THERMOPHYSICAL PROPERTIES OF SELECTED CASH CROPS GROWN IN GHANA

BY

KNUST

Prof Ato Bart-Plange

(MSc. Agricultural Engineering)

A Thesis submitted to the Department of Agricultural Engineering, Kwame Nkrumah University of Science and Technology in partial fulfilment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

PhD, Food and Postharvest Engineering

College of Engineering

August, 2014

CERTIFICATION

This is to certify that this thesis is the candidate's own account of his research

Prof. Ato Bart-Plange

……………………	………………………..	…………………
Student Name	**Signature**	**Date**

KNUST

Certified by Supervisors:

Prof. K. A. Dzisi	………………………..	…………………
Prof. A. Addo	………………………..	…………………
	Signature	**Date**

Certified by Head of Department:

Prof. S. K. Agodzo	…………………….	…………………
	Signature	**Date**

ABSTRACT

In this thesis, the influence of moisture on selected physical, compressive and thermal properties of cocoa beans, shea and cashew nut and kernel were studied. Standard methodologies that have been accepted internationally and used by several researchers globally were used for the determination of the selected properties in moisture content ranges normally used for the postharvest processing of the selected crops.

The results of moisture variation on physical properties of cocoa beans and cashew kernels such as 1000-bean mass, true density, porosity, emptying angle of repose and static coefficient of friction showed increasing trends with linear relationships while bulk density decreased linearly for cocoa bean and cashew kernel samples.

The compressive strain and Young's Modulus for cocoa beans decreased linearly with moisture from 0.009 to 0.0045, and 1300 to 205 MPa respectively. However the compressive stress decreased exponentially with increasing moisture content from 1.5 - 0.3 MPa while the crushing energy had more positive linear function with moisture content and increased from 0.013 - 0.2 J. For shea kernel, compressive stress, compressive strain and Young's Modulus decreased linearly from 2.0 - 0.8 MPa, 0.0085 - 0.002 mm/mm and 2000 – 100 MPa with increasing moisture content. Crushing energy increased non-linearly from 0.005 - 0.13 mJ in the moisture content range of 5% - 24% w.b. The compressive stress, strain, and Young's modulus for the cashew kernel increased from 0.214 - 1.214 MPa, 0.355 - 0.472 mm/mm, and 2.446 - 6.416 MPa respectively as moisture content increased from 5.0 - 9.0% wb.

Thermal conductivity increased linearly for ground cocoa beans sample from 0.0243 - 0.0311 W/^{o}Cm and for ground shea kernels from 0.0165 - 0.0458 W/^{o}Cm in the moisture content range of 12.59 - 43.84%w.b. at a constant bulk density of 295 kg/m^3. Specific heat, thermal conductivity and thermal diffusivity for ground cashew kernel were found to increase linearly from 1586 – 1756 J/kgº., 0.2103 - 0.2296 W/mK and 2.369×10^{-7} - 2.588×10^{-7} m^2/s with increasing moisture content from 5.0 - 9.0% w.b.

Keywords: Cocoa beans, shea kernel, cashew kernel, physical properties, compressive properties, thermal properties, moisture content.

Contribution to Science and Technology

From this study, the following have been established and therefore added onto the scientific knowledge on engineering properties of food materials:

1. The publication on the physical properties of cocoa beans has been cited by 96 related articles as found in google thus contributing to information on physical properties of food grains.
2. The findings on crushing energy provide useful information for food and agricultural engineers in the design of suitable cocoa beans, shea and cashew nut crackers.
3. In a bid to mechanize the various unit operations involved in the postharvest processing of shea and cashew kernel, information and data on the behaviour of these strength properties as a function of moisture is needed. These data when utilised fully will not only save energy but will promote the design and development of effective and efficient processing machines.
4. Attempts have been made to optimize the drying process and to minimize internal cracking during drying of food grains with the aid of mathematical and numerical drying models, but estimation of the thermal properties of the material being dried, is also required. Data generated on specific heat, thermal conductivity, thermal diffusivity could be used in the analysis of drying processes and storage conditions.

Publications from Candidate's Work

1. Bart-Plange, A., Dzisi, K. A., Addo, A., Teye, E. and Kumi, F. (2012). A comparative study of some physical properties of large and medium size Cocoa beans from Ghana. *ARPN Journal of Science and Technology. 2(3): 135-141*, *March.www.ejournalofscience.org. ISSN NO.: 2225-7217.*

2. Bart-Plange, A. P. Mohammed-Kamil, A. Addo and E. Teye (2012). Some Physical and Mechanical Properties of Cashew Nut and Kernel Grown in Ghana. *International Journal of Science and Nature (IJSN). 3(2): 406-415, May 2012.www.scienceandnature.org.* ISSN NO.: 2229-6441.

3. Bart-Plange, A., Addo, A., Abano, E.E. and Akowuah, J.O. (2012). Compressive Properties of Cocoa Beans Considering the Effect of Moisture Content Variations. *International Journal of Engineering and Technology (IJET UK). 2(5): 850-858* http:/www.iet-journals.org. ISSN NO.: 2049-3444.

4. Bart-Plange, A. Addo, J. O. Akowuah and J. Ampah (2012). Some moisture dependent compressive properties of Shea Kernel (vitellaria Paradoxa L). *Canadian Journal of Pure and Applied Sciences (CJPAS), 6(3): 2113-2119*, www.cjpas.net. *ISSN NO.: 1920-3853.*

5. Bart-Plange, A. Addo, F. Kumi, and A. K. Piegu (2012). Some moisture dependent thermal properties of Cashew kernel (*Anarcardium occidentale L.*). *Australian Journal of Agricultural Engineering. AJAE 3(2): 65-69.* ISSN NO.: 1836-9448.

6. Bart-Plange, A. Addo, S. K. Amponsah and J. Ampah (2012). Effect of Moisture, Bulk Density and Temperature on Thermal Conductivity of Ground Cocoa Beans and Ground Sheanut Kernels. *Global Journal of Science Frontier Research (GJSFR). 12(8).* ISSN NO.: 2249-4626.

ACKNOWLEDGEMENTS

I render my profound gratitude to the Almighty God for His abundant grace towards me.

I would like to acknowledge the contributions of Professors K. A. Dzisi and A. Addo, my supervisors for their guidance and invaluable advice through all the stages of this work.

Special thanks go to all staff of the Department of Agricultural Engineering for creating the enabling environment for me to work and to my past dedicated students for their assistance in various stages of this work.

I would also like to acknowledge the Kuapa Kokoo Limited, a cocoa buying agency in Kumasi, for providing cocoa bean samples which had been prepared to international quality standards for the study.

The contributions of the Forest Research Institute of Ghana and the Physics Department of the Kwame Nkrumah University of Science and Technology for providing access to their laboratories to conduct experiments on compression and thermal properties of samples used are acknowledged.

I acknowledge all my friends for their prayers and support in diverse ways which has brought me this far.

The efforts of my parents late Joseph Minnow Bart-Plange and Mrs Ellen Bart-Plange who made great sacrifices towards my education is gratefully acknowledged. I wish also to thank my siblings (Joe, Willie, Emmanuel, Henry, Eunice and Joyce) for their love and cooperation.

Finally I would like to acknowledge the love, support and encouragement of my wife Patience and my daughters Esme and Amy during all these years.

KNUST

DEDICATION

To the Glory of God and

To my wife and daughters:

Patience, Esme and Amy Bart-Plange

KNUST
NYANSAPƆ WƆSANE NO BADWENIMA

TABLE OF CONTENTS

CERTIFICATION ii

ABSTRACT iii

Contribution to Science and Technology iv

Publications from Candidate's Work...v

ACKNOWLEDGEMENTS vi

DEDICATION vii

TABLE OF CONTENTS viii

LIST OF TABLES...xvi

LIST OF FIGURES.. xvii

CHAPTER ONE 1

1.0 INTRODUCTION 1

1.1 Background of study 1

1.1.1 Crops in Focus 1

1.2 Engineering properties 3

1.2.1 Physical properties 5

1.2.2 Compressive properties 7

1.2.3 Thermal Properties 7

1.3 Problem Statement 8

1.4 Aim and Objectives of research 10

1.4.1 Specific Objectives...10

1.5 Research Questions 11

1.6 Justification of the objectives 11

1.7 Limitations of the Research 11
1.8 Organisation of the Research 12

CHAPTER TWO 13
2.0 LITERATURE REVIEW 13
2.1 Background to the study 13
2.2 Cash crops used for the study 13
2.2.1 Cocoa 13
2.2.2 Shea 15
2.2.3 Cashew 17
2.3 Physical properties 19
2.3.1 Physical attributes 21
2.3.2 1000-Bean Weight 25
2.3.3 Bulk Density 26
2.3.4 True Density 26
2.3.5 Porosity 27
2.3.6 Angle of repose 28
2.3.7 Coefficient of static friction 29
2.4 Mechanical properties 30
2.4.1 Force Deformation characteristics 31
2.4.2 Stress-Strain 32
2.4.3 Modulus of Elasticity 34
2.5 Thermal Properties 34
2.5.1 Specific Heat 35

2.5.2 Thermal Conductivity 36
2.5.3 Thermal Diffusivity..39
2.6 Moisture Content 40
2.6.1 Methods of Measuring Moisture Content 41
2.7 Effect of Moisture Content on Engineering Properties 42
2.8 Concluding Remarks 43

CHAPTER THREE...43
3.0 A COMPARATIVE STUDY OF SOME PHYSICAL PROPERTIES OF LARGE AND MEDIUM SIZE COCOA BEANS FROM GHANA 44
3.1 INTRODUCTION...45
3.2 MATERIALS AND METHODS..48
3.2.1 1000 bean mass 48
3.2.2 Bulk density 48
3.2.3 Filling and emptying angles of repose 48
3.2.4 Co-efficient of static friction 49
3.3 RESULTS AND DISCUSSION 50
3.3.1 Bulk Density 50
3.3.2 Emptying Angle of Repose 51
3.3.3 Filling Angle of Repose 53
3.3.4 1000- Bean Mass...54
3.3.5 Co-Efficient Of Static Friction...55
3.4 CONCLUSION 59
3.5 REFERENCES...59

CHAPTER FOUR 62

4.0 SOME PHYSICAL AND MECHANICAL PROPERTIES OF CASHEW NUT AND KERNEL GROWN IN GHANA 62

4.1 INTRODUCTION 63

4.2 MATERIALS AND METHODS 65

4.2.1 Sample Preparation 65

4.2.2 Experimental Procedures 67

4.3 RESULTS AND DISCUSSION 69

4.3.1 Physical Properties 69

4.3.2 Mechanical properties 76

4.4 CONCLUSIONS 81

4.4.1 Physical properties 81

4.4.2 Mechanical properties 82

4.5 REFERENCES 83

CHAPTER FIVE 87

5.0 COMPRESSIVE PROPERTIES OF COCOA BEANS CONSIDERING THE EFFECT OF MOISTURE CONTENT VARIATIONS 87

5.1 INTRODUCTION 87

5.2 MATERIALS AND METHODS 89

5.2.1 Sample preparation 89

5.2.2 Determination of physical properties 91

5.2.3 Compression test 91

5.2.4 Data analysis 92

5.3 RESULTS AND DISCUSSION 92

5.3.1 Linear Dimensions of test specimen 92
5.3.2 Displacement at Maximum Load 93
5.3.3 Compressive Stress and Strain 94
5.3.4 Young's Modulus and Crushing Energy 96
5.4 CONCLUSION 98
5.5 REFERENCES 98

CHAPTER SIX 102
6.0 COMPRESSIVE STRENGTH OF SHEA KERNEL WITH MOISTURE CONTENT VARIATION 102
6.1 INTRODUCTION 103
6.2 MATERIALS AND METHODS 106
6.2.1 Preparation of Sample 106
6.2.2 Determination of principal dimensions 107
6.2.3 Determination of compressive properties 107
6.3 RESULTS AND DISCUSSION 109
6.3.1 Size and shape dimensions 109
6.3.2 Displacement at maximum load 110
6.3.3 Compressive stress 111
6.3.4 Compressive strain 112
6.3.5 Young's modulus 112
6.3.6 Crushing energy 114
6.3.7 Engineering implications 115
6.4 CONCLUSIONS AND RECOMMENDATION 115

KNUST

6.5 REFERENCES 116

CHAPTER SEVEN.. 122

7.0 SOME MOISTURE DEPENDENT THERMAL PROPERTIES OF CASHEW KERNEL (*ANARCARDIUM OCCIDENTALE L*.).. 122

7.1 INTRODUCTION 123

7.2 MATERIALS AND METHODS 124

7.2.1 Materials.. 124

7.2.2 Sample Preparation 124

7.2.3 Bulk Density Determination 126

7.2.4 Determination of Thermal Properties.. 126

7.3 RESULTS AND DISCUSSION 129

7.3.1 Bulk Density 129

7.3.2 Specific Heat 130

7.3.3 Thermal Conductivity 131

7.3.4 Thermal Diffusivity.. 132

7.4 CONCLUSIONS 133

7.5 REFERENCES 133

CHAPTER EIGHT 139

8.0 EFFECT OF MOISTURE, BULK DENSITY AND TEMPERATURE ON THERMAL CONDUCTIVITY OF GROUND COCOA BEANS AND GROUND SHEANUT KERNELS 139

8.1 INTRODUCTION 140

8.2 MATERIALS AND METHODS 142

8.2.1 Sample Preparation 142

8.2.2 Experimental Setup 143

8.2.3 Thermal Conductivity Determination 144

8.2.4 Statistical Analysis 144

8.3 RESULTS AND DISCUSSION 145

8.3.1 Effect of Moisture Content..145

8.3.2 Effect of Bulk Density 146

8.3.3 Effect of Temperature..148

8.4 CONCLUSIONS 149

8.5 REFERENCES 150

CHAPTER NINE 154

9.0 GENERAL DISCUSSION...154

9.1 Introduction 154

9.2 Physical properties 155

9.3 Compressive properties 157

9.4 Thermal properties 160

9.5 Engineering implications...163

CHAPTER TEN..164

10.0 CONCLUSION AND RECOMMENDATIONS 164

10.1 Conclusions...164

10.1.1 Physical properties 164

10.1.2 Compressive properties...164

KNUST

10.1.3 Thermal properties 165
10.2 Recommendations and future work 165

REFERENCES.. 167

KNUST

LIST OF TABLES

Table 3-1: Categories of Cocoa in Ghana ··· 46

Table 5-1: Mean Dimensions of the Cocoa Beans Used for the Compression Experiment ··· 93

Table 6-1: Mean Dimensions of the Shea Kernel Specimen Used for the Compression Test ··· 110

Table 9-1: Moisture Effect on some Selected Properties of Cocoa Beans and Cashew Kernels. ··· 156

Table 9-2: Compressive Properties and their Moisture Effect for Cocoa, Cashew and Shea ··· 159

KNUST

LIST OF FIGURES

Figure 2-1: Cocoa beans prepared for export 15

Figure 2-2: Shea nut and Shea kernel 16

Figure 2-4: Lateral compression of shea kernel 33

Figure 3-1: Cocoa beans prepared for export 47

Figure 3-2: Effect of Moisture Content Variations on Bulk Density 50

Figure 3-3: Effect of Moisture Content Variations on Emptying Angles of Repose 52

Figure 3-4: Effect of Moisture Content Variations on the Filling Angles of Repose 53

Figure 3-5: Effect of Moisture Content Variations on the 1000 Bean Mass 55

Figure 3-6: Effect of Moisture Content Variations On Co-efficient of Friction on Mild steel 56

Figure 3-7: Effect of Moisture Content Variations On co-efficient of Friction on Plywood 57

Figure 3-8: Effect of Moisture Content Variations On Co-efficient of Friction on Rubber 58

Figure 4-1: a. Cashew nuts and b. Cashew kernels 66

Figure 4-2: Effect of moisture content on sphericity index of cashew nut/kernel 70

Figure 4-3: Effect of moisture content on kernel volume of cashew nut/kernel 71

Figure 4-4: Moisture content effect on kernel surface area of cashew nut/kernel 72

Figure 4-5: Effect of moisture content on true density of cashew nut/kernel 74

Figure 4-6: Effect of moisture content on bulk density of cashew nut/kernel 75

Figure 4-7: Effect of moisture content on percentage porosity of cashew nut/kernel 76

Figure 4-8: Relationship between maximum load of cashew nut/kernel and moisture content 77

Figure 4-9: Variation in maximum displacement of cashew nut/kernel with moisture content 78

Figure 4-10: Variation in compressive stress of cashew nut/kernel with moisture content 79

Figure 4-11: Variation in compressive strain of cashew nut/kernel with moisture content 80

Figure 4-12: Variation in young’s modulus of cashew nut/kernel with moisture content 81

Figure 5-1: Variation of cocoa bean moisture content versus displacement at maximum load 94

KNUST

Figure 5-2: Variation of Compressive strain and stress versus bean moisture content 95
Figure 5-3: Variation of Young's modulus and crushing energy against bean moisture content 96
Figure 6-1: Shea Nut and Shea Kernel 103
Figure 6-2: Lateral compression of shea kernel 108
Figure 6-3: Relationship between displacement at maximum load and moisture content 110
Figure 6-4: Relationship between compressive stress, compressive strain and moisture content 112
Figure 6-5: Relationship between Young's Modulus and moisture content 113
Figure 6-6: Relationship between crushing energy and moisture content 114
Figure 7-1: Effects of moisture content on bulk density of cashew nut/kernel 129
Figure 7-2: Moisture content variation on specific heat of cashew nut/kernel 130
Figure 7-4: Variations of moisture content on thermal diffusivity of cashew kernel 132
Figure 8-1: Schematic diagram of the thermal conductivity measuring apparatus 143
Figure 8-2: Thermal conductivity as a function of moisture content 145
Figure 8-3: Thermal conductivity as a function of bulk density. 147
Figure 8-4: Thermal conductivity as a function of temperature 148

KNUST
NYANSAPɔ Wɔ SANE NO BADWENIMA

CHAPTER ONE

1.0 INTRODUCTION

1.1 Background of study

1.1.1 Crops in Focus

Cocoa, shea nut and cashew are among the important cash crops grown in Ghana and information on their physical, thermal and mechanical properties, among others, are needed for handling, storage and processing operations.

1.1.1.1 Cocoa beans

Cocoa (*Theobroma Cacao*) is an ancient crop of the lowland tropical forest, which originated from the Southern and Central America (Lefeber *et al*., 2011). In West Africa, cocoa is one of the most important cash crops. Globally, Ghana's cocoa bean production is ranked second in the world after her western neighbour Côte d'Ivoire (FAOSTAT, 2005). Ghana is recognized as the world leader in premium quality cocoa beans production. Cocoa serves as the major source of revenue for the provision of socio-economic infrastructure in the country. In terms of employment, the industry employs about 60% of the national agricultural labour force in the country (Appiah, 2004 cited in Ntiamoah and Afrane, 2008). For these farmers, cocoa contributes about 70 -100% of their annual household incomes (COCOBOD, 2004 cited in Ntiamoah and Afrane, 2008). Cocoa seeds are the source of commercial cocoa beans and cocoa products include cocoa liquor, cocoa butter, cocoa cake and cocoa powder as well as chocolate. Cocoa powder is essentially used as flavour in biscuits, ice cream and cakes and is consumed by most beverage industries. Besides the traditional uses in chocolate manufacture and confectionery, cocoa butter, like shea butter, is also used in the manufacture of cosmetics. It is also a folk remedy for burns, cough, dry lips, fever, malaria, rheumatism and wounds. Studies show that the cocoa bean contains flavonoids with antioxidant properties that can reduce blood clot and the risk of stroke and cardiovascular attacks (ICCO, 2011).

1.1.1.2 Shea nut

Sheanut hails from the *Sapotaceae* family and the commonly known varieties include *Vitellaria paradoxa* (*Butryospermum parkii*) and *Vitellaria nilotica.* Shea nut is obtained from the shea tree, and is grown mostly throughout West and Central Africa in the semiarid Sahel from Senegal to Ethiopia (Aremu and Nwannewuihe, 2011). Shea nut contains reasonably high amounts of oleic acids from which the shea butter is obtained. Shea butter is one of the basic raw materials for most food, cosmetics, soap as well as the pharmaceutical industries (Boateng, 1992; Thioune *et al*., 2000) and it is sometimes used as a substitute for cocoa butter (Bekure *et al*., 1997). Sheanut serves as a main source of livelihood for the rural women and children in Northern Ghana who are engaged in its gathering (Fobil, 2002). The kernel is obtained from the nut by cracking with stones or mortar and pestle. Traditional methods of extraction of shea butter from the kernel involve a series of operations which includes steeping, roasting, pounding or grinding and boiling (Aviara *et al*., 2005). Shea butter is marketed as being effective at treating the following conditions; burns, eczema, rashes, severely dry skin, dark spots, skin discoloration, chapped lips, stretch marks, wrinkles and provides natural UV sun protection (Boateng, 1992).

1.1.1.3 Cashew nut

The cashew tree *(Anarcardium Occidentale)* is a native of Brazil and the Lower Amazons. The cashew has been a valuable cash crop in the Americas, the West Indies, Madagascar, India, and Malaysia (Frankel, 1991). The tree is now widely distributed throughout the tropics, particularly in many parts of Africa and Asia. The major producing countries of cashew are Tanzania, India, Mozambique, Srilanka, Kenya, Madagascar, Thailand, Malaysia, Indonesia, Nigeria, Senegal, Malawi, and Angola. Cultivation of the crop in Ghana was captured into world records in recent years starting with 500 tonnes in 1990 and increasing to 7500 tonnes in 2000. Cashew nut is a high value edible nut and it ranks third among the edible tree nuts of the world with a current output of about 700,000 metric tonnes nut in shell (FAO, 2005). Nuts may be sold raw or as processed kernels and may be further processed into value-added products such as fried, roasted, or chocolate-coated kernels and confectioneries (Azam- Ali and Judge, 2001; Ogunsina and Bamgboye, 2007). Cultivation of the cashew tree in Ghana started lately as compared to other producing countries in Africa. Following the gradual increasing interest of cashew production in Ghana, there is the need to expand the production base of the crop and compete with the leading producing and exporting nations in Africa (Ojolo and Ogunsina, 2007).

