. (1990) The Chemistry of Salt Attack in Masonry, "Amdel Technical Notes, p.3

Surej R. K. (1998) Development of New Durability Index for Clay Brick, *Journal of Architechtural Engineering, pg* 87-93T. Stambolov, "The Corrosive Action of Salts," Lithoclastia 1976, p.

Taylor M. Tam C. Gielen D. (2006) Energy efficiency and CO₂ emissions from the global cement industry. In: International Energy Agency - World Business Council for Sustainable Development Workshop Energy Efficiency and CO₂ emission Reduction Potentials and Policies in the Cement Industry, Paris, France

Tite M. S. Maniatis Y. (1975) Examination of ancient pottery using the scanning electron microscope, Nature, 257, p.122–123

Van Hees R. P. J. Brocken H. J. P. (2004) Damage development to treated brick masonry in a long-term salt crystallization test, Journal of Construction and Building Materials, 18, p.331–338

Vekey R. C. (1998) Brickwork and blockwork, In: Illston J. M. (ed) Construction materials their nature and behaviour. E & FN SPON, London, p.251–315

Vitruvius Pollio M. (1960) The ten books on architecture. (MH Morgan, Trans.) Courier Dover Publications, New York World Business Council for Sustainable Development (WBSCD) (2005). The cement sustainability initiative progress report) Weaver ME (1997) Architectural ceramics. Conserving buildings—a manual of techniques and materials. Wiley, New York, p.99–132

Weng C. H. Lin D. F. Chiang P. C. (2003) Utilization of sludge as brick materials, Adv Environ Res, 7, p.697-685

Winslow D. N. Kilgour C. L. Crooks R. W. (1988) Predicting the durability of bricks. ASTM Journal of Testing and Evaluation, 16(6), p.527–531

Young D. (1995) Rising damp and salt attack. Department of Environment and Natural Resource, Adelaide, Australia

Zsembery S. (2001) Manual 2: The Properties of *Clay Masonry Units, Clay Brick and Paver Institute* (CBPI), Australia

APPENDIX A

PROPERTIES OF CLAY MATERIALS

Table A1: Specific gravity, Atterberg limit, (%) particle size analysis (%) results of clay

samples investigated

ID	Specific Gravity	ATTERBERG LIMITS TEST, (%)			PARTICLE SIZE ANALYSIS (HYDROMETER) (%)				REMARKS	
	Grunny	W_L	W_P	I_P	Clay (C)	Silt (M)	Sand (S)	Gravel (G)		
Mankranso	2.64	38.9	22.4	16.5	25	47.0	27.5	0.5	Clayey, Sandy SILT with traces of Gravel	
Mfensi	2.40	68.9	34.4	34.5	46.2	35.8	18.0	7	Sandy, Silty GRAVEL	
Nyamebekyre	2.77	28.4	15.3	13.1	19.0	37.0	42.0	2.0	Clayey, Silty SAND with some Gravel	



APPENDIX B

PROPERTIES OF BURNT CLAY BRICKS

	cold crushing		Bulk density		A. porosity		W. Absorption		Total Shinkage	
temp:800		s/d		s/d		s/d		s/d		s/d
CLAY										
Mfensi	1.284175	0.171592	3.33336	1.98773	31.64086	5.007732	14.06018	2.773189	7.666667	4.515406
Makra	1.206229	0.2406	1.914813	0.056521	26.78834	3.501159	14.07629	5.714969	3.166667	1.105542
Nyamebe	1.611593	0.196933	1.718501	0.182163	22.34287	3.302386	13.01222	1.730262	4.833333	1.333333
	cold cr	ushing	Bulk d	ensity	A. porosity		W. Absorption		Total Shinkage	
temp:900		s/d		s/d		s/d		s/d		s/d
CLAY										
Mfensi	2.004832	0.378835	1.998068	0.068602	50.51923	4.182205	21.87494	1.822492	4	1.224745
Makra	1.250104	0.305476	1.614148	0.19 <mark>9486</mark>	20.95572	3.744047	13.29313	1.870979	3.5	1.699673
Nyamebe	1.935567	0.125181	1.559555	0.11571	19.96242	2.916769	12.69538	1.542267	3.833333	1.452966
					19					
			_							
	cold cr	ushing	Bulk d	ensity	A. porosity		W. Absorption		Total Shinkage	
temp:1050		s/d		s/d	K	s/d	17	s/d		s/d
CLAY						23				
			1			LSS?	S			
Mfensi	2.020365	0.174873	2.409155	0.116023	21.34567	2.098128	13.17145	1.167722	4.666667	1.870829
Makra	1.102736	0.204235	1.66686	0.193629	21.37893	3.127686	12.53734	0.711119	3.5	0.816497
Nyamebe	1.538567	0.256527	1.652933	0.414203	16.66463	3.328823	10.15285	0.610427	4.833333	1.333333