1.2 Engineering properties

Proper design of machines and processes to handle, store and process agricultural products and to convert them into food and feed requires an understanding of their engineering properties. These properties include size, shape and density, deformation in response to applied static and dynamic forces, moisture absorption and desorption characteristics, thermal properties, frictional characteristics, flow properties, aerodynamic and hydrodynamic properties, and response to electromagnetic radiation (Stroshine and Hamann, 1995).

According to Mohsenin (1980) and Gürsoy and Güzel (2010) engineering properties of food materials are essential data needed in the resolution of problems associated with the design of machines or analysis of the behaviour of produce during agricultural processes such as planting, harvesting, threshing, sorting, drying, storage and milling.

Several authors and researchers including Peleg (1983), Mohsenin (1980) and Stroshine and Hamann (1995) have indicated that besides a general increase in productivity at every stage of food production, an understanding of the basic physical properties of foods will result in reduced costs for handling and processing, reduction of damage and waste, savings in weight and bulk, improved shelf-life and stability, the development of new food materials, more objective standards of evaluation and maintenance of quality under adverse conditions of handling, storage, and distribution.

Engineering properties of food and biological materials may be classified as thermal (specific heat, thermal conductivity, and diffusivity), optical (colour, gloss, and translucency), electrical (conductivity and permittivity), mechanical (structural, geometrical, and strength), and physical (size, shape and mass characteristics) properties. Physical properties necessary in producing handling and processing machinery as well as quality evaluation include the following: linear dimensions, thousand seed mass, sphericity, bulk density, true density, porosity, angle of repose and static coefficient of friction (Baryeh, 2002; Kalkan and Kara, 2011; Tavakoli *et al.*, 2009).

Among these physical properties; dimensions, mass, volume, projected area, and surface area are most important in grading systems and dimensional grading of products decreases the packaging and transportation costs and allows usage of proper packaging models (Stroshine an Hamann, 1995; Mohsenin, 1986).

Food and biological materials are inhomogeneous in composition and have high variability thus affecting their behaviour and physical properties which are also dependent on moisture and temperature of the food material. Based on this, several researchers have determined the physical and mechanical properties of different agricultural products as a function of moisture content and variety in order to provide essential data for the design of processing equipment. These include Bargale *et al*., 1995 for canola and wheat; Çarman, 1996 for lentil; Gupta and Das, 1997 for sunflower; Murthy and Bhattacharya, 1998 for black pepper; Baryeh, 2001 for bambara groundnuts; Baryeh and Mangope, 2002 for pigeon pea; Özarslan, 2002 for cotton; Baryeh, 2003 for millet; Dursun, 2005 for caper seeds; Karababa, 2006 for popcorn; Kashaninejad *et al*., 2006 for pistachio nut; Özturk and Esen, 2008 for barley seeds.

KNUST

In order to understand the thermodynamic and transport behavior of foods during cooking to enable engineers to design safe, and convenient food processes and processors, several researchers have created mathematical models of foods which account for changes that occur during cooking, including changes in cellular structure, chemical composition, and water emission rates alongside thermal properties. Stroshine and Hamann (1995) indicated that the rate of heat transfer to a material depends on the heat transfer coefficient which is related to the surface area. The effects of size and surface area on drying rates of particulate materials can also be characterized by using the surface to volume ratio. Also, the ratio of surface area to volume affects drying time and energy requirements (Stroshine and Hamann, 1995).

1.2.1 Physical properties

Physical properties necessary in producing handling and processing machinery as well as quality evaluation include the following; linear dimensions, thousand seed mass, sphericity, bulk density, true density, porosity, angle of repose and static coefficient of friction.

According to Tavakoli *et al*. (2009) the physical properties of grains and seeds are essential for the design of equipment and the analysis of the behavior of the product during agricultural process operations such as handling, planting, harvesting, threshing, cleaning, sorting and processing.

Principal axial dimensions of food grains are useful in selecting sieve separators and in calculating grinding power during size reduction. They can also be used to calculate surface area and volume of grains, which are important during modeling of grain drying, aeration, heating, and cooling (Tavakoli *et al*., 2009).

Shape is important in orienting fruits and vegetables prior to mechanize operations such as peeling, removal of cores and pits, or positioning for machine assisted packing (Stroshine and Hamann, 1995).

The 1000 grain mass of cereal grains is used in the measurement of the relative amount of dockage or foreign material in a given lot of grain, and the amount of shrivelled or immature kernels (Varnamkhasti *et al*., 2007).

Bulk density, true density, and porosity play an important role in many applications such as design of silos and storage bins, separation from undesirable materials, separation and grading, and maturity evaluation (Mohsenin, 1980; Stroshine and Hamann, 1995; Bart-Plange *et al*., 2006).

The angle of repose is also important in designing equipment for mass flow and structures for storage. The angle of repose is particularly useful for calculating the quantity of granular materials which can be placed in piles or flat storages (Stroshine and Hamann, 1995; Mohsenin, 1980).

The knowledge of coefficient of friction of food grains on various structural surfaces is necessary in the analysis and design of post-harvest equipment such as grain bins, silos and conveyors (Nwakonobi and Onwualu, 2009).

1.2.2 Compressive properties

Useful data on the mechanical properties of nuts and kernels are necessary in the mechanization of various unit operations involved in the post-harvest processing and also help in the development of optimization parameters for efficient and effective processing equipment (Burubai *et al*., 2007). Compressive and other engineering properties are needed in the design of machines and the analysis of the behaviour of the product during unit operations such as drying, cleaning, sorting, crushing, and milling (Akaaimo and Raji, 2006 ; Irtwange, 2002). The increasing interest in shea butter and its uses in industries and the need for appropriate handling and processing of shea nut and kernel cannot be overemphasised. However the present methods of handling and processing are both laborious and time consuming (Aviara *et al.,* 2005). For effective and proper design and manufacture of systems and equipment in handling nuts and grains their mechanical properties such as the compressive properties must be available.

Compressive properties including rupture force, compressive strain and stress,Young's modulus and crushing energy are useful information in the design of kernel grinding machines. It has been revealed by Shitanda *et al*. (2002) that the compression behaviour of agricultural materials does not obey Hookes law in the same way metals do. Studies have shown that compressive properties are influenced by a number of factors such as the cultivar, temperature and moisture content of the product under consideration (Delwiche, 2000; Shitanda *et al*., 2002). The rupture force indicates the minimum force required for shelling nuts and grinding kernels (Sirissomboon *et al*., 2007; Galedar *et al*., 2009).

1.2.3 Thermal Properties

Knowledge of thermal properties of food and agricultural products, such as thermal conductivity, specific heat, and thermal diffusivity are essential for the proper design of processing equipment and prediction of those properties (Viviana *et al.,* 2008). Thermal properties and moisture dependency of various foods and agricultural products have been studied by researchers such as Kazarian and Hall (1965); Sherpherd and Bharddway (1986), Dutta *et al.* (1988) cited by Aviara and Hague (2001), Tansakul and Lumyong (2007) and Bart-Plange *et al.* (2009). For processes such as drying, boiling, roasting, and canning and for the design of food processing equipment, the knowledge of thermal properties is necessary. Furthermore, the temperature profile within a material cannot be determined without knowing the thermal properties of that material and even though that of some foods are available, that of cocoa, shea and cashew grown in Ghana are not available.

1.3 Problem Statement

As modern technology become complex coupled with the high standards being set locally and by importing countries of food and biological materials, a good understanding of the significant physical and thermal properties of food materials is needed. It is essential to understand the physical laws governing the response of biological materials so that machines, processes and handling operations can be designed for maximum efficiency in order that the highest quality of the end product can be assured. Such basic information should be valuable to engineers, food scientists and processors who urgently need them for modeling and equipment design and manufacture. Most of the primary crop processing in Ghana for crops such as cocoa, shea and cashew is still done using traditional and laborious methods. It has therefore become imperative to investigate the characteristics of these crops with a view to better understand the physical and thermal properties that come to play during mechanical and thermal processing and handling operations.

The scientific literature is flooded with moisture-dependent physical properties of agricultural materials including radish and alfalfa seeds (Yang and Zhao, 2001), bambara groundnut (Baryeh, 2000), millet (Baryeh, 2002), vetch seed (Yalcin and Ozarslan, 2004), pomegranate seed (Kingsley *et al*., 2005), cowpea (Bart-Plange *et al*., 2005), maize (Bart-Plange *et al*., 2006), jatropha fruits (Pradhan *et al*., 2009), wheat (Kalkan and Kara, 2011) and cowpea (Ampah *et al*., 2012). Negligible information is available on compressive and thermal properties of cash crops especially cocoa bean, shea and cashew nuts grown in Ghana. Bart-Plange and Baryeh (2003) studied the physical properties of category B cocoa bean considering the effect of moisture content and established the moisture dependence of properties considered.

Food and biological materials are hygroscopic and absorb moisture under humid conditions until they reach equilibrium with the surrounding. A range of moisture content exists within which optimum performance is achieved during processing and storage. Therefore, the effect of moisture content on the physical, mechanical and thermal properties of the crops grown in Ghana is of importance in the design of handling, processing and storage equipment. Cocoa, cashew and shea are important sources of food materials and ingredients which are essential components for many processed foods. Processing of these beans and nuts often requires that the seeds be hydrated first to facilitate operations such as milling, cooking or canning. Thus, absorption of water to these materials is of both theoretical and practical interest to processing industries (Kashaninejad *et al*., 2005).

Water content is not a thermophysical property but significantly influences all thermophysical properties. If the food is a living commodity, such as fruits and vegetables, its water content changes with maturity, cultivars, stage of growth, harvest and storage conditions. Values of most thermophysical properties can be calculated directly from the water content (Stroshine and Hamann, 1995).

Negligible information is available on important engineering properties of cash crops such as shea and cashew kernel grown in Ghana. Some information exist on the Physical and thermal properties of shea nut and kernel grown in Nigeria (Aviara *et al*., 2005; Aremu and Nwannewuihe, 2011).

Effects of moisture content and loading on compressive stress, compressive strain, Young's modulus and crushing energy of cocoa bean, shea and cashew nut are needed for the design of processing equipment but there is little data available.

1.4 Aim and Objectives of research

The aim of the study was to obtain data on essential thermophysical properties of cocoa beans, cashew nut and shea nut grown in Ghana.

The main objective of this study was to determine the variation that exist between moisture and selected physical, compressive and thermal properties needed in postharvest handling of cocoa beans, cashew nut and shea nut grown in Ghana.

1.4.1 Specific Objectives

The specific objectives of this study were to investigate the effect of moisture variation on:

1. size and shape properties, 1000 grain mass, bulk density, true density, angle of repose and coefficient of static friction for cocoa beans, cashew nut and cashew nut, .
2. compressive stress and strain, young's modulus, and crushing energy of cocoa beans, cashew nut and sheanut that are relevant for the design of processing equipment and
3. thermal conductivity of cocoa beans, cashew nut and sheanut needed in food processing.

1.5 Research Questions

The hygroscpicity of food and biological materials has been established in literature (Moshenin, 1980). What are the effects of moisture content variation on physical, compressive and thermal properties of cash crop grown in Ghana such as cocoa bean, cashew and shea kernel? There is very little information on this apart from some physical properties reported on cocoa beans (Bart-Plange and Baryeh, 2003),

1.6 Justification of the objectives

Ghana was captured into world market records in 1990 with total cashew production of 500 tonnes and by the year 2000, production had increased to 7500 tonnes (Azam-Ali and Judge, 2001). Following the increase in production of the cashew and shea crop in Ghana, alongside cocoa, there is the projection that these crops can become the leading export agricultural products in Ghana in the future. As production grows, there is the need to develop processing and storage facilities for the products. This therefore will require an intensive study of the various engineering properties of cocoa beans, shea and cashew nut in order that engineers can come up with various designs of equipment that will make processing easier in Ghana.

The study will provide essential data required by Engineers, Agriculturist, Food Scientist and other stakeholders in handling, processing and storage of the crops in focus and will contribute to the establishment of a data base on physical properties of crops grown in Ghana.

1.7 Limitations of the Research

Samples used for the determination of thermal conductivity of cashew kernels were loosely packed in the sample holder which could influence the results of thermal conductivity obtained. Also the moisture content range for cashew nut and kernels used was from 5% to 9% for the thermophysical properties determined which may be difficult to use to predict values outside the moisture content range considered. Compresive loading of the bean and kernel samples considered horizontal lateral loading only.

1.8 Organisation of the Research

Chapter 1 gives an introduction to the research and Chapter 2 focusses on the relevant literature needed for the study. Chapter 3 presents a comparative study of some physical properties of large and medium size cocoa beans from Ghana while Chapter 4 looks at some physical and mechanical properties of cashew nut and kernel grown in Ghana.

Chapters 5 and 6 consider compressive properties of cocoa beans considering the effect of moisture content variations and some moisture dependent compressive properties of shea kernel (vitellaria Paradoxa L) respectively.

Chapters 7 and 8 study some moisture dependent thermal properties of cashew kernel *(Anarcardium occidentale L.)* and the effect of moisture, bulk density and temperature on thermal conductivity of ground cocoa beans and ground shea nut kernels respectively

Chapter 9 presents a general discussion on the publications in Chapters 3 to 8 and engineering implications of the study.

Finally, Chapter 10 gives a summary of the study.

KNUST

CHAPTER TWO

2.0 LITERATURE REVIEW

2.1 Background to the study

This chapter reviews relevant literature on the research areas from the internet, journals, and some text books. The literature review covers cash crops such as cocoa, shea and cashew nut and kernel as well as relevant physical, mechanical and thermal properties as they relate to postharvest processing and storage.

2.2 Cash crops used for the study

2.2.1 Cocoa

Cocoa (*Theobroma Cacao*) is an ancient crop of the lowland tropical forest, which originated from the Southern and Central America (Lefeber *et al*., 2011). In West Africa, cocoa is one of the most important cash crops. Globally, Ghana′s cocoa bean production is ranked second in the world after her western neighbour Côte d'Ivoire (FAOSTAT, 2005). The cocoa beans from Ghana are also viewed as the best premium quality in the world (Ntiamoah and Afrane, 2008). The cocoa crop does not only serve as the major source of revenue for farmers′, accounting for about 70–100% of annual household incomes (Ntiamoah and Afrane, 2008) but also the provision of socio-economic infrastructure in Ghana. The cocoa industry continues to employ about 60% of the national agricultural labour force in the country (Appiah, 2004).

Freshly harvested cocoa beans have been found to have an unpleasant and astringent flavour, hence it is extremely essential to ferment, dry, and roast raw cocoa beans to obtain the desired organoleptic properties (Beckett, 2009; De Vuyst *et al*., 2008; Thompson *et al*., 2007). The drying of cocoa beans is associated with moisture content changes accompanied by shrinkage and volume changes (Gereke and Niemz, 2010).

2.2.1.1 Uses

Ghana's cocoa beans are usually processed into chocolate, cocoa powder, cocoa liquor, cocoa butter, and cake. Cocoa is a popular raw material in the pharmaceutical, cosmetics, and the food industries. Among other health benefits, the crop is very low in cholesterol and a good source of protein, potassium and zinc (Steinberg *et al*., 2003; Cooper *et al*., 2007; Cienfuegos-Jovellanos *et al*., 2009; Nutrtion data.com, 2011). In view of this, the government of Ghana is committed to ensuring the country processes more of the cocoa beans into downstream products for both the local and international markets (Awua, 2002).

2.2.1.2 Processing

Postharvest operations for cocoa generally consist of manual seed extraction by breaking the pod and removing the seeds, fermenting, drying, cleaning, sorting and grading. In Ghana these post harvest handling operations are often done excellently by the farmer on small-scale and manually leading to superior quality specifications which explains why cocoa beans from Ghana have established a worldwide reputation as the ingredient of preference by quality oriented cocoa products manufacturers.

In Ghana quality control measures are strictly enforced to ensure the marketing of high-quality Cocoa. This explains why Ghana is still the leading producer of good-quality Cocoa world-wide (Jonfia-Essien, 2004). Figure 2-1 shows samples of Ghana's cocoa beans prepared for export.

Figure 2-1: Cocoa Beans Prepared for Export

Uniformity in size of Cocoa bean is of paramount interest as it helps to achieve effective bean cleaning. Not all seeds from the pod are useful in processing as some fall short in quality and size.

2.2.2 Shea

Shea (*Vitellaria paradoxa*) belongs to the *Sapotaceae* family. This oil rich tree is found in dry savannas, forests and parklands of the Sudan zone, but it does not extend into coastal areas. Shea tree grows naturally in the wild and takes 30 years to grow to maturity but bush fires and harsh weather can reduce the length of years for maturity (Fobil, 2002) though it begins fruiting between eight and fifteen years. At harvest, the kernels have a moisture content of between 40-50%. After the kernels have been removed from the nut, it is sun dried to a moisture content of about 30% and to store safely the kernels are mechanically dried to a moisture content less than or equal to 7% (Fobil, 2002).

2.2.2.1 Uses

Its oil, shea butter, popularly called "*nkuto*" is used to maintain and protect the skin from the environment. The American Shea Butter Institute lists the following skin conditions for which shea butter can be useful in treating: dry skin, skin rash, skin peeling, after tanning, blemishes and wrinkles, itching skin, sunburn, shaving cream for a smooth silky shave. small skin wounds, skin cracks, tough or rough skin (on feet), cold weather, stretch mark prevention during pregnancy, insect bites, healthy skin, muscle fatigue, aches and tension, skin allergies such as poison ivy or poison oak, eczema, dermatitis and skin damage from heat. Shea oil is used in the manufacture of cosmetics, pharmaceuticals, soaps and candles (Aviara *et. al.*, 2005). In an agribusiness in sustainable natural african plant products (ASNAPP) publication, Acquaye *et al*. (2001) reported that the shea butter may be used in the manufacturing of cocoa butter substitute and Swiss chocolates.

2.2.2.2 Processing

Shea nut serves as a main source of livelihood for the rural women and children who are engaged in its gathering (Fobil, 2002). The kernel is obtained from the nut (Figure 2-2) by cracking with stones or mortar and pestle.

Figure 2-2: Shea Nut and Shea Kernel

Traditional methods of extraction of shea butter from the kernel involve a series of operations which includes steeping, roasting, pounding or grinding and boiling (Aviara *et al.*, 2005).

There is increasing interest in shea butter and its uses in industries which means an increment in handling and processing of shea nut and kernel. However, the present methods of handling and processing are both laborious and time consuming (Aviara *et al.*, 2005). There is therefore the need for the development of improved methods of processing. For effective and proper design and manufacture of systems and equipment in handling shea kernel through such processes as cleaning, grading, drying, size reduction and many others, the physical properties of shea kernel must be known.

2.2.3 Cashew

The cashew tree (*Anarcardium Occidentale* L.) is a native of Brazil and the Lower Amazons. It has been a valuable cash crop in the Americas, the West Indies, Madagascar, India and Malaysia (Frankel, 1991). The tree is now widely distributed throughout the tropics particularly in many parts of Africa and Asia. The five major producing countries are Vietman, India, Nigeria, Côte d'Ivoire and Brazil.

Cashew nut is a high value edible nut and it ranks third among the edible tree nuts of the world with a current annual output of 28400 tonnes in Ghana (FAO, 2012). Nuts may be sold raw or as kernels and may be further processed into value-added products such as fried, roasted, or chocolate-coated kernels and confectioneries (Azam-Ali and Judge, 2001; Ogunsina and Bamgboye, 2007). Following the gradual increasing interest in cashew production in Ghana, there is the need to expand the production base of the crop so as to compete with the leading producing and exporting nations in Africa (Ojolo and Ogunsina, 2007).

2.2.3.1 Uses

Cashew Nut Shell Liquid (CNSL), an oil which is found between the seed coat (pericarp) and the cashew nuts, is used in industry as a raw material for brake lining compounds, as a water proofing agent, a preservative and in the manufacturing of paints and plastics. It is toxic and corrosive to the skin.

Edible oil can also be extracted from cashew nuts but no evidence of it being carried out commercially has been found (Azam-Ali and Judge, 2001). A number of processes have now been developed for converting the cashew apple into various products such as jam, juice, syrup, chutney and beverage (Winterhaler, 1991). Nuts may be sold raw or as processed kernels and may be further processed into value-added products such as fried, roasted, or chocolate-coated kernels and confectioneries (Azam- Ali and Judge, 2001).

2.2.3.2 Processing

The postharvest processing of cashew involves cleaning, soaking, roasting, shelling, cleaning, drying, peeling and grading. The harvested nuts using appropriate mesh sieve (Errington and Coulter, 1994) are cleaned and soaked in water to avoid scorching them during the roasting operation (Brown, 1989).

The nut is then roasted which makes the shell brittle and loosens the kernel from inside of the shell which is then cracked either manually, using a hammer, or mechanically (Fellows *et al*., 1999). The existing roasting methods include steam roasting, open pan, drum roasting and the 'hot oil' method (Azam-Ali and Judge, 2004).

In the manual shelling process, the nuts are placed on a flat stone and cracked with a wooden mallet (Hall, 1998). This is followed by separation of shell pieces and kernels from the unshelled nuts which are returned to the shelling operation. Figure 2-3a and b present raw and shelled respectively.

Figure 2-3: a) Raw Cashew Nut Ready for Shelling and b) Shelled Cashew Kernel

Drying the shelled kernel to produce the blanched kernel and to protect the kernel from pest and fungal attack at this vulnerable stage (Jaffee and Morton, 1995) is follwed by manually peeling the testa from the kernel by gently rubbing with the fingers and grading of the kernels which is the last opportunity for quality control of the kernels. After the kernels are extracted from the shells, dried and peeled, they are graded for export on the basis of shape, size and colour using internationally accepted grading systems (Coulter, 1989).

2.3 Physical properties

Agricultural materials and food products have several unique characteristics which set them apart from engineering materials. Unlike engineering materials, the irregular shape of most agricultural materials and food products complicates the analysis of their behaviour.

The study of physical properties plays an important role in developing sensors to control machines and processes and to detect quality difference in products.

According to Richard and Donald (1995), these sensors may monitor basic properties such as size, density, force-deformation behaviour, or interaction with infra red radiation. Also, Unal *et al*. (2008), reported that knowledge of physical properties constitutes important and essential engineering data in the design of machines, storage structures and processes.

The study of physical properties can as well facilitate the designing and sizing of machine components to singulate seeds and drop them into the soil, handle food crops after harvesting, to clean, grade, separate and convey agricultural materials (Stroshine and Hamann, 1995).

Many agricultural engineers have made efforts to design domestic processing machines that would be affordable and economical enough to mitigate the many challenges of the rural farmer. Some designs and manufacture of domestic machines for the processing of agricultural produce such as cassava, soy beans, maize, ground nuts, pineapples, to mention a few, have contributed immensely to reduce post harvest losses (Asiedu, 1989). Several researchers have studied the physical properties of different agricultural materials and food products. Ojolo and Ogunsina (2007) did a study on the development of a cashew nut cracking device and came up with a design that can be used in rural areas where there is no electricity. Lewis (1999) also investigated the physical properties of food and food processing systems and revealed that knowledge of size, shape, density, and aerodynamic properties of kernels and plant parts are important to the proper design of threshing machines for separating kernels from straw.

Nevertheless, some physical properties have been studied for various grains and nuts such as millet (Baryeh, 2001); sugar beet (Dursun *et al.*, 2006); category B cocoa bean (Bart-Plange and Baryeh, 2003); cowpea seed (Yalcin, 2006); filbert nut and kernel (Pliestic *et al.*, 2006); roselle seeds (Juana *et al.*, 2008); and white speckled red kidney bean grains (Esref and Halil, 2007).

2.3.1 Physical attributes

The physical attributes of agricultural and food materials vary over a wide range of values. Rapid and accurate determinations of physical attributes are needed in processing agricultural materials. According to Mustafa (2006), shape and physical dimensions are important in screening solids to separate foreign materials in sorting and sizing of fruits and vegetables. He added that shape and size determine how many fruits can be packed in shipping containers or plastic bags of a given size. Quality differences in fruits, vegetables, grains and seeds can often be detected by differences in density. When grains and other particulate solids are transported pneumatically or when fruits and vegetables are transported hydraulically, the design fluid velocities are related to both density and shape. Some techniques have been developed for measuring the physical attributes of these agricultural materials.

2.3.1.1 Size and shape

Length, width and thickness determination is useful in the design of seed metering devices, sorting sieves and pneumatic conveying systems and planters attached to combine harvesters. Clearance between the cylinder and the concave of a combine harvester is also reliant on size and shape dimensions (Stroshine and Hamann, 1995).

The major diameter, length, is the longest dimension of the longest projected area. The minor diameter, thickness, is the shortest dimension of the minimum projected area. The intermediate diameter, width, is the minimum diameter on the maximum projected area and is often assumed to be equal to the longest diameter of the minimum projected area (Stroshine and Hamann, 1995).

Differences in size and shape can be used to improve the quality of particulate agricultural products by removing foreign materials and damaged particles. Seeds may be separated into size categories before they are sold to ensure proper singulation during planting.

Dimension is known to increase with increasing moisture content up to a certain point after which there is no more appreciable increase. Most experiments are carried out between 5% and 25% moisture content which is the range for storage and processing for most grains and seeds.

Deshpande and Ojha (1993) have found the principal dimensions of soyabeans to increase linearly with increasing seed moisture content, while Hsu *et al*. (1991) found principal dimensions of pistachios nut to increase nonlinearly with increase in seed moisture content. Such dimensional changes are important in designing seed pod threshers and in filling drying and storage bins.

Linear increase in volume with increase in seed moisture content have been observed by Deshpande *et al*. (1993) for soybean, Dutta *et al*. (1988) for gram, Aviara *et al*. (1999) for guna seeds and Ogut (1998) for white lupin. These differences could be due to the shape and dimensional change characteristics of the different seeds. The seed volume of pigeon pea has been found to vary nonlinearly with moisture as a result of the reduction in the seed dimensions as the seed moisture content increase (Baryeh and Mangope, 2002).

Principal axial dimensions of barley grain are useful in selecting sieve separators and in calculating grinding power during size reduction. They can also be used to calculate surface area and volume of grains, which are important during modelling of grain drying, aeration, heating, and cooling (Tavakoli *et al*., 2009).

In fruit and vegetable packing operations, size is a grading factor used to establish economic value while shape may be used to achieve a desirable orientation (Stroshine and Hamann, 1995).

2.3.1.2 Sphericity and Equivalent Diameter

One commonly used technique for quantifying differences in shapes of fruits, vegetables, grains and seeds is to calculate sphericity. Sphericity can be defined in several ways, but the one most commonly used is based on the assumption that the volume of the solid can be approximated by calculating the volume of a triaxial ellipsoid with diameters equal to the major, minor and intermediate diameters of the object (Stroshine and Hamann, 1995; Mohsenin, 1986)).

Sphericity is defined as the ratio of this volume to the volume of a sphere which circumscribes the object (ie. A sphere with diameter equal to the major diameter of the object):

$$\text{Sphericity} = \left[\frac{\textit{Volume of ellipsoid with equivalent diameters}}{\textit{Volume of circumscribed sphere}}\right]^{1/3} = \frac{(abc)^{1/3}}{a} \qquad (1)$$

Where, the major, minor and intermediate diameters are respectively a, b and c. This equation is for grains which are elongated like an ellipse.

The geometric mean diameter (Dg) or equivalent diameter according to Mohsenin (1970) may be calculated from Equation 2

$$Dg = (LWT)^{1/3} \qquad (2)$$

The degree of sphericity (ϕ) is then calculated from equation 2 (Mohsenin, 1970)

$$\varnothing = \frac{(LWT)^{1/3}}{L} X\ 100 \qquad (3)$$

$$\varnothing = \frac{Dg}{L} \text{ X } 100$$

Jain and Bal (1997) have also stated that the Sphericity may be given by:

Sphericity = $\frac{B[2L-B]^{1/3}}{L}$ (4)

Where $B = (WT)^{0.5}$ (5)

Baryeh and Mangope (2002) studied the effect of moisture on sphericity of pigeon pea and observed a reduction from 0.91 to 0.82 for the seed moisture range increase from 5% to 20%. Thus its shape deviates more and more from the shape of a sphere as moisture absorption occurs. This is due to the differential dimensional changes of the three major dimensions as the seed absorbs moisture.

On the other hand, the sphericity of barley grains increased linearly from 47.55% to 49.35% as the moisture content increased from 7.34% to 21.58% (d.b.). This suggests that as the grain's moisture content increases, its shape approaches a spherical shape (Tavakoli *et al*., 2009).

2.3.1.3 Volume and Surface Area

Volume of solids can be determined experimentally by liquid or gas displacement. Volumes of smaller grains and seeds can also be measured with pycnometers or graduated burettes. Jain and Bal (1997) have also stated that the seed volume, V and grain surface area, S may be given by:

V = $\frac{\Pi B^2 L^2}{6(2L-B)}$ (6)

S = $\frac{\Pi B L^2}{2L-B}$ (7)

Where, B = $(WT)^{0.5}$

Linear increase in volume with increase in seed moisture content have been observed by Deshpande *et al.* (1993) for soybean, Jain and Bal (1997) for millet, Dutta et al. (1988) for gram, Aviara *et al*. (1999) for guna seeds and Ogut (1998) for white lupin. Baryeh and Mangope (2002), however, found the seed volume to decrease with increasing seed moisture content.

Surface area (S) can also be determined from the equation $S = \Pi D_g^2$, which utilizes the geometric mean diameter (Mohsenin, 1970).

The surface area affects the rate of moisture loss during drying of grains, seeds, and other particulate materials. The rate of heat transfer to the material also significantly depends on the heat transfer surface. The smaller the volume of material per unit surface, the better its condition for rapid heat transfer (Tavakoli *et al*., 2009).

Linear increase in surface area with increase in seed moisture content have been observed by Ampah *et al*. (2012) for cowpea and Tavakoli *et al*. (2009) for barley grains.

2.3.2 1000-Bean Weight

The 1000-bean weight is the weight of 1000 single grains which includes the dry matter, the moisture present and the void spaces within the grains.

The mass of 1000 beans increased linearly with an increase in moisture content for cocoa beans (Bart-Plange and Baryeh, 2003), hemp seeds (Sacilik *et al*., 2003), flaxseed (Wang *et al.*, 2007), barley grains (Tavakoli *et al.*, 2009), spinach seeds (Kilickan *et al*., 2010), red pepper seeds (Üçer *et al*., 2010) and black cumin *(*Gharibzahedi *et al*., 2010).

The thousand grain mass of cereal grains is a useful index to “milling outturn” in measuring the relative amount of dockage or foreign material in a given lot of grain, and the amount of shriveled or immature kernels (Saiedirad *et al*., 2008 cited in Tavakoli *et al*., 2009).

2.3.3 Bulk Density

This is the ratio of the mass of grains to the volume including the void space. The bulk density can be determined using a container of known volume. The container is weighed, filled with the seeds and weighed. The bulk density is calculated as the mass of seed divided by the container volume. This may also be done using the air comparison pycnometer. This method was used by Baryeh and Mangope (2002) in the determination of bulk density of QP-38 variety pigeon pea.

Bulk density can also be determined with a weight per hectolitre tester, which is calibrated in kg per hectolitre. This has a predetermined volume and a measure of the weight easily enables the researcher to determine the bulk density. This method has been used by several researchers including Akinci *et al*. (2004) for Juniperus drupacea fruits; Deshpande *et al*. (1993) for soybeans; Suthar and Das (1996) for karigda seeds and Jain and Bal (1997) for pearl millet.

According to Baryeh (2000) the bulk density of bambara groundnuts decreases as the moisture content increases up to 25%, beyond which it does not change appreciably. The bulk density of cumin seeds (Singh and Goswami, 1996), sunflower seeds (Gupta and Das, 1997) and soybeans (Deshpande et al., 1993) also decrease as moisture content increases. However, on the other hand, the bulk density of coffee (Chandrasekar and Viswanathan, 1999), pumpkin seeds (Joshi *et al*., 1993) and karingda seeds (Suthar and Das, 1996) increase as moisture content increases. These discrepancies could be due to the cell structure and the volume and mass characteristics of the grains and seeds as moisture content increases.

2.3.4 True Density

True density is the weight per unit volume of an individual seed. The true density is defined as the ratio between the mass of seeds and the true volume of the seeds excluding void spaces, and determined using the toluene (C_7H_8) displacement method. Toluene is used instead of water because it is absorbed by seeds to a lesser extent. The volume of toluene displaced is found by immersing a weighted quantity of seeds in the measured toluene (Tavakkoli *et al*., 2006 cited by Ahmadi *et al*., 2009)

Kernel and bulk density data have been used in research to determine the dielectric properties of cereal grains (Nelson and You, 1989) and for determining volume fractions for use in dielectric mixture equations.

Pneumatic sorting tables are used to separate seeds of cereal crops by true density. Seeds of various impurities such as centourea, rye grass, field mustard and wild oats greatly differ in true density from the seeds of cereal crops. The true density of grain mixtures is determined either in solution or in suspension (Klenin *et al*., 1986 cited in Tavakoli *et al*., 2009)

The true density increases nonlinearly from 0.75 to 1.21 g/mm^3 as the seed moisture content increases from 5% to 25% for pigeon pea (Baryeh and Mangope, 2002). Linear increase of seed density as the seed moisture content increases has been found by Singh and Goswami (1996) for cumin seeds and Ampah *et al*. (2012) for cowpea seeds..

Deshpande *et al*. (1993), Joshi *et al*. (1993), Suthar and Das (1996), however, found the true density to decrease with seed moisture content for soybeans, karingda seeds and pumpkin seeds respectively. These seeds thus have lower weight increase in comparison to volume increase as their moisture content increase (Baryeh, 2000).

2.3.5 Porosity

This is defined as the percentage of the total container volume occupied by air spaces between the particles. Porosity can be determined using the air comparison pycnometer. Porosity depends on true and bulk densities and hence its magnitude of variation depends on these factors and is different for each seed or grain. The porosity of the seeds was calculated from the values of the bulk and particle densities that were obtained using the relation below:

$$P = \frac{(\rho_p - \rho_b)100}{\rho_p} \quad (8)$$

Where, P = porosity (%), ρ_p = particle density (kgm^{-3}), and ρ_b = bulk density (kgm^{-3})

This method has been used by other researchers such as Mohsenin (1970) and Thompson and Isaac (1967) to calculate porosity.

According to Bart-Plange and Baryeh (2003), high porosity at high moisture content indicates that less number of beans can be stored at high moisture content than at low moisture content due to increase in interbean voids when the porosity is high for cocoa beans.

The porosity is the most important factor for packing and it affects the resistance to airflow through bulk seeds (Tavakoli *et al*., 2009).

2.3.6 Angle of repose

This includes the filling angle of repose and the emptying angle of repose. It is affected by the surface characteristics, shape and the moisture content of the grains. The filling angle of repose is the angle with the horizontal at which the material will stand when piled. When grains are removed from an opening in the bottom or the side of a bin, the angle which the grain surface assumes with the horizontal is called the emptying or funnelling angle of repose.

Tavakoli *et al*. (2009) found the values for the filling angle of repose to increase from 31.16° to 36.90° with an increasing moisture range of 7.34%–21.58% (d.b.) for barley grains. This increasing trend of repose angle with moisture content occurs because surface layer of moisture surrounding the particle holds the aggregate of grain together by the surface tension. The angle of repose is also important in designing the equipment for mass flow and structures for storage (Stroshine and Hamann, 1995).

A linear increase in angle of repose as the seed moisture content increases has also been reported by Baryeh and Mangope (2002) for pigeon pea, Bart-Plange and Baryeh (2003) for cocoa beans, Kabas *et al*. (2007) for cowpeas and Igbozulike and Aremu (2009) for Garcinia kola seeds, The angle of repose is particularly useful for calculating the quantity of granular materials which can be placed in piles or flat storages (Stroshine and Hamann, 1995).

The angle of repose determines the maximum angle of a pile of grain in the horizontal plane, and is important in the filling of a flat storage facility when grain is not piled at a uniform bed depth but rather in a conical heap (Mohsenin, 1986 cited by Varnamkhasti *et al*, 2007).

Low angle of repose of cocoa beans is often advisable during belt conveying while high angle of repose is more desirable when unloading onto a horizontal surface.

2.3.7 Coefficient of static friction

Coefficient of static friction is known as the $\tan^{-1}$ of the angle which the tilting table makes with the horizontal when grains just start moving along the table.

An increase in the coefficient of static friction with moisture content has been observed by Tavakoli *et al*. (2009) for barley grains using glass, galvanized iron sheet and plywood; Baryeh (2000) for groundnuts using plywood, galvanized iron and aluminium; Singh and Goswami (1996) for cumin seeds using plywood, galvanised steel and aluminium; Kabas *et al*. (2007) for cowpeas using rubber, plywood and galvanized shee and Aviara *et al.* (2005) for sheanut using metal sheet, formica and plywood.

The materials used for the experiments were considered because they are commonly used in the handling and processing of grains and construction of storage and drying bins. The observed increased friction coefficient at higher moisture content may be owing to the water present in the grain and the grains possibly become rougher on the surface as the moisture content increases making the coefficient of friction increase (Baryeh and Mangope, 2002).

The friction coefficient is important in the design of conveyors because friction is necessary to hold cocoa beans to the conveying surface without slipping or sliding backward.

The knowledge of friction coefficients of grain is needed for designing conveying equipment. For instance friction between an un-consolidated material and a conveyor belt affects the maximum angle with the horizontal, which the conveyor can assume when transporting the solid. Husking characteristics of paddy are also dependent upon its shape and size (Shitanda *et al*., 2001; Varnamkhasti *et al*., 2007)

2.4 Mechanical properties

Mechanical properties are properties concerning the behaviour of agricultural materials under applied forces. The study of mechanical properties is needed for texture analysis and better understanding of product quality. Useful data on the mechanical properties of shea nut and kernel are necessary in the mechanization of various unit operations involved in post-harvest processing and also help in the development of optimization parameters for efficient and effective processing equipment (Burubai *et al*., 2007). Compressive and other engineering properties are needed in the design of machines and the analysis of the behaviour of the product during unit operations such as drying, cleaning, sorting, crushing and milling (Akaaimo and Raji, 2006; Irtwange and Igbeka, 2002).

Force-deformation testing of agricultural materials can also be used to study damage which occurs during harvesting and handling of grains, seeds, fruits and vegetables. Knowledge of the behaviour of a particular agricultural material from testing or from test data enhances the evaluation of its engineering design. One most important consideration in engineering design is to ensure that stresses in components do not exceed the strength of agricultural materials. Damages done to agricultural materials during harvesting, handling and transportation can reduce their structural integrity (Mohsenin, 1986). Those damages that are often recorded include bruising and splitting (vegetables and fruits), cracking and chipping (grains, seeds and eggs), and cuts (fruits and seeds) (Geankpolis, (1983). The amount of force required to produce a given amount of deformation depends on many factors including the rate at which the force is applied, the previous history of loading, moisture content and the composition of the product (Bahnasawy, 2007). These factors play important roles when the qualitative evaluation of the grain's hardness is required during size reduction processes. Several scholars have investigated the mechanical properties of different agricultural materials and food products. Wang *et al.* (2004) reviewed the firmness detection by excitation dynamic characteristics for peach and observed that impact orientation, detected orientation, impact velocity and impact material did not significantly affect the dominant frequency.

Other fruits and vegetables whose mechanical properties have been studied include; cucumber (Thompson *et al.*, 1992), apples and pears (Garcia *et al.*, 1995), apples (Grotte *et al.*, 2001), and garlic (Xu, 2005).

2.4.1 Force Deformation characteristics

Agricultural materials and food products deform in response to applied forces. The nature of these responses varies widely among different materials. The uniaxial compression technique is the most popular method used for compression tests to determine force deformation characteristics. This technique involves trimming of the agricultural product into a precise geometry to facilitate the measurement of the various forces. Biological materials possess some unique characteristics (Stroshine and Hamann, 1995).

2.4.2 Stress-Strain

According to Stroshine and Hamann (1995) compression test may be conducted on grains and seeds at different moisture content levels using the Instron Universal Testing Machine (IUTM) controlled by a micro- computer. Prior to the compression test, the linear dimensions and the sphericity of the seeds are measured. During the compressive test, the seed is placed laterally (Figure 2-4) or axially on the stable up platform and compression is done with a motion probe at a constant speed until the specimen is fractured. The data acquisition system generates rupture load and displacement automatically during the compression. The load-displacement curve is used to derive the compressive properties of seeds. The maximum compressive load, the load at which the bean fractures is determined by the ratio of peak load of the displacement curve. Treating the seed as a sphere, the maximum compressive stress, strain, and crushing energy are determined using the following equations:

$$\sigma_{max} = \frac{\mathrm{P}_{max}}{dL} \quad (9)$$

$$\varepsilon_{max} = \frac{\delta l}{l} \quad (10)$$

$$E_c = \frac{P}{2} \times \Delta D \quad (11)$$

Where,

σ_{max} is the maximum compressive stress in MPa, P_{max} is the maximum load in N, d is the mean diameter in mm, and L is the mean length in mm. ε_{max} is maximum compressive strain in mm/mm, l is the mean width of the specimen in mm, ΔD is the displacement interval in mm, E_c is the crushing energy in J,

KNUST

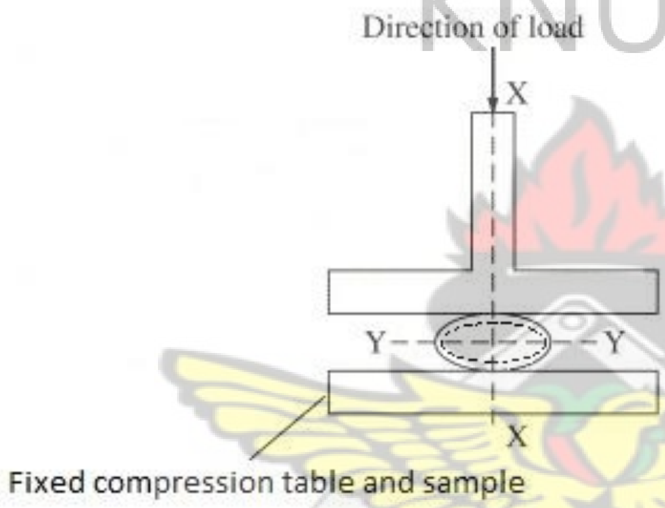

Figure 2-4: Lateral Compression of Shea Kernel

Several researchers have studied the mechanical properties of various food and biological materials (Altuntas and Karadag (2006) for sainfoin seed; (Khan *et al*., 2010) for industrial hemp stalks; (Shitanda *et al*., 2002; Corrêa *et al*., 2007) for rough rice (Rybiński *et al*., 2009) for pulse seeds; (Khazaei and Mann, 2004) for sea buckthorn berries; (Kalkan and Kara, 2011) for wheat grains; Galedar *et al*. (2009) for pistachio nuts and kernel and (Isik and Unal, 2007) for white speckled red kidney bean. Bahnasawy (2007) and Erica *et al.* (2005) separately used (CNS Farnell Com, U.K.), and (Shimadzu Autograph DSS-10T-S) testing machines to determine compressive forces of Kiwifruit and Safflower seeds respectively.

2.4.3 Modulus of Elasticity

It is defined as the ratio of the stress applied to the strain produced. It may be referred to as the stress required in producing a unit quantity of elastic strain (Gupta, 2006). For engineering materials, the relationship between stress and strain in the linear region of the stress-strain curve is described using the modulus of elasticity while in the case of biological materials, the apparent modulus of elasticity where stress and strain relationship is nonlinear is used.