W CONTRA

Table B1: Properties of burnt bricks produced in the laboratory

	cold cr	ushing	Bulk d	ensity	A. po	A. porosity		orption	Total Shinkage		
temp:800		s/d		s/d		s/d		s/d		s/d	
CLAY											
Mfensi	0.762576	0.079287	1.661469	0.009759	24.72132	4.124831	14.89429	2.570129	2.833333	0.849837	
Makra	0.861576	0.225678	1.719228	0.001905	26.27339	3.260068	15.2842	3.260068	2.333333	0.62361	
Nyamebe	0.813213	0.047535	1.867238	0.070381	29.46155	0.223245	15.79609	0.475834	4.833333	1.333333	
	cold cr	ushing	Bulk d	ensity	A. po	rosity	W. Absorption		Total Shinkage		
temp:900		s/d		s/d		s/d		s/d	s/d		
CLAY											
Mfensi	1.831398	0.151918	2.081846	0.083187	36.83895	2.559718	17.67442	0.523299	4.333333	2.198484	
Makra	0.888681	0.169844	1.749891	0.039118	30.05013	0.432275	17.18669	0.63123	2.166667	0.666667	
Nyamebe	1.436046	0.183649	1.861492	0.054169	22.0473	4.689481	11.92729	2.866288	3.833333	1.452966	
					A C						
	cold cr	ushing	Bulk d	Bulk density		A. porosity		W. Absorption		Total Shinkage	
temp:1050		s/d		s/d		s/d		s/d		s/d	
CLAY											
Mfensi	2.230099	0.242472	1.719701	0.014622	26.32327	1.356815	15.3147	0.9192	4.333333	1.527525	
Makra	1.303023	0.287428	1.82798	0.072966	21.26659	0.152924	11.65585	0.548913	2.833333	0.408248	
Nyamebe	1.587519	0.060309	1.641385	0.01162	21.05067	0.372876	12.82719	0.317982	4	1.224745	

Table B2: Properties of burnt bricks after 90 days exposure in seawater



	cold cr	ushing	Bulk d	3ulk density A. porosity W. Absorption Total S		W. Absorption		Total S	ninkage	
temp:800		s/d		s/d		s/d		s/d		s/d
CLAY										
Mfensi	0.903338	0.054386	1.706472	0.005644	18.02645	0.930014	10.56549	0.579936	2.833333	0.849837
Makra	0.789155	0.078099	1.584933	0.054446	26.34346	4.376283	14.8825	2.566191	2.333333	0.62361
Nyamebe	1.19263	0.054733	1.499731	0.138992	23.28703	3.29585	13.05995	2.090055	4.833333	1.333333
	cold cr	ushing	Bulk density		A. porosity		W. Absorption		Total Shinkage	
temp:900		s/d		s/d	s/d			s/d	s/d	
CLAY						_				
Mfensi	1.382702	0.115051	1.753948	0.007262	37.59501	4.048253	21.42532	2.21937	4.333333	2.198484
Makra	0.812674	0.055316	1.58278	0.027378	26.64138	3.036312	16.80386	1.627678	2.166667	0.666667
Nyamebe	0.739659	0.476581	1.70922	0.012478	7.173614	2.425694	4.207594	1.449898	3.833333	1.452966
	cold cr	ushing	Bulk d	ensity	A. po	rosity	W. Absorption		Total Shinkage	
temp:1050		s/d		s/d		s/d	s/d			s/d
CLAY										
Mfensi	1.834028	0.153844	1.706472	0.005644	18.02645	0.930014	10.56549	0.579936	4.333333	1.527525
Makra	1.257255	0.165536	1.619223	0.017644	19.93926	1.546652	12.32597	1.089496	2.833333	0.408248
Nyamebe	1.381953	0.093863	1.617162	0.014451	15.22178	0.589533	9.416662	0.448693	4	1.224745

Table B3: Properties of burnt bricks after 90 days exposure in 0.5 NaCl



	cold cr	ushing	Bulk d	ensity	A. po	rosity	W. Abs	orption	Total Shinkage	
temp:800		s/d		s/d		s/d		s/d		s/d
CLAY										
Mfensi	0.650304	0.150693	1.906193	0.021562	18.66947	0.142704	9.796214	0.185675	2.833333	0.849837
Makra	0.593009	0.16676	1.799259	0.052496	26.68439	1.641093	14.87004	1.345952	2.333333	0.62361
Nyamebe	1.087034	0.30027	1.571017	0.037179	20.31514	5.998201	13.02885	4.126374	4.833333	1.333333
	cold cr	ushing	Bulk d	ensity	A. porosity		W. Absorption		Total Shinkage	
temp:900		s/d		s/d		s/d		s/d	s/d	
CLAY										
Mfensi	1.469113	0.165512	1.64392	0.006365	28.79321	0.45096	17.5163	0.342137	4.333333	2.198484
Makra	0.788534	0.037443	1.701587	0.001403	24.66163	1.084222	14.49385	0.649131	2.166667	0.666667
Nyamebe	1.163311	0.295366	1.69285	0.038898	15.06466	3.839451	8.955836	2.473828	3.833333	1.452966
	cold cr	ushing	Bulk d	ensity	A. po	rosity	W. Absorption		Total Shinkage	
temp:1050		s/d		s/d		s/d		s/d		s/d
CLAY										
Mfensi	2.135225	0.461192	1.804911	0.011296	27.35823	3.433343	15.14635	1.807434	4.333333	1.527525
Makra	1.05631	0.293639	1.626648	0.002863	19.57834	0.81898	12.03693	0.524666	2.833333	0.408248
Nyamebe	1.474238	0.361979	1.608168	0.030124	19.22373	1.788711	11.93716	0.888661	4	1.224745

Table B4: Properties of burnt bricks after 90 days exposure in $0.5 \text{ M} \text{ Na}_2 \text{SO}_4$