KNUST

2.5 Thermal Properties

Most processed foods and many freshly consumed foodstuffs receive some type of heating or cooling during handling or manufacturing. Design and operation of processes involving heat transfer requires special attention, due to the heat-sensitivity of foods. Both theoretical and empirical relationships used when designing or operating heat processes require knowledge of the thermal properties of the foods under consideration. Food thermal properties can be defined as those properties controlling the transfer of heat in a specified food. They are usually grouped as thermodynamical properties (e.g., specific volume, specific heat, enthalpy, and entropy) and heat transport properties (thermal conductivity and thermal diffusivity). However, when considering the heating or cooling of foods, it is well known that other physical properties such as density, porosity, and viscosity must be considered because of their intrinsic relationship with the mentioned thermal properties (Stroshine and Hamann, 1995). In the food and agricultural industries, all processing operations as well as storage of many of their products are subjected to various types of thermal processing before they are sold out to consumers. Thermal processes that involve heat transfer are heating, cooling, drying, and freezing (Tansakul and Lumyong, 2008).

Knowledge of thermal properties of food and agricultural products, such as thermal conductivity, specific heat, and thermal diffusivity are essential for the proper design of equipment and prediction of those properties (Viviana *et al.,* 2008). These properties greatly depend on the temperature, state (frozen or unfrozen), compositional parameters (moisture content, fat content, protein, and ash), and fibre orientation. Heat may be transferred through these products by conduction, convection, or radiation. For many heat transfer processes associated with storage and processing, heat is conducted within the product and a moving fluid which surrounds or comes in contact with the product.

General models were developed to predict thermal properties of each specific food material based on its composition and temperature. These models were used on the assumption that each component has the same thermal properties regardless of structure in different food materials (Choi and Okoi, 1986; Tansakul and Lumyong, 2008). This assumption is not always true as reported by Sweat and Haugh (2006), Tansakul and Chaisawang, (2007). They, however, concluded that empirical models of thermal properties for food and agricultural materials could give more specific and accurate predictions.

2.5.1 Specific Heat

Specific heat is the quantity of heat required to raise the temperature of 1kg of material by 1°C. It is the ability of a food product to store heat relative to its ability to conduct (lose or gain) heat. It is strictly based on how much energy is needed not the rate at which it takes to raise the temperature (Fontana *et al*., 1999). Specific heat depends on the nature of the process of heat addition, such as a constant pressure process or a constant volume process. The pressure dependence of specific heat for solids and liquids is very little until extremely high pressures are involved. Most of the food processing operations are at atmospheric pressure (Mohsenin, 1980).

Hence, specific heat of food materials is usually presented at constant pressure. The commonly used units are the kJ/ (kg-K), Btu/ (Ib-F) and cal/(g-K). The specific heat of agricultural products depends essentially on their moisture content and to a lesser extent on temperature.

An important equation relating specific heat, mass of the sample (M), the amount of heat that must be added (Q), and the initial and final temperatures of the sample (T_1 and T_2) may be given by:

KNUST

$$Q = M\,C_p\,(T_2 - T_1) \tag{12}$$

According to Mohsenin (1980), there are several methods of determining specific heat of food and agricultural materials: Empirical equations, Method of mixtures, Method of guarded-plate, Method of comparison calorimeter, Method of calculated specific heat, adiabatic calorimeter and Method of differential scanning calorimetry. Among the published methods for specific heat measurement, differential scanning calorimetry (DSC) has so far been the most accurate and rapid method (Yang *et al*., 2002). The specific heat has often been measured with calorimeters of one form or another using the method of mixtures. Quite a number of researchers have used the method of mixtures to determine the specific heat of food products. Hwang and Hayakawa (1980) reported the use of a vacuum bottle calorimeter in measuring the specific heat of foods, Shepherd and Bhardwaj (1986) used an aluminium calorimeter placed in an insulated vacuum flask to measure the specific heat of pigeon pea and gram and Dutta *et al.* (1988) used an ice calorimeter in the determination of the specific heat of wheat, rice, barley and oats.

2.5.2 Thermal Conductivity

Thermal conductivity is defined as the ability of a material to conduct heat. The importance of thermal conductivity is to predict or control the heat flux in food during processing such as cooking, frying, freezing, sterilization, drying or pasteurization. It is necessary to ensure the quality of the food product and the efficiency of the equipment. The equation that relates the thermal conductivity to the amount of heat that flows through the material per unit of time (dQ/dt), the cross sectional area of the material through which the heat flows (A), and the temperature difference per unit of length of the conducting material (dT/dx) is given as:

$$\frac{dQ}{dt} = -kA\frac{dT}{dX} \tag{13}$$

KNUST

2.5.2.1 Methods for Determining Thermal Conductivity

The thermal conductivity of food and agricultural products as reported by Mohsenin (1980) may be determined either by the transient heat flow method or the one dimensional steady-state heat flow method. Timbers (1995) calculated the thermal conductivity of rapeseeds from its thermal diffusivity measured with the Dickerson apparatus. Singh and Goswani (2007); Wallapapan and Sweat (1999); Transakul and Lumyong (2007); and Dutta (1988) used the line heat source thermal conductivity probe to measure the thermal conductivity of cumin seed, defatted soy flour, straw mushroom, and gram respectively, while Aviara and Haque (2001), and Izadifar Baik (2007) determined the thermal conductivity of non-fat dry milk and rhizome using the steady state method.

2.5.2.2 Line Heat Source Method

According to Mohsenin (1980), the line heat source method is one of the most common transient methods used particularly with granular materials. It utilises a constant heat source to an infinite solid along a line with infinitesimal diameter, such as a thin resistant wire. Having the heat source imbedded in the mass of the material whose conductivity is to be measured, the line source is energized and the temperature rise at a given distance from the source is measured after a short heating time. In the initial phase, the temperature will rapidly rise, and as the heat begins to soak in, the rate of rise becomes constant. From the straight portion of the rate curve (temperature vs. time) the thermal conductivity can be calculated.

The rate of rise in temperature of the specimen is then a function of thermal conductivity of the material. The equation used for calculating thermal conductivity is reduced to the following form:

KNUST

$$k = \frac{Q}{4\pi(t_2 - t_1)} \ln \frac{\theta_2}{\theta_1} \qquad (14)$$

Where,

$Q = I^2R$ =heat input per meter of the line source

k = thermal conductivity of the medium infinite in size surrounding the heat source

t_1 = initial temperature

t_2 = final temperature

θ_1 = initial time

θ_2 = final time

2.5.2.3 Factors affecting thermal conductivity

According to Ibrahim *et al.* (2006), thermal conductivity differs with each substance and depends in each case on structure, volume, weight, humidity, pressure and temperature. Also thermal conductivity is dependent upon the physical and chemical nature of the material and its temperature. The relationship between thermal conductivity and moisture content is a linear function.

The thermal conductivity of foods is influenced by a number of factors concerned with the nature of food (for example cell structure, the amount of air trapped between the cells and the moisture content) and the temperature and pressure of the surroundings (Fellows, 1992).

2.5.3 Thermal Diffusivity

Thermal diffusivity is the ability of a material to conduct thermal energy relative to its ability to store thermal energy. Thermal diffusivity determines how fast heat propagates or diffuses through a material. It helps estimate processing time of canning, heating, cooling, freezing, cooking or frying. Water content, temperature, composition, and porosity affect thermal diffusivity (Fontana *et al*., 1999). An object with a higher thermal diffusivity will always heat faster in comparison to that with a lower thermal diffusivity. Ozişik (1993) stated that the higher the thermal diffusivity, the shorter the time required for the heat to propagate within the solid. It can be calculated indirectly from measured thermal conductivity, density and specific heat. It can also be determined from the solution of a one-dimensional steady state heat transfer equation.

Thermal conductivity, thermal diffusivity and specific heat capacity each can be measured by several well-established methods (Mohsenin, 1980), but measuring any two of them would lead to the third through the relationship:

$$\alpha = \frac{k}{\rho C_p} \qquad (15)$$

Where,

α is the thermal diffusivity,

k is the thermal conductivity,

ρ is the bulk density

c_p is the specific heat

Many researchers have estimated thermal diffusivity using the various methods. Aviara and Haque (2000) researched into the moisture dependence of thermal properties of shea nut kernel and calculated the thermal diffusivity from the values of specific heat, thermal conductivity and bulk density. Other researchers who have used similar methods include: Yang and Zhao (2001), Goswani and Singh (2000) and Transakul and Lumyong (2007).

2.6 Moisture Content

Moisture content is one of the most commonly measured properties of food materials. Moisture plays an important role in postharvest handling operations such as drying, storage, marketing and roasting of crops such as cocoa, cashew and shea.

Moisture measurement during drying is essential to follow up drying process and to decide when drying is achieved. High risks of mould growth and aflatoxin production may be caused by high product storage moisture content. Marketing value may be affected by moisture content level and may influence trade negotiations and trust while roasting temperature and length of roasting may be controlled with the knowledge of product moisture content and this could affect energy requirement during roasting. Moisture level in food materials is important to food scientists for legal and labeling requirements, economic reasons, microbial stability, food quality and processing among others (Mohsenin, 1970, Stroshine and Hamann, 1995). Knowledge of the moisture content is often necessary to predict the behaviour of foods during processing, *e.g.* mixing, drying, flow through a pipe or packaging.

It is therefore important for food scientists to be able to reliably measure moisture contents. Thiex and van Erem (1999) indicated that a number of analytical techniques have been developed for this purpose, which vary in their accuracy, cost, speed, sensitivity, specificity and ease of operation. The choice of an analytical procedure for a particular application depends on the nature of the food being analyzed and the reason the information is needed.

2.6.1 Methods of Measuring Moisture Content

The methods of determining moisture content in food grains are divided into three broad categories:

Direct measurement: water content is determined by removing moisture and then by measuring weight loss;

Indirect measurement: an intermediate variable is measured and then converted into moisture content. Building up calibration charts before applying indirect measurements is a prerequisite;

Empirical measurement: refers to methods such as biting, shaking, crunching, commonly used by both producers and small traders. These empirical measurements are both indirect and subjective.

Direct methods are considered to provide true measurements of moisture content, and are used to calibrate more practical and faster indirect methods. Direct methods are mainly devoted to research purposes because it requires special equipment (e.g. an oven and analytical balance), and measurements can only be implemented in laboratories. This study focused on the use of direct measurement for moisture content determination

.

2.6.1.1 Direct measurements

Different methods are used to remove all the water but chemically bound water: heating in an oven, use of microwaves or infrared radiation. For food grains, a reference method has been established and moisture content may be expressed on wet or dry basis. According to Lewis (1987), moisture content MC can be expressed on either wet basis as:

$$MC = \frac{mass\ of\ water\ content}{mass\ of\ sample} \times 100 \tag{16}$$

or on dry basis as:

KNUST

$$MC = \frac{mass\ of\ water}{mass\ of\ solid} \times 100 \tag{17}$$

2.7 Effect of Moisture Content on Engineering Properties

Food and biological materials are hygroscopic and absorb moisture under humid conditions until they reach equilibrium with its surroundings. A range of moisture content exists within which optimum performance is achieved during processing and storage. Therefore, the effect of moisture content on the physical, mechanical and thermal properties of the crops grown in Ghana is of importance in the design of handling, processing and storage equipment. Processing of beans and nuts often requires that the seeds be hydrated first to facilitate operations such as milling, cooking or canning and therefore, absorption of water to these materials is of both theoretical and practical interest to processing industries (Mohsenin, 1980).

Water content is not a thermophysical property but significantly influences all engineering properties of food and biological materials. If the food is a living commodity, such as fruits and vegetables, its water content will change with maturity, cultivars, stage of growth, and harvest and storage conditions. Values of most thermophysical properties can be calculated directly from the water content (Stroshine and Hamann, 1995). The amount of moisture in agricultural materials and food product greatly affects the properties such as size and shape, density, force-deformation characteristics, thermal conductivity, heat capacity and electrical resistance.

A number of agricultural and food engineers have studied the effect of moisture on various engineering properties. Dursun (2006) studied some physical properties of sugar beet seed and noted that the axial dimensions and average diameters increased as the moisture content increased. Pradhan *et al.* (2008) investigated the moisture dependent physical properties of jatropha fruit and gathered that as moisture content increases from 7.9% to 23.33% d.b., the average length, width and thickness of jatropha fruit changes from 29.31mm to 29.90mm, 22.18mm to 22.83mm, and 21.36mm to 22.07mm respectively.

KNUST

A study on the thermal properties of straw mushroom by Transakul and Lumyong (2007) also drew conclusions that an increase in moisture content of mushroom samples with increase in temperature, resulted in an increase in values of thermal properties, i.e., specific heat, bulk thermal conductivity and bulk thermal diffusivity. Several other biological materials whose engineering properties have been affected by moisture content include: cumin seed (Singh and Goswani, 2000), Shea nut kernel (Aviara and Haque, 2000), millet (Baryeh, 2001), Radish and alfalfa seed (Yang and Zhao, 2001), raw and parboiled paddy (Reddy and Chakraverty, 2004), safflower seed (Erica *et al.*, 2004), cowpea seed (Yalcin, 2006), filbert nut and kernel (Pliestic *et al.*, 2006), peanut and kernel (Aydin, 2006) and kiwi fruit (Sayed and Maryam, 2007).

2.8 Concluding Remarks

Several researchers have worked on variation of physical, mechanical and thermal properties of grains, seeds and nuts across the globe. In Ghana, some work has been done on the physical properties of some varieties of maize, cowpea, bambara groundnuts, rice, millet and Category B cocoa beans. Very little information is found on thermal and mechanical properties of cocoa, cashew and shea nuts grown in Ghana which is required for handling, processing and storage operations.

CHAPTER THREE

3.0 A COMPARATIVE STUDY OF SOME PHYSICAL PROPERTIES OF LARGE AND MEDIUM SIZE COCOA BEANS FROM GHANA

Published as Bart-Plange, A., Dzisi, K. A., Addo, A. and Teye, E. (2012). ***ARPN Journal of Science and Technology. 2(3): 135-141, March.*****www.ejournalofscience.org. ISSN NO.: 2225-7217**

KNUST

ABSTRACT

The physical properties of cocoa are necessary for the design of equipment to handle, transport, process and store the commodity. Cocoa beans can be categorised into several groups based on their sizes. A comparative study of the physical properties of the large group (category B) and the medium group (category D) cocoa beans were evaluated as a function of moisture content (mc) within the moisture content range of 5.67 - 25.04% on wet basis. The bulk density decreased linearly from 559.60 - 505.05 kg/m^3 from a moisture content range of 8.6 - 23.78% for category B and from 699.9 - 630.18 kg/m^3 between a moisture content of 9.19 - 25.05% for category D. The 1000-bean mass increased linearly from 984.75 – 1112 g and 1125 – 1247 g when moisture increased from 9.19 - 25.04% and 8.6 - 23.78% for categories D and B respectively. The emptying angle of repose for category D at moisture content. range of 9.19 - 25.04% increased from 27.98 – 46.52. Category B. with m.c. range of 7.56 – 18.8% also increased from 27.26 – 37.47^o. The filling angle of repose for category D increased with values ranging from 30.33 - 42.98^o from moisture.content of 9.19 - 25.04%, while for category B at moisture content of 5.67-22.0% the filling angle of repose increased non-linearly from 23.74 – 33.81^o. The static coefficient of friction increased linearly from 0.56 - 0.69, 0.48 - 0.60 and 0.21 - 0.28 for plywood, mild steel and rubber respectively for category B and for category D, a linear

increment in static co-efficient of friction from 0.53 - 0.62 and 0.56 - 0.63 was observed for mild steel and plywood while in the case of the rubber, static co-efficient of friction increased non linearly from 0.12 - 0.32.

Keywords: Cocoa, physical properties, 1000-bean mass, bulk density, angle of repose, co-efficient of static friction.

KNUST

3.1 INTRODUCTION

Coupling the ever increasing commercial value of food materials with the high standards being set by importing countries as well as the complexity of modern technology, a good understanding of the significant physical properties of food materials is needed.

It is essential to understand the physical laws governing the response of these biological materials so that machines, process and handling operations can be designed for maximum efficiency in order that the highest quality of the end product can be assured. Such basic information should be valuable to engineers, food scientists and processors who might need them. Several researchers have determined the physical and mechanical properties of different agricultural products as a function of moisture content in order to provide essential data for the design of equipment for the handling, conveying, separation, drying, aeration, storing and processing of seeds. These include researchers such as [1] for bambara groundnuts; [2] for maize; [3] for rice and [4] for spinach seed.

Amelonado cocoa is one such food material that has very high commercial value worldwide and whose cultivation and processing is of great interest not only to producing countries like Brazil, Cote D'Ivoire, Nigeria, Ghana, Malaysia among others but importers and chocolate manufactures alike. cocoa is an international commodity with an estimate of five (5 US dollars) billion dollars in world trade [5].

The genus Theobroma, of which the cocoa tree belongs, occur wild in the Amazon Basin and other tropical areas of South and Central America [6]. Today, cocoa can be divided into three main types namely; Criollo, Forastero and Trinitario. The Amelonado variety, which comes from the Forastero, is currently widely grown in Brazil, West Africa and South-East Asia. Approximately 60% of the world's supply of Cocoa originates from West Africa [6]. Postharvest operations for cocoa generally consist of manual seed extraction by breaking the pod and removing the seeds, fermenting, drying, cleaning, sorting and grading. In Ghana, these post harvest handling operations are often done excellently by the farmer on small-scale and manually leading to superior quality specifications which explains why cocoa beans from Ghana have established a worldwide reputation as the ingredient of preference by quality oriented cocoa products manufacturers. According to the Quality Control Division (QCD) of the Ghana cocoa Board, Cocoa beans are sorted by size based on number of beans weighing 100 g into various categories. Table 3-1 shows five categories that are declared for the main harvesting season.

Table 3-1: Categories of Cocoa in Ghana

Classification	Beans count/100g
Large (Category B)	0-100
Medium (Category D)	101-120
Small (Category G)	121-130
Very small (Category F)	131-150
Remnants (Category SR)	151-250

However, the sizes depend on environmental factors and the hybrids grown. In Ghana, quality control measures are strictly enforced to ensure the marketing of high-quality cocoa. This explains why Ghana is still the leading producer of good-quality cocoa world-wide [6]. Figure 3-1 shows samples of Ghana's cocoa beans prepared for export.

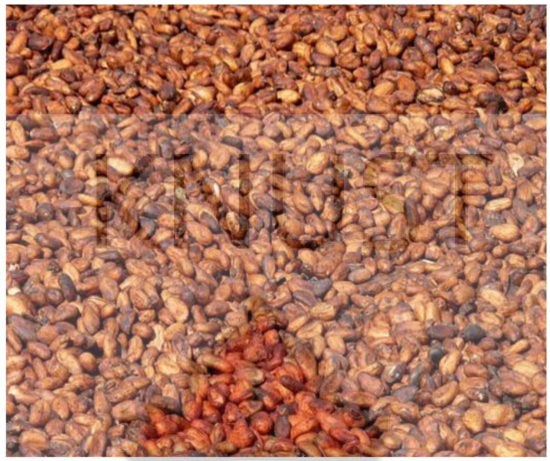

Figure 3-1: Cocoa Beans Prepared for Export

Uniformity in size of cocoa bean is of paramount interest as it helps to achieve effective bean cleaning. Not all seeds from the pod are useful in processing as some fall short in quality and size.

Water is one of the most important components affecting all the physical properties of food materials. Cocoa beans, like all food materials, are hygroscopic and absorb moisture under humid condition until they reach equilibrium with the surrounding. A range of moisture content exists within which optimum performance is achieved. Therefore, the effect of moisture content on the physical properties of the two top categories (B & D) of Ghana's Cocoa beans is of importance in the design of the handling, processing and storage equipment. The objective of this study was to measure and compare the variations that exist in the physical properties of two categories (B & D) of Ghana's cocoa beans as moisture content varies.

3.2 MATERIALS AND METHODS

The Cocoa used for the experiment had all the quality checks performed and ready for export to the international market. The data available were those obtained from a study of the effect of moisture on the physical properties of categories B and D, representing the large and medium sizes respectively, of Ghana's cocoa beans. The data used were on the following physical properties:

3.2.1 1000 bean mass

The mass of 1000-beans was obtained by counting 1000 beans for the desired moisture content and replicated five times. The weight was then taken using an electronic balance with 0.01 g accuracy. Other researchers have used this method including; [7] [8] [9] [10] [11].

3.2.2 Bulk density

The bulk density is the ratio of the mass sample of the seeds to its total volume. Bulk density, true density, and porosity play an important role in many applications such as design of silos and storage bins, separation from undesirable materials, sorting and grading, and maturity evaluation [10]. The bulk density of the Cocoa beans at the desired moisture content was determined by filling a 1000 ml container with the beans from a height of about 15 cm, striking the top level and then weighing the contents on an electronic balance [12] [13] [9].

3.2.3 Filling and emptying angles of repose

The filling angle of repose was determined by the method described by [14] and used by other researchers [15] [8] [16]. The beans at the desired moisture content were allowed to fall onto a wooden circular plate of 20 cm diameter mounted on a laboratory stand from a height of 15 cm to form a natural heap. The height of the heap was measured and the angle of repose (Θ_f) was calculated as:

$$\theta_f = \tan^{-1}\left(\frac{h}{100}\right) \quad (1)$$

The emptying angle of repose was obtained using a plywood box of dimensions 300 mm x 300 mm x 300 mm which had a front sliding panel. The box was filled with the beans at the moisture content being investigated, and the front sliding panel was quickly slid upward allowing the beans to flow out and form a natural heap. The angle of repose (Θ_e) was determined from measured height of beans at two points in the sloping bean heap and the horizontal distance between the two points using the relation:

$$\theta_e = \tan^{-1}\left(\frac{h_2 - h_1}{X_2 - X_1}\right) \quad (2)$$

Where,

x_1 is the horizontal distance corresponding to h_1 (*mm*)

x_2 is the horizontal distance corresponding to h_2 *(mm)*

h_1 is the height of a point on the surface of sloping pile of beans *(mm)*

h_2 is the height of a point above h_1 on the surface of sloping pile of beans *(mm)*

This procedure has been used by other researchers for grains and seeds [17] [15].

3.2.4 Co-efficient of static friction

The co-efficient of static friction was determined with respect to three surfaces: plywood, mild steel and rubber. These are common materials used for the transportation, storage and handling operations. A hollow PVC cylinder of 100 mm diameter and 50 mm height with open ends was filled with the beans at the desired moisture content and placed on an adjustable tilting table such that the cylinder does not touch the table surface. The tilting surface was gradually raised by means of a screw device until the cylinder with the beans just starts to slide down. The angle of the surface was read from a scale and the static co-efficient of friction was taken as the tangent of this angle. This method was used by others: [17] [18].

3.3 RESULTS AND DISCUSSION

The data were processed and suitable graphical representations were made of the various physical properties as they varied with moisture content so as to make a comparative study possible. Two graphs were produced on the same chart for both categories B and D for each property. Attempts were then made to explain the possible cause(s) of the differences that exist between the behaviour of the two categories as moisture content changes.

3.3.1 Bulk Density

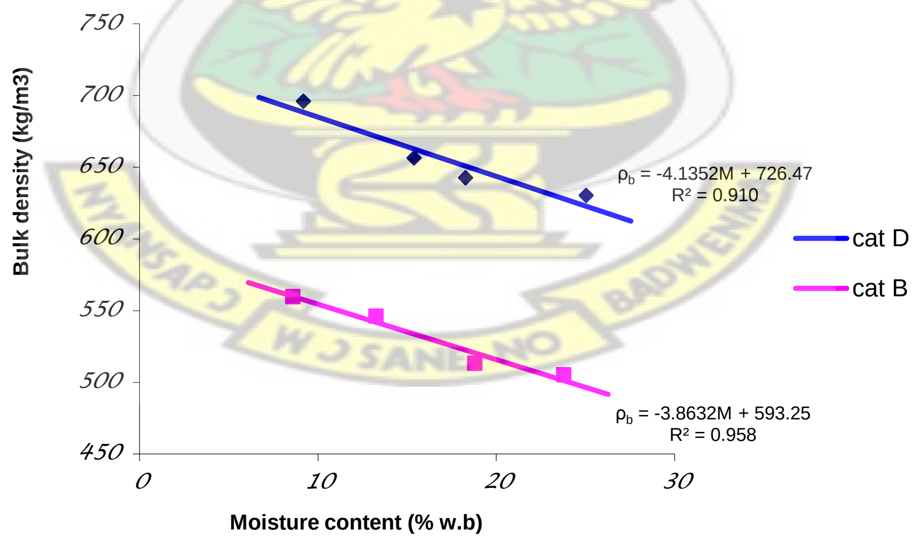

Figure 3-2: Effect of Moisture Content Variations on Bulk Density

Figure 3-2 depicts the variation of bulk density (ρ_b) with moisture content, (M) for categories B and D Cocoa beans. The bulk densities ranged from 559.60 kg/m^3 at 8.6% moisture content to 505.05 kg/m^3 at 23.78% moisture content for category B and 699.9 kg/m^3 at 9.19% moisture content to 630.18kg/m^3 at 25.05% moisture content for cat. D. The bulk density decreases linearly with increasing moisture content for both categories, the relations being:

$$\rho_b = -3.863M + 593.2 \qquad \text{(cat. B, } r^2 = 0.958) \qquad (3)$$

$$\rho_b = -4.135M + 726.4 \qquad \text{(cat. D, } r^2 = 0.910) \qquad (4)$$

The decrease in bulk density is an indication of a general lower bean weight in comparison to volume increment as moisture content increases. The bulk density of category D is higher than that of category B for the same moisture content. The smaller sizes as well as extent of variation in the shape of category D may have accounted for their higher values. The bulk densities of coffee (arabica and robusta), neem nuts and sunflower showed a similar decreasing variation with moisture content as found by [19] [20] and [21].

3.3.2 Emptying Angle of Repose

The variation in the emptying angle of repose, θ_e, with moisture content (M) is displayed in Figure 3-3. The emptying angle of repose increased linearly with increasing moisture content for category B, with the relation:

$$\theta_e = 0.915M + 21.32 \qquad \text{(cat B, } r^2 = 0.923) \qquad (5)$$

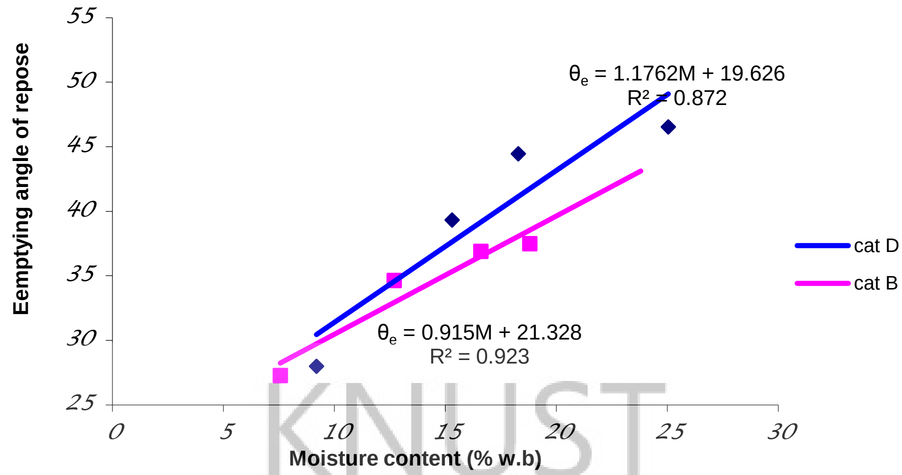

Figure 3-3: Effect of Moisture Content Variations on Emptying Angles of Repose

While for category D it increased non–linearly with increasing moisture content, the relation being given as:

θ_e=1.176M + 19.62 (cat D, r^2= 0.872) (6)

Category D displayed higher emptying angles of repose (from 27.98 to 46.52^o within a moisture content range of 9.19 to 25.08%) than those of cat B which increased from 27.26 to 37.47^o within a moisture content range of 7.56 to 18.8%. This may be due to variations in the surface texture of both categories as well as the relatively smaller sizes of the category. D beans. The variation exhibited in category. D is somewhat similar to that of bambara groundnut [1]. The emptying angle of repose of Coffee [21], neem nuts [19] and sunflower [22] were reported to have increased linearly with moisture content which is similar to that of Category B.

3.3.3 Filling Angle of Repose

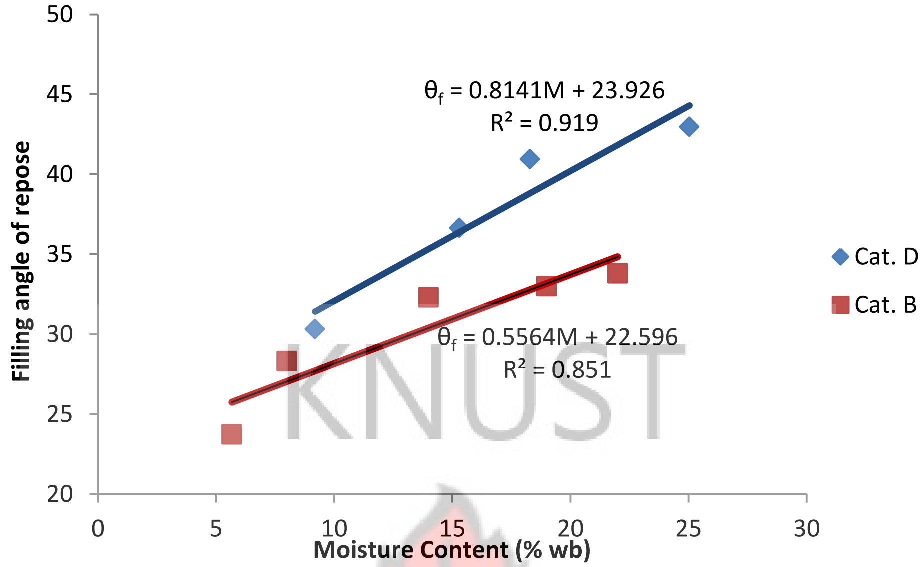

Figure 3-4: Effect of Moisture Content Variations on the Filling Angles of Repose

Figure 3-4 shows graphically how the filling angle of repose (θ_f) varies with moisture content (M). From moisture content of 5.67 to 22%, the filling angle of repose increases for category D with values ranging from 30.33 to 42.98^o. As moisture content increases from 9.19 to 25.04% for category B a non-linear increment is observed in its values from 23.74 to 33.81^o. At about 14% moisture content the filling angle of repose shows slight changes.

The graph for category D exhibits higher values than that of category B, which may be due to the differences in the sizes since smaller sizes can interlock more to cause a higher heap formation than relatively bigger sizes. It may also be due to the ability of moisture to adhere more on the surface of the smaller beans.

The relationship between the moisture content (M) and the filling angle of repose (θ_f) may be expressed as,

$\theta_f = 0.814M + 23.92$ (cat. D, r^2= 0.919) (7)

$\theta_f = -0.0556M + 22.59$ (cat. B, r^2 = 0.0.851) (8)

The results obtained were slightly lower than those obtained for both arabica and robusta coffee [21], even though there exist an increasing linear relation. A similar relation was observed for neem nuts [19].

3.3.4 1000- Bean Mass

The 1000-bean mass, M_{1000}, of categories B and D cocoa beans is graphically depicted in Figure 3-5. The mass of a 1000 bean mass increased with increasing moisture content for both categories. From the moisture content of 9.19 to 25.01%, category D recorded a mass ranging from 948.75 to 1112 g, while category B ranged from 1125 to 1300 g within the moisture content range of 8.6 to 23.08%. The relation is given by,

$M_{1000} = 8.831M + 1100.6$ (cat. B, r^2=0.984) (9)

$M_{1000} = 6.538M + 935.1$ (cat . D, r^2=0.998) (10)

The bigger dimensions of category B as compared to those of category D confirms the categorisation made by the Ghana Cocoa Board. Both categories exhibited linear relationship with increasing moisture variation. It has also been found that there exist linear relations for bambara groundnuts, coffee, sunflower, flaxseeds, barley grain and black cumin respectively [1][21][20][23][10][11].

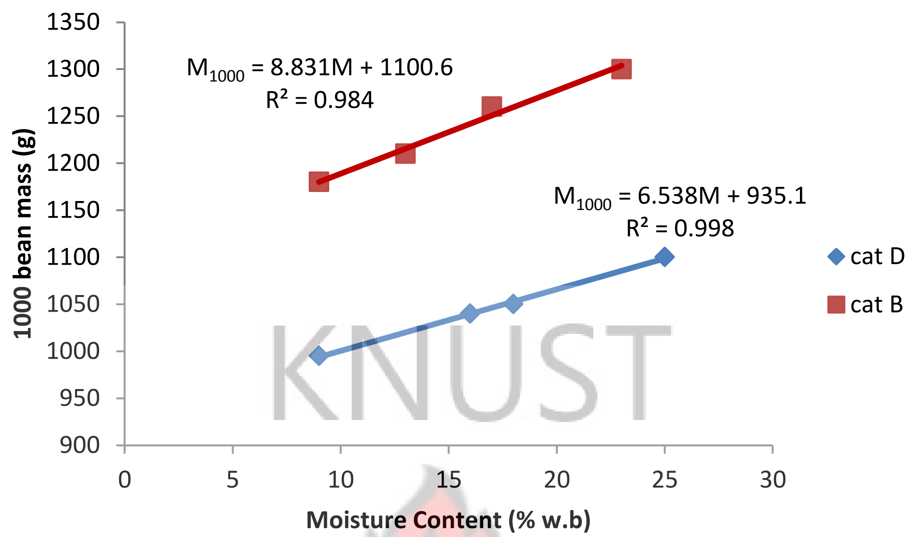

Figure 3-5: Effect of Moisture Content Variations on the 1000 Bean Mass

3.3.5 Co-Efficient Of Static Friction

Mild Steel

The values of the co-efficient of static friction (μ_S) between cocoa beans and mild steel from a moisture content of 9.19 to 25.04% w.b. for category D was 0.53 to 0.615 while that for category B was from 0.48 to 0.60 from a moisture content of 8.6 to 18.8%. This is depicted graphically in Figure 3-6 where both categories show an increase in their frictional co-efficient, linearly, on mild steel with increasing moisture content. However, category B possesses higher frictional co-efficient of static frictions than category D for moisture content above 14.73%. Below this moisture content the reverse occurs.

The co-efficient of static friction ((μ_s) of cocoa beans (categories B and D) bears the following relationships with the corresponding moisture contents:

$$\mu_s = 0.011M + 0.398 \qquad \text{(cat. D, } r^2 = 0.830) \qquad (11)$$

$$\mu_s = 0.005M + 0.489 \qquad \text{(cat. B, } r^2 = 0.945) \qquad (12)$$

The reason for the increasing friction co-efficient at higher moisture content may be due to the water present in the bean offering a cohesive force on the surface of contact in both cases. The difference in sizes (weight) and differences in surface characteristics could also account for the reason why category B shows higher frictional values than category D.

Chandrasekar and Visvanathan [21] found a linear relation between moisture content and the co-efficient of static friction for coffee (arabica and robusta) on mild steel. The friction was less for the robusta parchment than for arabica at all moisture contents. They also reported a similar positive correlation. Also, [10] [11] found an increasing linear relationship for barley and black cumin grains respectively on mild steel, glass and plywood.

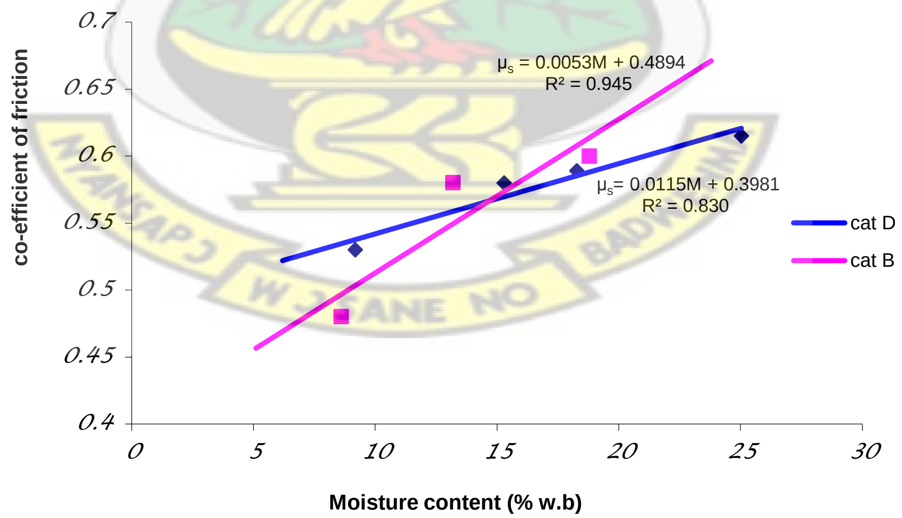

Figure 3-6: Effect of Moisture Content Variations on Co-efficient of Friction on Mild Steel

3.3.5.1 Plywood

The effect of moisture content of cocoa beans on frictional co-efficient (μ_p) against a plywood surface is given in Figure 3-7 for both category B and D. The co-efficient of static friction (μ_p) showed a positive linear correlation with moisture content for both categories with the relation:

$$\mu_p = 0.012M + 0.451 \qquad \text{(cat. B, } r^2\text{=0.999)} \qquad (13)$$

$$\mu_p = 0.004M + 0.523 \qquad \text{(cat. D, } r^2\text{= 0.993)} \qquad (14)$$

It was observed that the friction offered was less for category D beans than for category B at all moisture contents above 8.28%. The reason for the increases in friction co-efficient on a plywood surface at higher moisture content may be due to the water present in the bean that causes the beans to become rougher offering a cohesive force on the surface of contact in both cases. The difference in sizes as well as rougher surface development could also account for the reason why category B shows higher frictional values than category D.

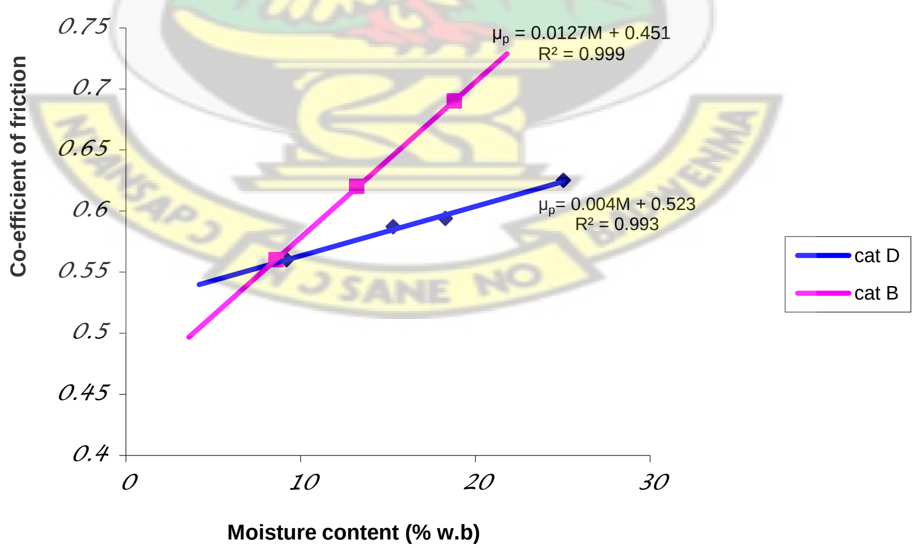

Figure 3-7: Effect of Moisture Content Variations on Co-efficient of Friction on Plywood

This was similar to the co-efficient of friction on plywood which also increased linearly for neem nuts, sunflower, coffee and black cumin grains as moisture content increased as reported by [19][20][21][11] while it showed a non-linear relationship with bambara groundnuts [1].

3.3.5.2 Rubber

The co-efficient of static friction (μ_R) on a rubber surface as displayed in Figure 3-8 increased linearly with increasing moisture content for category B, with the relation:

$$\mu_R = 0.004M + 0.184 \qquad \text{(cat B, } r^2 = 0.945) \qquad (15)$$

The co-efficient of static friction for category D increased non– linearly with increasing moisture content, the relation being given as:

$$\mu_R = 0.001M^2 + 0.62M - 0.327 \qquad \text{(cat B, } r^2 = 0.987) \qquad (16)$$

Category D displayed higher co-efficient of static friction than those of cat B at moisture content range of 8.6 to 25% wb.

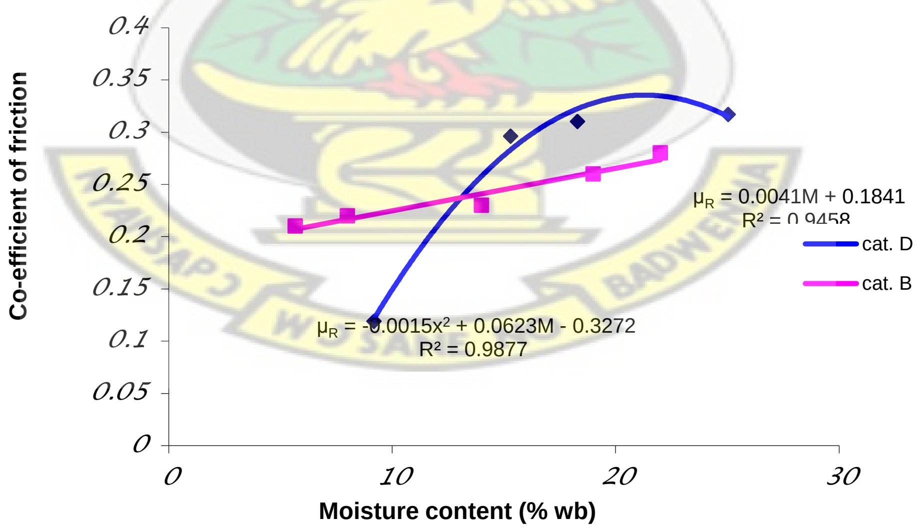

Figure 3-8: Effect of Moisture Content Variations on Co-efficient of Friction on Rubber

This may be due to variations in the surface texture of the both categories as well as the relatively smaller sizes of the category D beans. The co-efficient of static friction on rubber surface increased with increasing moisture content for coffee and lentil seeds as reported by [21][23].

3.4 CONCLUSION

The investigation into the comparative study of the categories B and D Cocoa beans revealed the following:

1. A decrease was observed in the bulk density of both categories with category D exhibiting higher values than category B.
2. The emptying and filling angles of repose increased for both categories, category D exhibiting greater angles than category B in each property.
3. The 1000 bean mass of category B was higher than those of category D even though both categories showed an increase in mass as moisture content rises.
4. The co-efficient of static friction increased for both categories on all the surfaces used; for plywood category D displayed higher values than category B; for mild steel category D displayed higher static frictional co-efficient than category B; for rubber category D had lower co-efficient of static frictions than category B until a moisture content of about 13% when the opposite is observed.

3.5 REFERENCES

[1] Baryeh, E. A. (2001). Physical properties of Bambara groundnuts. *Journal of Food Engineering. 47: 321-326.*

[2] Bart-Plange, A., Addo, A. and Dzisi, K. A. (2005). Effect of rewetting and drying on selected physical properties of '*Obatanpa*' Maize Variety. *Journal of the Ghana Institute of Engineers 3(1): 12-15.*

[3] Varnamkhasti, M. G., Mobli, H., Jafari, A., Rafiee, S., Soltanabadi, M. H. and Kheiralipour, K. (2007). Some engineering properties of paddy (var. sazandegi). *International Journal of Agriculture and Biology. [Accessed 20 August 2010]* Available at http://www.fspublishers.org

[4] Kiliçkan, A., Üçer, N. and Yalçin, I. (2010). Some physical properties of spinach (Spinacia oleracea L.) seed. *African Journal of Biotechnology 9(5): 648-655.*

[5] ICCO. (2002). International Cocoa Organization. http://www.icco.org

[6] Jonfia-Essien, W. A. (2004). Cocoa: West Africa (Ghana). In R. Hodges and G. Farrell (Eds), Crop Post Harvest: Science and Technology, 2: 216-245, Blackwell Publishing, Oxford, UK.

[7] Aviara, N. A., Gwandzang, M. I. add Hague, M. A. (1999). Physical properties of guna seeds. *Journal of Agricultural Engineering Research, 73: 105-11.*

[8] Bart-Plange, A. and Baryeh, E. A. (2003). The physical properties of category B Cocoa beans. *Journal of Food Engineering, 60: 219-227.*

[9] Coskuner, Y. and Karababa, E. (2007). Some physical properties of flaxseed (*Linum usitatissimum L.). Journal of Food Engineering, 78: 1067-1073.*

[10] Tavakoli, M., Tavakoli, H., Rajabipour, A., Ahmadi, H. and Gharibzahedi, S. M. T. (2009). Moisture-dependent physical properties of barley grains. *International Journal of Agricultural and Biological Engineering 2(4).*

[11] Gharibzahedi, S. M. T., Mousavi, S. M., Moayedi, A., Garavand, A. T., Alizadeh S. M. (2010). Moisture-dependent engineering properties of black cumin (Nigella sativa L.) seed. *Agric. Eng. Int: CIGR 12(1).*

[12] Konak, M., Carman, K. and Aydin, C. (2002). Physical properties of chick pea seeds. *Biosystems Engineering.* 82(1): 73-78.

[13] Paksoy, M. and Aydin, C. (2004). Some physical properties of edible squash (*Cucurbita pepo L.) seeds. Journal of Food Engineering*. 65: 225-231.

[14] Bouman, G. (1992). Grain Handling and Storage (Developments in Agricultural Engineering 4). pp 19- 26.

[15] Jain, R. K., and Bal. S. (1997). Physical properties of pearl millet. *Journal of Agricultural Engineering Research.* 66: 85-91.

[16] Ozturk, I., Kara, M., Elkoca, E. and Ercisli, S. (2009). Physico-chemical grain properties of new common bean cv. *'Elkoca-05' Scientific Research and Essay.* 4 (2):088-093.

[17] Singh, K. K. and Goswami, T. K. (1996). Physical properties of cumin seed. *Journal of Agricultural Engineering Research*. 64: 93-98.

[18] Suthar, S. H., and Das, S. K. (1996). Some physical properties of karinga seeds. *Journal of Agricultural Engineering Research.* 65: 15-22.

[19] Visvanathan, R., Palanisamy, P. T., Gothandapani, P. T., and Sreenarayanan, V. V. (1996). Physical properties of neen nut. *Journal of Agricultural Engineering Research.* 63: 19-26.

[20] Gupta R. K. and Das S. K. (1997). Physical properties of sunflower seeds. *Journal of Agricultural Engineering Research.* 66: 1- 8.

[21] Chandrasekar, V., and Visvanathan, R., (1999). Physical and thermal properties of coffee. *Journal of Agricultural Engineering Research.* 73: 227-234.

[22] Wang, B., Li, D., Wang, L., Huang, Z., Zhang, L., Chen, X. D. and Mao, Z. (2007). Effect of moisture content on the physical properties of fibered flaxseed. *International Journal of Food Engineering*. 3(5).

[23] Carman, K. (1996). Some physical properties of lentil seeds. *Journal of Agricultural Engineering Research.* 63: 87-92.

CHAPTER FOUR

4.0 SOME PHYSICAL AND MECHANICAL PROPERTIES OF CASHEW NUT AND KERNEL GROWN IN GHANA

Published as Bart-Plange, A., Mohammed-Kamil, A. P., Addo, A. and Teye, E (2012). International Journal of Science and Nature (IJSN). 3(2): 406-415, May 2012.www.scienceandnature.org. ISSN NO.: 2229-6441

KNUST

ABSTRACT

Physical and mechanical properties often needed for designing of cleaning, dehulling and sundry grain processing machineries were determined for cashew nut and kernel at moisture content of 5.0 - 9.0% wb. The average length, thickness, width, equivalent diameter, sphericity, unit mass, and volume for Cashew nuts were 41.15 mm, 23.92 mm, 32.76 mm, 31.89 mm, 77.37%, 13.1 g, and 312.54 mm^3 respectively. Those of the kernels were 33.16 mm, 15.87 mm, 17.91 mm, 21.23 mm, 64.02%, 4.28g, and 101.47 mm^3 respectively. The bulk density of Cashew nut and kernal decreased from 625.62 - 592.68 kgm^{-3} and 559.60 - 505.06 kgm^{-3} respectively. However, the true density, surface area, and porosity for kernels increased from 1100.16 - 1209 kgm^{-3}, 2754.68 - 2918.18 mm^2, and 43.19 - 51.02% respectively as moisture content increased (5.0 - 9.0%) wb. Also, for the nuts it increased from 946.23 - 991.29 kgm^{-3}, 1189.98 - 1309.02 mm^2, and 40.86 - 49.05% respectively as moisture content increased (5.0 - 9.0%) wb. The maximum compressive load, maximum displacement, stress, strain, and Young's modulus for the nuts increased from 0.445 - 0.574 kN, 7.760 - 8.008 mm, 2.225 - 2.872 MPa, 0.777 - 0.801 mm/mm and 4.666 - 9.853 MPa and for the kernel it increased from 0.146 - 0.213 kN, 3.006 - 4.105mm, 0.214 - 1.214 MPa, 0.355 - 0.472 mm/mm, and 2.446 - 6.416 MPa respectively as moisture content

increased from 5.0 - 9.0% wb. The relationship between compressive stress properties studied and moisture content were found to be significant at 0.05 probability.

4.1 INTRODUCTION

The cashew tree *(Anarcardium Occidentale)* is a native of Brazil and the Lower Amazons. The tree has been a valuable cash crop in the Americas, the West Indies, Madagascar, India and Malaysia (Frankel, 1991). The tree can grow up to about 12 metres high and has a symmetrical spread of up to approximately 25 metres.

The tree has a leathery oval leaves and bears pear-shaped fruits referred to as cashew apples which is red or yellowish in colour (Azam-Ali and Judge, 2001). At the end of each fruit is a kidney-shaped ovary, the nut, with a hard double shell. This yields two "Oils" one of which is found between the seed coat (pericarp) and the nuts and is called the Cashew Nut Shell Liquid (CNSL). It is used in industry as a raw material for brake lining compounds, as a water proofing agent, a preservative and in the manufacturing of paints and plastics. It is toxic and corrosive to the skin.

Edible oil can also be extracted from cashew nuts but there is no evidence of it being carried out commercially (Azam-Ali and Judge, 2001). A number of processes have now been developed for converting the cashew apple into various products such as jam, juice, syrup, chutney and beverage (Winterhaler, 1991). Nuts may be sold raw or as processed kernels and may be further processed into value-added products such as fried, roasted, or chocolate-coated kernels and confectioneries (Azam-Ali and Judge, 2001).

The economic importance of this special tree is such that though it is a native to Central and South America, it is now widely distributed throughout the tropics, particularly in many parts of Africa and Asia. Cashew tree tolerates a wide range of conditions including drought and poor soil, but cannot withstand cold frost. World Bank data estimates that 97% of production is from wild trees and only 3% is from established plantation (Rosengarten, 1984). Those that are cultivated are propagated by seed which are planted at a depth of 5 cm to 10 cm and at a rate of 2-3 per hole due to poor germination rate. The cashew tree matures and starts bearing fruits in the third or fourth year and reaches their mature yield by the seventh year with an average nuts yield ranging from 7 to 11 kg per annum. The tree can live for 50 to 60 years. The major producing countries of Cashew are Tanzania, India, Mozambique, Sri Lanka, Kenya, Madagascar, Thailand, Malaysia, Indonesia, Nigeria, Senegal, Malawi, and Angola. Cultivation of the crop in Ghana was captured into world records in recent years starting with 500 tonnes in 1990 and increasing to 7500 tonnes in 2000. Majority of the cashew farms are located in the Brong Ahafo Region with some few found in the Northern, Ashanti and Eastern regions.

Physical properties of agricultural materials and food products have several unique characteristics which set them apart from engineering materials. Unlike engineering materials, the irregular shape of most agricultural materials and food products complicates the analysis of their behaviour. Following this result, the study of physical properties plays an important role in developing sensors to control machines and processes. Also, it helps to detect quality difference in agricultural products. Esref and Halil (2007) reported that knowledge of physical properties constitutes important and essential engineering data in the design of machines, storage structures and processes.

Mechanical properties are properties that concern the behaviour of agricultural materials under applied forces. The study of mechanical properties is needed for textural analysis and better understanding of product quality. For example, firmness of horticultural products as measured by instrumental methods is frequently used to determine their maturity and ripeness. These are important in handling, storing, and processing procedures.

Force-deformation testing of agricultural materials can also be used to study damage which occurs during harvesting and handling of grains, seeds, fruits and vegetables. Knowledge of the behaviour of a particular agricultural material from testing or from test data enhances the evaluation of equipment used for its handling. One of the most important consideration in engineering design is to ensure that stresses in components do not exceed the strength of agricultural materials. The physical and mechanical properties of cashew nut and kernel are therefore essential for the design and construction of equipment and structures for handling, tranportation, processing, harvesting and storage of the nuts and kernels. The objective of this study was to investigate some moisture dependent physical and mechanical properties of cashew nut and kernel grown in Ghana.

4.2 MATERIALS AND METHODS

4.2.1 Sample Preparation

The cashew nuts used in the present study were procured from the local market at Wenchi in the Brong Ahafo Region of Ghana during the December 2009 harvesting season. The cashew samples were then transported to Nsawkaw, the administrative capital of the Tain District where they were processed at a local cashew processing company. Figures 4-1a and b show cashew nuts and kernels.

a.  b. 

Figure 4-1: a. Cashew Nuts and b. Cashew Kernels

The samples were manually cleaned to remove foreign materials, broken or immature nuts. The moisture content of the samples was determined by using a standard hot air oven method at 105°C for 24 hours (Dursun et *al*., 2006). In order to attain the desired moisture levels for the study, samples were conditioned by adding a calculated amount of distilled water based on equation (1) (Solomon and Zewdu, 2008, Bart-Plange and Baryeh, 2003):

$$Q = \frac{W_i(M_f - M_i)}{100 - M_f} \quad (1)$$

Where;

Q is the mass of water to be added in kg;
W_i is the initial mass of the sample in kg;
M_i is the initial moisture content of the sample in % db and
M_f is the final moisture content in % db.

The samples were sealed in separate polythene bags and kept in a refrigerator at 5°C for five days for the moisture to distribute uniformly throughout the sample. Before starting the test, the required quantity of seeds were taken out of the refrigerator and allowed to warm up to room temperature for about two hours (Nimkar and Chattopadhyay, 2001).

The moisture content of cashew nut/kernel was determined at four (4) moisture levels (5.0, 6.5, 8.0, and 9.0% wb). These values are within the range of moisture contents encountered for cashew nut/kernel from harvest to storage. It is recommended that for storage, the moisture content for cashew nut/kernel should be at 5% (Azam-Ali and Judge, 2001).

4.2.2 Experimental Procedures

To determine the average size of the seed, a sample of 100 seeds were randomly picked and the three principal dimensions namely, length *(a)*, width, *(b)* and thickness *(c)* axes were measured using a micrometer screw gauge with an accuracy of 0.01 mm. The width and thickness were measured perpendicular to the major axis. The geometric mean diameter *(Dg)* or equivalent diameter *(De)* as used by some researchers was calculated using the following relationship (Mohsenin, 1980):

$$D_e = (abc)^{1/2} \tag{2}$$

The Sphericity index (ϕ) of cashew nut and kernel were calculated using the following formula (Mohsenin, 1980).

$$\phi = \frac{(abc)^{1/2}}{a} x\ 100 \tag{3}$$

Jain and Bal (1997) have stated that kernel volume, V , and kernel surface area, S , may be given by equations (4), (5)(and (6):

$$V = \frac{\pi B^2 a}{6(2a - B)} \quad (4)$$

$$S = \frac{\pi B a^2}{2a - B} \quad (5)$$

$$Where; B = (bc)^{1/2} \quad (6)$$

The bulk density of nuts and kernels is defined as the ratio of the mass of sample of seeds to its total volume was measured by pouring samples into a cylindrical container of known volume, striking excess samples without compacting the nuts and kernels (Zewdu and Solomon, 2009; Karababa and Coskuner, 2007). The bulk density was calculated by dividing the mass of samples filling the cylinder with the volume of the cylinder.

The true density defined as the ratio of the mass of the sample to its kernel volume was determined using the water displacement method (Baryeh, 2001). A nut of known mass was immersed inside a known volume of water in a measuring cylinder. Owing to the short duration of the experiment and considering the nature of the skin of the samples which could easily absorb water, the amount of displacement was quickly recorded from the graduated scale of the cylinder. The experiment was repeated four times and the average values recorded. The ratio of weight of kernels to the volume of displaced water gave the true density (Ogunsina and Bamgboye, 2007; Karababa, 2006).

Porosity is the fraction of the space in the bulk sample which is not occupied by the kernels (Karababa, 2006; Baryeh and Mangope, 2002).

The porosity of bulk samples was computed from the values of true (kernel) density and bulk density using the following relationship (Mustafa, 2006; and Pradhan *et al.*, 2008):

$$\varepsilon = \frac{\rho_t - \rho_b}{\rho_t} x100 \qquad (7)$$

For the determination of mechanical properties, the Instron Universal Testing Machine (UTM) which is one of the most popular destructive test devices was used. The test was based on the force-deformation characteristics of the nut and this was done at four different moisture contents with four replications.

The device has three main components which are stable up and motion bottom of platform, a driving unit, and a data acquisition system. In order to conduct the test, samples were placed on the stable up platform and pressed with a motion probe. The rupture force of sample was measured by the dynamometer and data acquisition system, and the mechanical parameters of the test were automatically generated by the machine when programmed to determine the required mechanical properties of the cashew nut/ kernel.

4.3 RESULTS AND DISCUSSION

4.3.1 Physical Properties

4.3.1.1 Dimension of Cashew nut and kernel

At the moisture content of 5.0% wb the average length, thickness, width, equivalent diameter were 41.15 mm, 23.92 mm, 32.76 mm, 31.89 mm for cashew nuts and the corresponding values for kernel at the same moisture content were 33.16 mm, 15.87 mm, 17.91 mm and 21.23 mm respectively.

4.3.1.2 Sphericity Index

The values of sphericity index of the cashew nut and kernel were calculated individually with Eq. (3) by using the data on geometric mean diameter and the major axis of the cashew nut/kernel. The results obtained are represented in Figure 4-2. The sphericity decreased marginally from 64.02 to 63.66% and 77.90 to 77.68% at moisture content range of 5.0% to 9.0% wb for cashew nut and kernel respectively. A similar trend of sphericity has been reported by Aydin *et al.* (2002) for mahaleb, Özarslan (2002) for cotton and Sacilik *et al.* (2003) for hemp seed. The relationship between sphericity and moisture content for nut and kernel can be represented by:

$$\phi_n = 0.069M + 77.19 \qquad (8)$$

$$\phi_k = 0.061M + 64.13 \qquad (9)$$

The values for the coefficient of determination, R^2 were 0.872 and 0.880 respectively. The relationship between sphericity and moisture content was found to be significant at a significance level of 0.05.

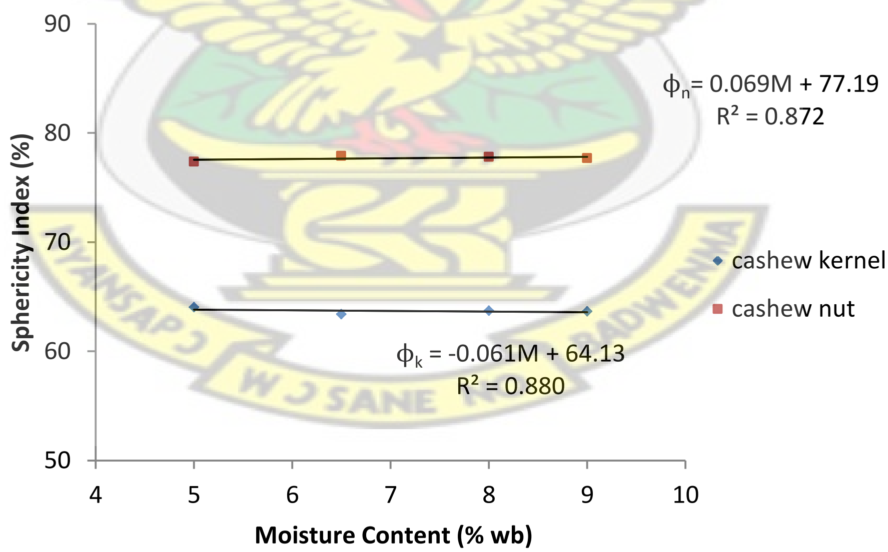

Figure 4-2: Effect of Moisture Content on Sphericity Index of Cashew Nuts/Kernels

4.3.1.3 Kernel Volume

The volume variation with kernel moisture content is shown in Figure 4-3. The volume increased linearly with a corresponding increase in moisture. When the moisture content changed from 5.0% to 9.0% wb, the volume increased from 101.47 mm^3 to 110.83 mm^3 for cashew kernel. Similarly, the volume of cashew nuts increased with moisture content from 312.54 mm^3 at 5.0% wb to 332.94 mm^3 at 9.0% wb.The relationship between the nut and kernel volumes and moisture content is given by the following equations:

$V_n = 4.761M + 289.30 \quad (R^2 = 0.965)$

$V_K = 2.283M + 89.64 \quad (R^2 = 0.976)$

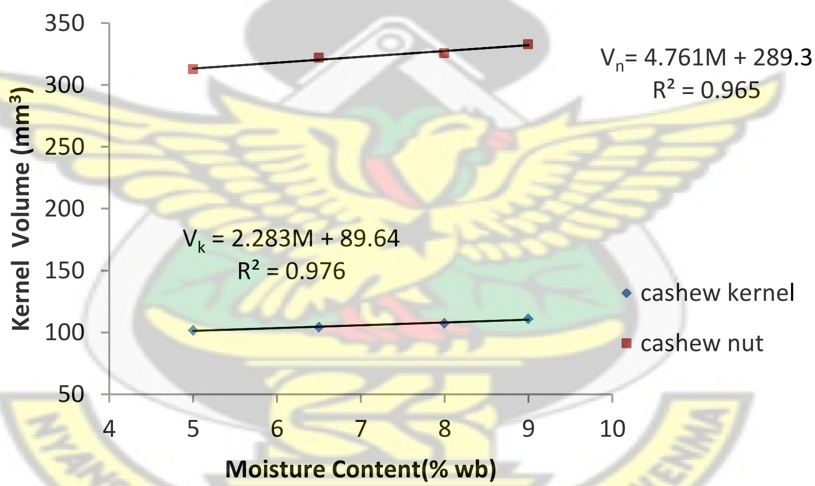

Figure 4-3: Effect of Moisture Content on Kernel Volume of Cashew Nut/Kernel

The increase in volume is obviously as a result of the increase in moisture. It can be seen from the graph (Figure 4-3) that the nuts absorbed more moisture than the kernels and this could be due to the CNSL between the shells and the kernel. Similar results have been recorded for a number of food and agricultural products.

Some of these products are; Popcorn kernel (Karababa, 2006); Millet (Baryeh, 2002); Moth gram (Nimkar *et al.*, 2005). Conversely, coriander seeds (Yalcin and Karababa, 2007); and Bambara groundnuts (Baryeh, 2001), recorded non linear relationship.

4.3.1.4 Surface Area

The values for surface area are presented in Figure 4-4. The surface area of the cashew kernel increased from1188.98 m^2 to 1309.02 m^2 and 2754.68 m^2 to 2918.36 m^2 for nut with moisture variation of from 5.0% to 9.0% wb. The relationship between moisture content and surface area (S) appears linear and can be represented by the regression equations:

S_n =38.54M + 2559 (R^2 0.957) (12)

S_K = 28.54M + 1046 (R^2 0.982) (13)

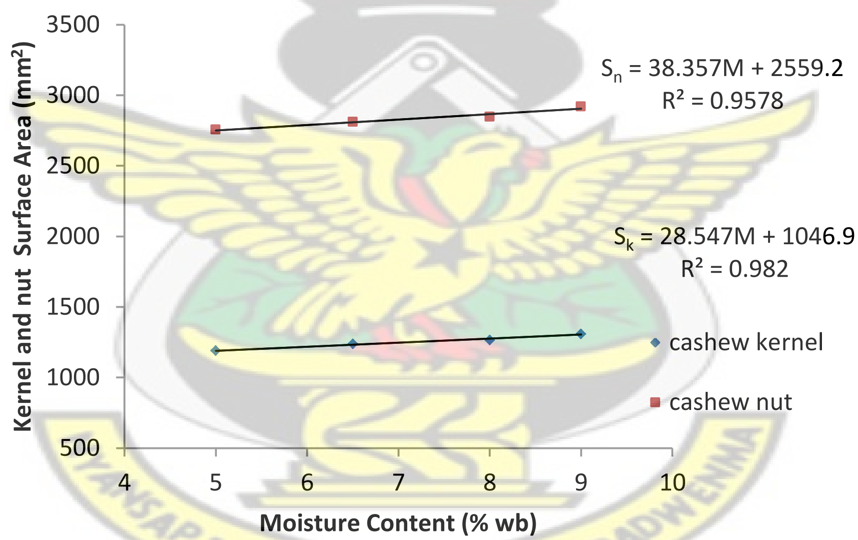

Figure 4-4: Moisture Content Effect on Kernel Surface Area of Cashew Nuts/Kernels

Sherpherd and Bhardwaj (1986); Baryeh (2001 and 2002) found similar results of surface area with pigeon pea, soybeans, bambara nuts and millet seeds respectively. However, Hsu *et al.* (1991) found the surface area of pistachios to decrease with increasing grain moisture content.

4.3.1.5 True Density

The variation of true density with grain moisture content is depicted in Figure 4-5. The true density increases linearly from 946.23 kgm^{-3} to 991.29 kgm^{-3} and 1100.16 kgm^{-3} to 1209.51 kgm^{-3} for kernel and nut respectively as the moisture content increased from 5.0% to 9.0% wb. The relationship between true density and moisture content was obtained as:

$$\rho_{tn} = 24.66M + 72.1 \quad (R^2 = 0.889) \tag{14}$$

$$\rho_{tk} = 11.79M + 889.2 \quad (R^2 = 0.966) \tag{15}$$

This increase in true density indicates that there is a higher grain mass increase in comparison to its volume increase as its moisture content increases. This plot of true density agrees with the findings of Singh and Goswani (1996) for cumin seed; Gupta and Das (1998) for sunflower seeds; Aviara *et al.* (1999) for guna seeds and Chandrasekar and Viswanthan (1999) for coffee. It is, however, contrary to the results of Esref and Halil (2007); Baryeh (2001) and Dursun *et al.* (2006) who found the true density to decrease with increase in moisture content for red kidney bean, barbunia bean, bambara groundnuts and sugar beet respectively. These seeds thus have lower weight increase in comparison to volume increase as their moisture contents increase.

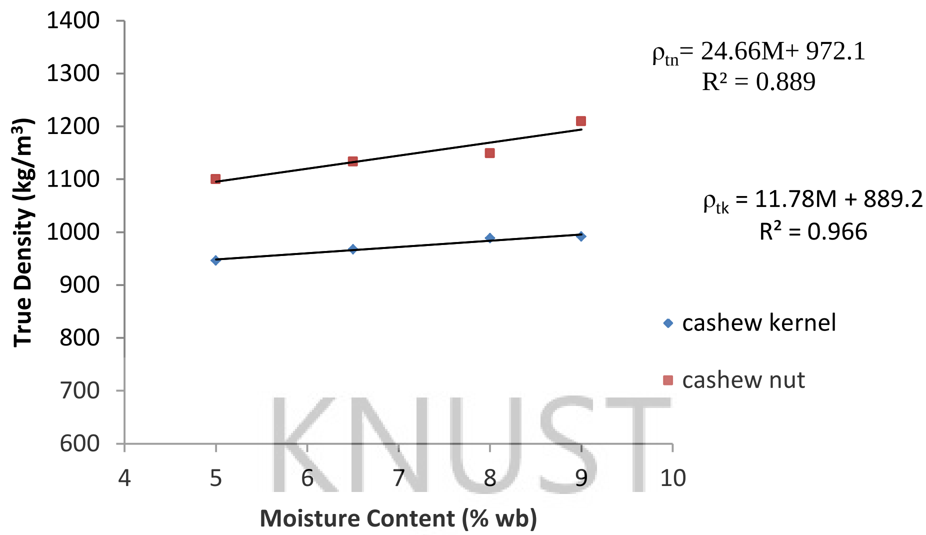

Figure 4-5: Effect of Moisture Content on True Density of Cashew Nut/Kernel

4.3.1.6 Bulk Density

The values of bulk density of cashew nut at different moisture levels varied from 625.62kgm^{-3} to 592.42kgm^{-3} when the moisture content increased from 5.0% to 9.0% wb. In addition, bulk density of kernel at different moisture levels also varied from 559.60kgm^{-3} to 505.06kgm^{-3} (Figure 4-6) and indicated a decrease in bulk density with an increase in moisture content. The decrease in bulk density with an increase in moisture content is mainly due to the higher increase in volume than the corresponding increase in mass of the material. The negative linear relationship of bulk density with moisture content was also observed by Aydin (2003) and Gupta and Das (1997) for almond nut, and sunflower seed respectively. Bulk density was found to have the following relations with moisture content:

$$\rho_{bn} = 8.534M + 666.80 \quad (R^2 = 0.976) \tag{16}$$

$$\rho_{bk} = 12.10M + 621.10 \quad (R^2 = 0.882) \tag{17}$$

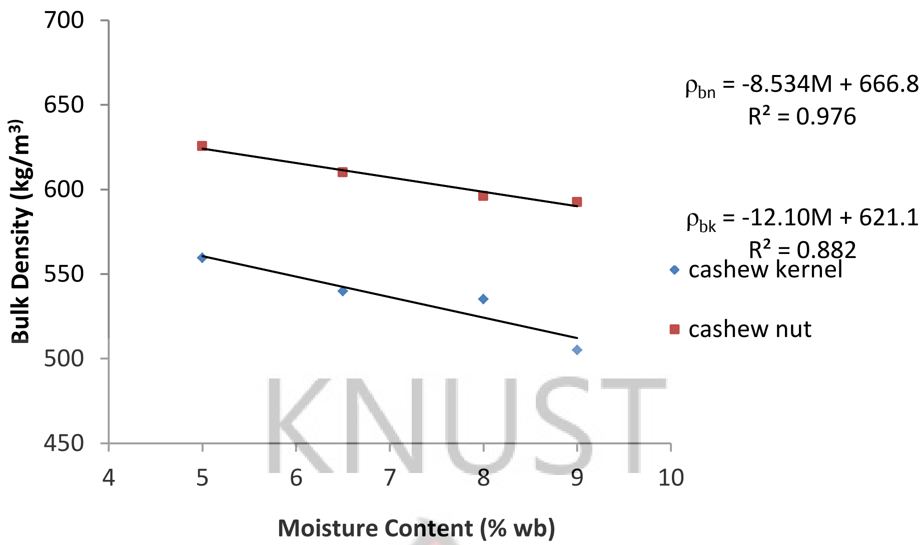

Figure 4-6: Effect of Moisture Content on Bulk Density of Cashew Nut/Kernel

4.3.1.7 Bulk Porosity

The porosity of the samples calculated using Equation7 at different moisture content is shown in Figure 4-7. The porosity increased linearly from 30.86% to 40.05% (kernel) and 43.19% to 51.02% (nut) with increase in moisture content from 5.0% to 9.0% wb. The increase in moisture content could be attributed to the expansion and swelling of the samples that might have resulted in more void spaces between the samples and hence the increase in bulk volume. The relationship between porosity and moisture content is given by:

$$\varepsilon_k = 2.123M + 20.09 \quad (R^2 = 0.946) \tag{18}$$

$$\varepsilon_n = 1.863M + 33.85 \quad (R^2 = 0.980) \tag{19}$$

Similar observations were reported for tef seed (Zewdu and Solomon, 2007); Niger seed (Solomon and Zewdu, 2009); category B cocoa bean (Bart-Plange and Baryeh, 2003); moth gram (Nimkar *et al.*, 2005); amaranth seeds (Abalone *et al.*, 2004); peanut and kernel (Aydin, 2006). However, a reverse relationship had been found for okra seed (Sahoo and Srivastava, 2002). This is an indication that porosity of different food and agricultural products could respond differently for changes in moisture contents which could be attributed to their morphological characteristics.

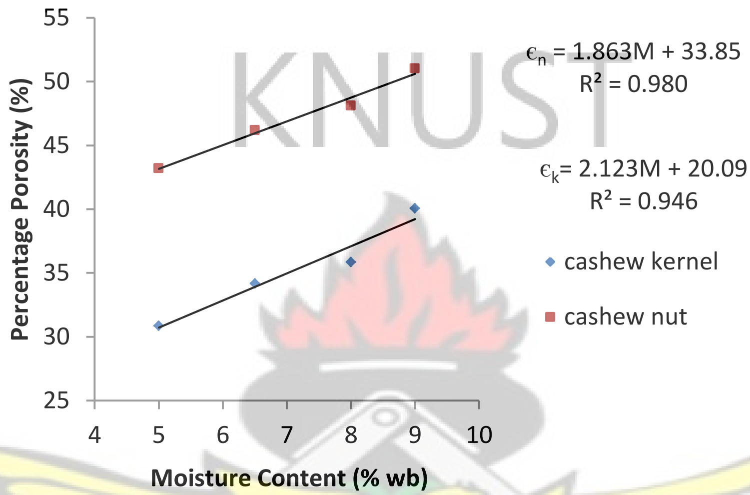

Figure 4-7: Effect of Moisture Content on Percentage Porosity of Cashew Nut/Kernel

4.3.2 Mechanical properties

4.3.2.1 Maximum compressive load

Figure 4-8 shows the relationship between maximum compressive load and moisture content. The value of the compressive load increased progressively as the moisture content was varied. The load at 5.0% wb moisture content increased from 0.445kN to 0.574kN at 9.0% wb for kernel and 0.146kN to 0.213kN at the same variation of moisture content for nuts.

The regression equation to express the relationship existing between compressive load and moisture content is as follows:

$$P_k = 0.029M + 0.296 \quad (R^2 = 0.934) \tag{20}$$

$$P_n = 0.017M + 0.059 \quad (R2 = 0.997) \tag{21}$$

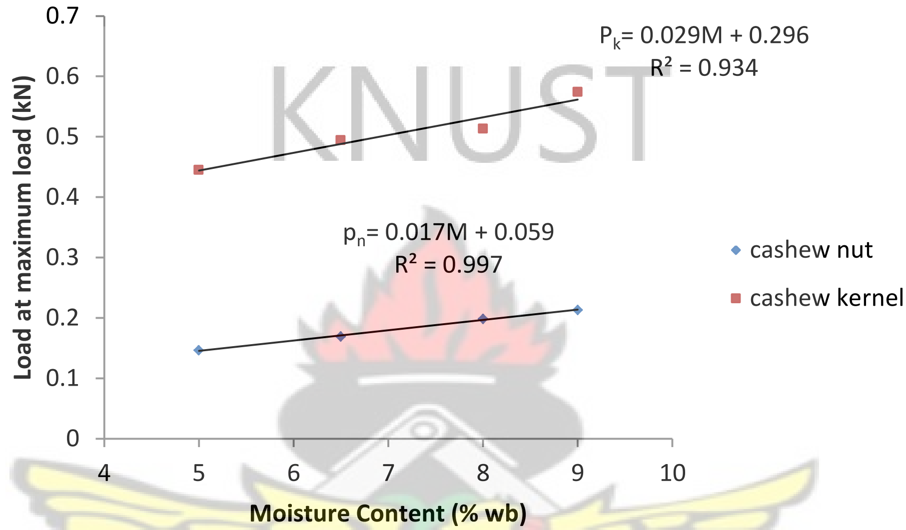

Figure 4-8: Relationship between Maximum Load of Cashew Nut/Kernel and Moisture Content

From the linear relationship, it can be said of the two slopes that the load required to crack the nuts was smaller than the load required to crush the kernels.

4.3.2.2 Maximum displacement

The maximum displacement of the cashew nut/kernel obtained from the experiments in the moisture content range of 5.0-9.0% wb was found to lie between 3.006-4.105mm (nuts) and 7.76-8.008 mm (kernel) respectively. The variation of maximum displacement with moisture content is shown in Figure 4-9. The average displacement for crushing the cashew kernel was 6.89 mm and for cracking the cashew nut was 4.50 mm.

The experimental values of the cashew nut/kernel as a function of moisture content in this study were correlated using the regression equations:

$$D_k = 0.052M + 7.472 \quad (R^2 = 0.672) \tag{22}$$

$$D_n = 0.317M + 1.292 \quad (R^2 = 0.870) \tag{23}$$

The kernel is tougher as compared with the nuts and therefore the kernel required a higher compression depth than the nuts.

KNUST

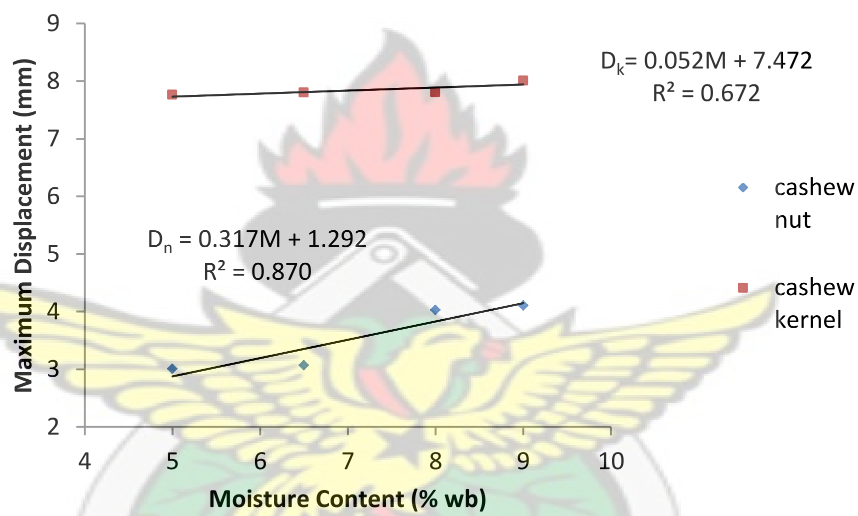

Figure 4-9: Variation in Maximum Displacement of Cashew Nut/Kernel with Moisture Content

4.3.2.3 Stress at maximum load

The relationship between compressive stress and moisture content is shown in Figure 4-10. The experimental values of compressive stress increased from 2.225-2.872MPa and 0.214-1.215MPa for cashew kernel and nut respectively. At the same variations of moisture content with stress both nuts and kernels samples exhibited linear relationships.

The regression equation resulting from the various relationships are as follows:

$$\sigma_k = 0.147M + 1.479 \qquad (R^2 = 0.933) \qquad (24)$$

$$\sigma_n = 0.255M + 1.076 \qquad (R^2 = 0.997) \qquad (25)$$

The cashew kernel recorded higher values than the cashew nuts. The reason accounting for this is the fact that, during the compression process, it took more force crushing the kernel than cracking the nut due to the oily nature of the kernel.

KNUST

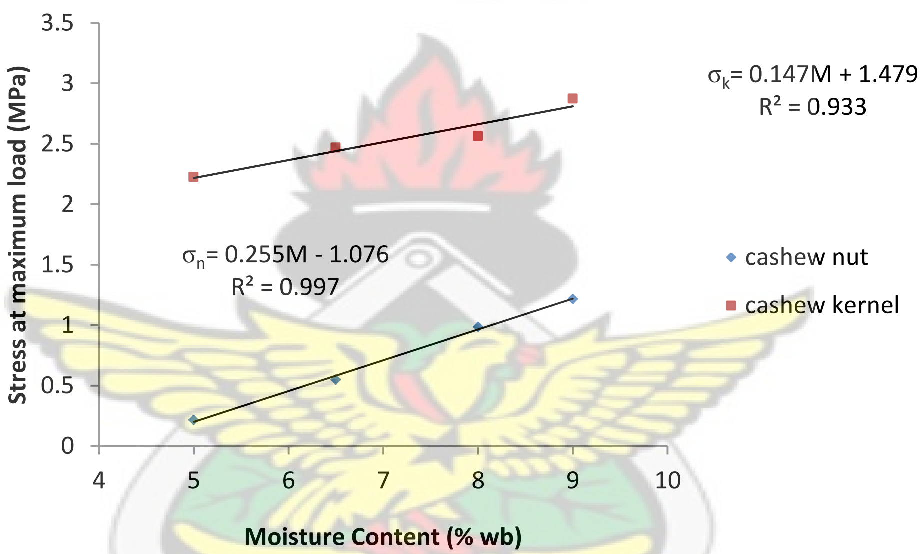

Figure 4-10: Variation in Compressive Stress of Cashew Nut/Kernel with Moisture Content

4.3.2.4 Strain at maximum load

The relationship between compressive strain and moisture content for cashew nut/kernel is shown in Figure 4-11. The values of both the cashew nuts and kernels increased as moisture content increased. The compressive strain of the cashew kernel increased from 0.777 mm/mm at a moisture content of 5.0% wb to 0.801 mm/mm at a moisture content of 9.0% wb. Similarly, the compressive strain of the nuts recorded, varied from 0.355 mm/mm at 5.0% wb to 0.472 mm/mm at a moisture content of 9.0% wb. The relationships between the cashew nut/kernel and moisture content are represented by the regression equations:

$$\epsilon_k = 0.005M + 0.746 \quad (26)$$

$$\epsilon_n = 0.028M + 0.200 \quad (27)$$

with the values of the coefficient of determination R^2 of 0.863 and 0.909 respectively. The strain values of the cashew kernel were higher than thoset of the nuts. The relationship between compressive strain and moisture content was found to be significant at a significance level of 0.05.

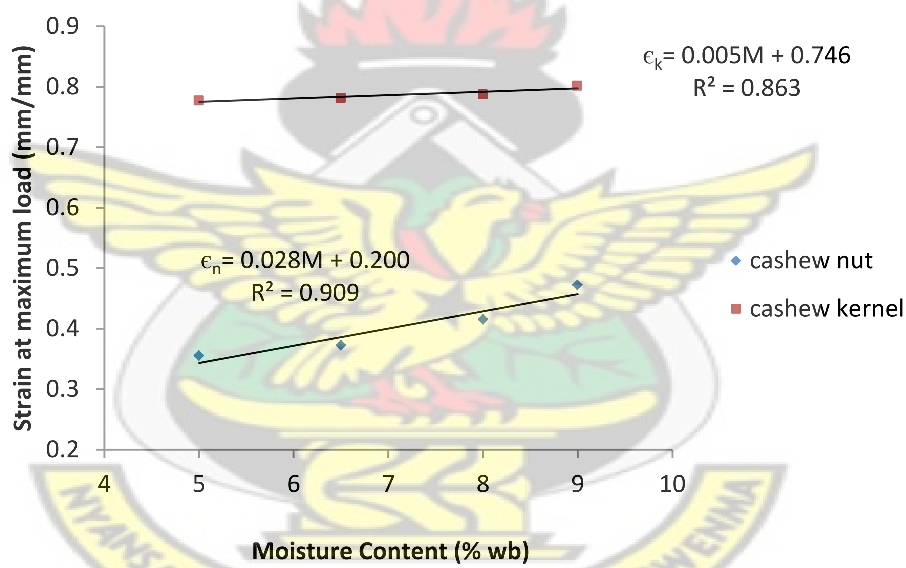

Figure 4-11: Variation in Compressive Strain of Cashew Nut/Kernel with Moisture Content

4.3.2.5 Young's modulus

Figure 4-12 shows the reationship between the Young's modulus and moisture content. Young's modulus increased from 4.666-11.139 MPa when the moisture content increased from 5.0-9.0% wb for the kernel. Similarly, the experimental values of Young's modulus increased from 2.446-

6.416 MPa with coresponding increase in moisture content from 5.0-9.0% wb. The relationship of Young's modulus and moisture content can be represented by the following equation:

$$C_k = 1.656M - 3.640 \quad (28)$$

$$C_n = 0.864M - 1.982 \quad (29)$$

with a value for R^2 of 0.996 and 0.843 respectively. A similar experiment conducted by Sayed and Maryam (2007) also recorded a similar linear relationship for kiwifruit.

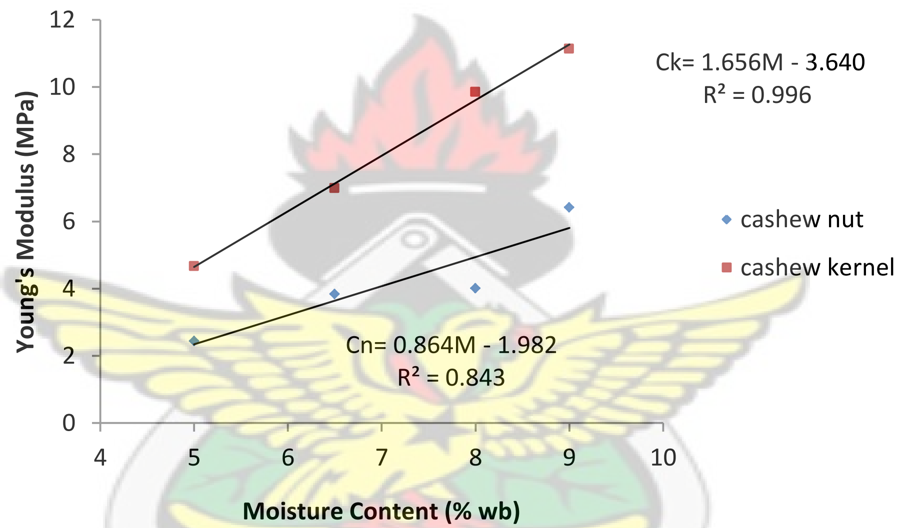

Figure 4-12: Variation in Young's Modulus of Cashew Nut/Kernel with Moisture Content

4.4 CONCLUSIONS

For the moisture content range between 5.0% wb and 9.0% wb all the various engineering properties of the cashew nut/kernel studied were found to be moisture dependent.

4.4.1 Physical properties

The length, width, thickness, and equivalent diameter increased marginally from 33.16 mm to 34.98 mm, 17.91 mm to 18.99 mm and 15.87 mm to 16.64 mm for the kernel and

41.16 mm to 42.25 mm, 32.76 mm to 33.16 mm, and 23.92 mm to 25.21 mm for nuts respectively with increase in moisture content from 5.0%-9.0% wb.

The sphericity decreased marginally from 64.02% to 63.66% (kernel) and 77.90% to 77.37% (nuts) as moisture content varied within the predetermined range of 5.0-9.0% wb. Also, the kernel and nut volumes increased linearly from 101.47 mm^3 to 110.83 mm^3 and 312.54 mm^3 to 332.94 mm^3 respectively.

True density of both kernel and nut were also seen to increase from 1100.16 kgm^{-3} to 1209.51 kgm^{-3} and 946.23 to 991.29 kgm^{-3} but on the other hand bulk density decreased from 625.62 kgm^{-3} to 592.42 kgm^{-3} and 559.60 to 505.06 kgm^{-3} as moisture content was increased from 5.0% to 9.0% wb.

With increasing moisture content, bulk porosity of the kernel and nut increased linearly from 40.86 % to 49.05% and 43.19% to 51.02% respectively.

4.4.2 Mechanical properties

Maximum compressive load of cashew kernel increased from 0.445 kN at a moisture content of 5.0% wb to 0.574 kN at 9.0% wb moisture content whilst that of cashew nuts increased from 0.146 kN to 0.213 kN at the same moisture content range. Similarly, the maximum displacement for the kernel and nut also increased from 7.760 mm to 8.008 mm and 3.006 mm to 4.105 mm respectively.

The compressive stress at maximum load, increased linearly from 2.225 MPa to 2.872 MPa for cashew kernel and 0.214 MPa to 1.215 MPa for cashew nut at a moisture content range from 5.0% to 9.0% wb. The compressive strain values of the cashew nut and kernel also increased from 0.777 mm/mm to 0.801 mm/mm and 0.355 mm/mm to 0.472 mm/mm respectively at a moisture content range of 5.0-9.0% wb.

As moisture content varied from 5.0% to 9.0% wb, the Young's modulus of cashew kernel and nut increased progressively from 4.666 MPa to 9.853 MPa and 2.446 MPa to 6.416 MPa respectively.

4.5 REFERENCES

Abalone, R., Cassinera, A., Gastón, A. and Lara, M. A. (2004). Some physical properties of Amaranth seeds. *Biosystems Engineering*. 89(1): 109-117.

Aviara, N. A., Gwandzang, M. I. and Hague, M. A. (1999). Physical properties of guna seeds. *Jounral of Agricultural Engineering Research.* 73: 105-11.

Aydin C. (2003): Physical properties of almond nut. *Journal of Food Engineering*. 60: 315–320.

Aydin, C. (2006). Some Engineering properties of peanut and kernel. *Journal of Food Engineering*. 79,810-816.

Aydin, C., Ogut, H., and Konak, M. (2002). Some physical properties of Turkish Mahaleb. *Biosystems Engineering.* 82 (2): 231-234.

Azam-Ali, S. H. and Judge, E. C. (2001). Small-Scale cashew nut processing, Schumacher Centre for Technology & Develoment, Bourton Dunsmore, Rugby, Wickshire, CV39QZ, UK

Bart-Plange, A. and Baryeh, E. A. (2003). The physical properties of category B cocoa beans. *Journal of Food Engineering.* 60 (3): 219-227.

Baryeh, E. A. (2002). Physical properties of millet. *Journal of Food Engineering*. 51: 39-46.

Baryeh, E. A. (2001). Physical properties of Bambara groundnuts. *Journal of Food Engineering*. 47: 321-326.

Baryeh, E. A. and Mangope, B. K. (2003). Some physical properties of QP 38 variety pigeon pea. *Journal of Food Engineering.* 56: 341-347.

Chandrasekar, V. and Viswanathan, R. (1999). Physical and thermal properties of coffee. *Journal of Agric. Engineering research.* 73: 227-234

Coskuner Y, Karababa E (2005). Some Physical Properties of Flaxseed (*Linum usitatissimum* L.), *Journal of Food Engineering*. 78: 1067-1073.

Coskuner, Y. and Karababa, E. (2007). Properties of coriander seeds (*Coriandum sativum). Journal of Food Engineering.* 80: 408-416.

Dursun, I. Dursun, E. and Tuğrul, K. M. (2006). Some physical properties of sugar beet seed. *Journal of Stored Products Research*. 43: 149-155.

Esrif, I. and Halil, Ü. (2007). Moisture-dependent physical properties of white speckled red kidney bean grains. *Journal of Food Engineering*. 82: 209-216.

Frankel, H. (1991). Engineering properties of foods. *American Society of Agricultural Engineers* (ASAE). St. Joseph, Michigan, 407p.

Gupta, R. K. and Das, S. K. (1997). Some physical properties of green gram. *Journal. of Agricultural Engineering Research.* 72: 175-180

Gupta, R. K. and Das, S. K. (1998). Friction coefficients of Sunflower seeds and kernels on various structural surfaces. *Journal of Agricultural Engineering Research.* 66: 1-8.

Hsu, M. H., Mannapperuma, J. D., and Singh, R. P. (1991). Physical and thermal properties of pistachios. *Journal of Agricultural Engineering Research.*49: 311-321.

Jain, R. K. and Bal, S. (1997). Properties of pearl millet. *Journal of Agric. Engineering Research.* 66: 85-91.

Karababa, E. (2006). Physical properties of popcorn kernels. *Journal of Food Engineering.* 72: 100-107.

Karababa, E., and Coşkuner, Y. (2007). Some physical properties of flaxseed (*Linum usitatissimum* L.). *Journal of Food Engineering*. 78: 1065-1073.

Majdi A. A. and Taha M. R. (2007). Effect of moisture content on some physical properties of green wheat. *Journal of Food Engineering.* 79: 1467-1473.

Mohsenin, N. N. (1980) Physical properties of plant and Animal materials. Gordon and Breach Science Publishers, New York. pp. 51-87

Mustafa, C. (2006). Physical properties of barbunia bean seed. *Journal of Food Engineering.* 80: 353-358.

Nimkar, P. M. and Chattopadhyay, P. K. (2001). Some physical properties og green gram. *Journal of Agric. Engineering Research.* 80: 183-189.

Nimkar, P.M., Dipali, S. and Renu, M. D. (2005). *Biosystems Engineering*. 91(2): 183-189.

Ogunsina B. S. and Bamgboye A. I. (2007). Effects of pre-Shelling treatment on the physical Properties of cashew nut (*Anacardium Occidentale*). *Institute of Agrophysics. Polish Academy of science*. 21: 385-389.

Ozarslan, C. (2002). Physical properties of cotton seed. *Biosystems Engineering.* 83 (2): 169-174

Pradhan, R. C., Naik, S. N., Bhatnagar, N. and Vijay, V. K. (2008). Industrial crops and food products. Doi: 10. 1016/jindcrop. 07. 002.

Rosengarton, P. (1984). Physical properties of plant and Animal materials. Second Edition, Gordon and Breach Science Publishers, New York. 891p.

Sacilik, K., Ozturk, R., and Keskin, R. (2003). Some physical properties of hemp seed. *Biosystems Engineering.* 86(2): 191-198.

Sacilik, K., Öztürk, R. and Keskin, R. (2003). Some physical properties of hemp seed. *Biosystems Engineering*. 86(2): 191-198.

Sahoo, P. K. and Srivastava, A. P. (2002). Physical properties of Okra seed. *Biosystems Engineering.* 83 (4): 441-448.

Sayed, M. A. R. and Maryam, B. P. (2007). Some physical and mechanical properties of kiwi fruit. *International Journal of Food Engineering*. 3(6): 56-75.

Shepherd, H. and Bhardwaj, R. J. (1986). Moisture dependent physical properties of pigeon pea. *Journal of Agric. Engineering Research.* 35: 227-234.

Singh, K. K. and Goswami, T. K. (1996). Physical properties of cumin seed. *Journal of Agricultural Engineering Research.* 64: 93-98.

Solomon, W. K. and Zewdu, A. D. (2008). Moisture dependent physical properties of Niger (*Guiconia abyssinica* Cass.) seed. *Industrial Crops and Products.* Doi: 10. 1016/jindcrop. 04. 018.

Winterhaler, H H. (1991). Physical properties related to drying twenty food grains. Paper 80-353, *American Society of Agricultural Engineers*. St Joseph, Michigan.

Zewdu, A. D. and Solomon, W. K. (2007). Moisture dependent physical properties of tef seed. *Biosystems Engineering*. 96(1): 57-63.

CHAPTER FIVE

5.0 COMPRESSIVE PROPERTIES OF COCOA BEANS CONSIDERING THE EFFECT OF MOISTURE CONTENT VARIATIONS

Published as Bart-Plange, A., Addo, A., Abano, E.K. and Akowuah, J.O. (2012). *International Journal of Engineering and Technology (IJET UK). 2(5): 850-858*

http:/*www.iet-journals.org*. ISSN NO.: 2049-3444

KNUST

ABSTRACT

The compressive properties of premium quality cocoa beans from Ghana considering the effect of moisture content in the moisture range of 7% to 22 % (w.b) were studied. The results of the study demonstrated that the displacement at maximum load and crushing energy had more positive linear function with moisture content and increased significantly from 0.80 mm to 1.87 mm and from 0.013 J to 0.2 J respectively. The compressive strain and Young's modulus decreased significantly in linear relationship with very high correlation coefficient within the confines of the moisture content, which increased from 0.009 to 0.0045, and 1300 MPa to 205 MPa respectively. The compressive stress, however, decreased exponentially with increasing moisture content from 1.5 MPa to 0.3 MPa. These findings provide useful information for food and agricultural engineers in the design of suitable cocoa beans crackers.

5.1 INTRODUCTION

Cocoa (*Theobroma Cacao*) is an ancient crop of the lowland tropical forest, which originated from the Southern and Central America (Lefeber *et al*., 2011). In West Africa, cocoa is one of the most important cash crops. Globally, Ghana's cocoa bean production is ranked second in the world after her western neighbour Côte d'Ivoire (FAOSTAT, 2005). The cocoa beans from Ghana are also viewed as the best premium quality in the world (Ntiamoah and Afrane, 2008). The cocoa crop does not only serve as the major source of revenue for farmers', accounting for about 70–100% of annual household incomes (Ntiamoah and Afrane, 2008) but also the provision of socio-economic infrastructure in Ghana. The cocoa industry continues to employ about 60% of the national agricultural labour force in the country (Appiah, 2004). Ghana's cocoa beans are usually processed into chocolate, cocoa powder, cocoa liquor, cocoa butter, and cake. Cocoa is a popular raw material in the pharmaceutical, cosmetics, and the food industries. The crop is very low in cholesterol and a good source of protein, potassium, and zinc (Nutrtion data.com, 2011). In view of this, the government of Ghana is committed to ensuring that the country processes more of the cocoa beans into downstream products for both the local and international markets (Awua, 2002).

Freshly harvested cocoa beans have been found to have an unpleasant and astringent flavour, hence it is extremely essential to ferment, dry and roast raw cocoa beans to obtain the desired organoleptic properties (Beckett, 2009; De Vuyst *et al*., 2009; Thompson *et al*., 2007). The drying of cocoa beans is associated with moisture content changes accompanied by shrinkage and volume changes (Gereke and Niemz, 2010). The hydroscopicity of the cocoa bean affects its physical and mechanical properties. The knowledge of mechanical properties provides the basis for avoiding failure in engineering applications. From an engineering point of view, information and data on the mechanical properties of cocoa beans are necessary in the mechanization of various unit operations involved in the post-harvest processing. It also helps in the development of optimization parameters for efficient and effective processing equipment (Burubai *et al.*, 2007). Compressive and engineering properties are important in many problems associated with the design of machines and the analysis of the behaviour of the product during unit operations such as drying, cleaning, sorting, crushing, and milling (Akaaimo and Raji, 2006). The solutions to problems of these processes involve knowledge of the compressive and engineering properties

(Irtwanged Igbeka, 2002). This was supported by Kutte (2001) that in the design of any agricultural handling and processing machine, properties of the crop must be taken into account.

It is reported that production of cocoa beans jumped from 20% to 35% in the 2004/2005 harvesting season (Ntiamoah and Afrane, 2008). The increase in cocoa bean production has called for the design of processing machines in the processing of the beans into finished products. In the mechanization of the unit operations involved in the cocoa industry, the compressive properties of the beans play an essential role in the design of optimized cocoa bean processing machines. The study of material properties includes its compressive behaviour. The compressive behaviour of industrial hemp stalks (Khan *et al*., 2010), rough rice (Shitanda *et al*., 2002; Corrêa *et al*., 2007), pulse seeds (Rybiński *et al*., 2009), sea buckthorn berries (Khazaei and Mann, 2004), and wood (Gereke and Niemz, 2010) have been investigated. The compression behaviour of agricultural materials has been shown not to obey Hookes law the way metals do (Shitanda *et al*., 2002). Their compression properties are reported to be significantly affected by factors such as moisture content and temperature (Delwiche, 2000; Shitanda *et al*., 2002). Bart-Plange and Baryeh (2003) studied the physical properties of category B cocoa beans considering the effect of moisture content. Additionally, the influence of moisture content variation on the mechanical properties of Ghana's cocoa bean has been studied (Okyere, 2005; Anass, 2006). However, the effect of moisture content on the compressive properties of cocoa beans is unavailable in scientific literature.

Therefore, the objective of this research was to investigate the effect of moisture content on the compressive properties of cocoa beans that are relevant for the design of processing machines.

5.2 MATERIALS AND METHODS

5.2.1 Sample preparation

Cocoa beans of good quality were obtained from the 2004/2005 harvesting season from the warehouse of the Quality Control Division of the Ghana Cocoa Board and the Kuapa Kokoo

Limited, a cocoa buying company in Kumasi, Ghana. The cocoa had been prepared for export to the international market, making it very suitable for the study. The initial moisture content of 7.00%wb was determined by keeping a ground sample of 5g in the oven set at a temperature of 130^0 for two hours (Food Storage Manual, 1995). The desired moisture content for higher values were obtained by adding distilled water of mass following equation (1):

$$M_w = \frac{Mi(m_f - m_i)}{(100 - m_i)} \quad (1)$$

Where,

M_w is the mass of distilled water (g),

M_i is the initial mass of sample (g),

m_f is the final moisture content of sample (%w.b.) and

m_i is the initial moisture content of sample (%w.b.).

The prepared samples were sealed in airtight polythene bags and kept in a refrigerator at 5 ^oC for one week to allow the moisture to diffuse uniformly into the beans. Prior to using the beans they were taken out of the refrigerator and allowed to warm up to room temperature. Similar approaches have been used by Aviara *et al*. (1999) for guna seed, Deshpande *et al*. (1993) for soybean, and Singh and Goswami (1996) for cumin seed. After conditioning the samples to the desired moisture levels of 7, 10, 14, 18 and 22%, the dimensional properties were determined for four replicates and the mean values calculated.

5.2.2 Determination of physical properties

The average size was determined based on 100 randomly selected seeds. To determine the average size of the seed, a sample of 100 seeds were randomly picked and the three principal dimensions namely, length *(a)*, width, *(b)* and thickness *(c)* axes were measured using a micrometer screw gauge with an accuracy of 0.01mm. The width and thickness were measured perpendicular to the major axis. The geometric mean diameter *(Dg)* or equivalent diameter *(De)* as used by some researchers was calculated using the following relationship (Mohsenin, 1980) :

$$D_g = (abc)^{1/3} \tag{2}$$

The Sphericity index (∅) were calculated using the following formula (Mohsenin, 1987):

$$\emptyset = \frac{(abc)^{1/3}}{a} \tag{3}$$

5.2.3 Compression test

The compression test was conducted on the cocoa beans at five moisture content levels (7%, 10%, 14%, 18, 22% w.b) using the Instron Universal Testing Machine (IUTM) controlled by a micro-computer. Prior to the compression test, the linear dimensions and the sphericity of the cocoa beans were measured. During a compressive test, the cocoa bean was placed laterally on the stable up platform and was compressed with a motion probe at a constant speed until the specimen fractured. The data acquisition system generated the rupture load and the displacement automatically during the compression. The load-displacement curve was used to derive the compressive properties of cocoa beans. The maximum compressive load, the load at which the bean fractures, was determined by the ratio of peak load of the displacement curve.

Treating the cocoa bean as a sphere the maximum compressive stress, strain, and crushing energy were determined using the following equations:

$$\sigma_{max} = \frac{P_{max}}{dL} \quad (4)$$

$$\varepsilon_{max} = \frac{\delta l}{l} \quad (5)$$

$$E_c = \frac{P}{2} \times \Delta D \quad (6)$$

Where,

σ_{max} is the maximum compressive stress in MPa, P_{max} is the maximum load in N, d is the mean diameter in mm, and L is the mean length in mm. ε_{max} is maximum compressive strain in mm/mm, l is the mean width of the specimen in mm, ΔD is the displacement interval in mm, E_c is the crushing energy in J,

5.2.4 Data analysis

An analysis of variance (ANOVA) was performed to examine the effects of experimental factors and their interactions using SPSS 2007. Means of treatments were compared using Fisher's least significant difference. Regression analysis was performed on the data to examine the trends of compressive properties in relation to the cocoa bean moisture content with MS excel. A significant level of probability $p < 0.05$ was used for all analysis. All measurements were replicated four times.

5.3 RESULTS AND DISCUSSION

5.3.1 Linear Dimensions of test specimen

Table 5-1 shows the mean linear dimensions length, width, thickness, effective mean diameter and sphericity of the cocoa bean specimen used for the compression test. The mean linear dimensions slightly increased from 21.47 to 22.08 mm, 12.01 to 12.65 mm, 7.27 to 7.32mm, and 12.26 to 12.61 for various dimensions of length, width, thickness, and effective diameter respectively. The sphericity values were fairly constant ranging from 0.57 to 0.58. The mean values of principal dimensions recorded in the experiment agreed with what Bart-Plange and Baryeh (2003) reported for category B cocoa beans within the moisture content range studied.

Table 5-1: Mean Dimensions of the Cocoa Beans Used for the Compression Experiment

Moisture content (% w.b)	**Mean Length Mm**	**Mean width mm**	**Mean thickness mm**	**Mean effective diameter (mm)**	**Sphericity**
7	21.47	12.01	7.27	12.26	0.57
10	21.69	12.09	7.19	12.28	0.57
14	22.04	12.49	7.21	12.49	0.57
18	22.05	12.62	7.31	12.59	0.58
22	22.08	12.65	7.32	12.61	0.58

5.3.2 Displacement at Maximum Load

The variation of cocoa bean moisture content versus displacement at maximum load is shown in Figure 5-1. The compressive strength of the cocoa bean was described by the natural rest position of the bean (lateral orientation). It is clearly indicated that displacement at maximum load of the cocoa beans increased with increase in moisture content from 0.80 mm to 1.87 mm.

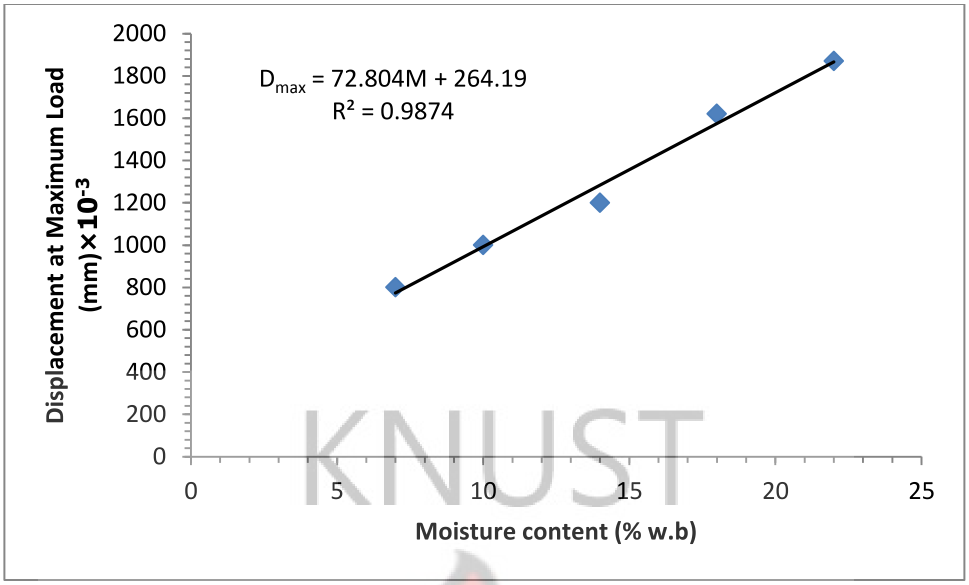

Figure 5-1: Variation of Cocoa Bean Moisture Content against Displacement at Maximum Load

The trend of the variation illustrates that as moisture content increases, the maximum deformation of the bean also increase. The relationship can be best described by a linear function with a very high correlation coefficient of 0.99 expressed by the following equation:

$$D_{max} = (72.80M + 264.19) \times 10^{-3} \quad (7)$$

5.3.3 Compressive Stress and Strain

Figure 5-2 illustrates the variation of compressive stress against the cocoa bean moisture content. It is possible to verify that maximum lateral compression exponentially decreased with increase in moisture content from 1.5 MPa to 0.3 MPa when the moisture content increased from 7% to 22% (w.b).

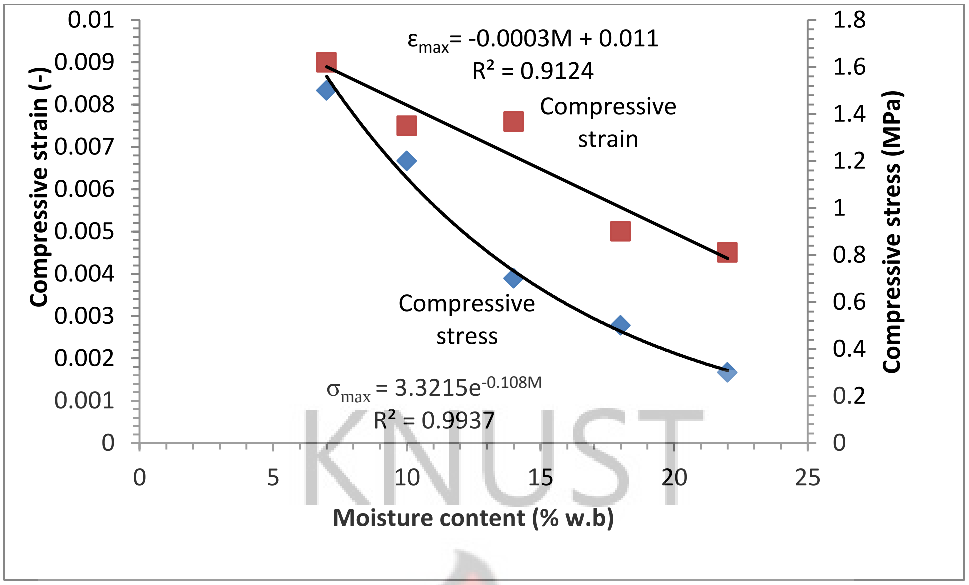

Figure 5-2: Variation of Compressive Strain and Stress Versus Bean Moisture Content

There was a similar reduction in compressive strain as moisture content increased from 0.009 to 0.0045 mm/mm. However, the decrease in compressive strain was better explained by a linear relationship (Figure 5-2). The influences of cocoa bean moisture content on the compressive stress and strain were well expressed by equations 8 and 9, which had high correlation coefficients ranging between 0.91 and 0.99. Gereke and Niemz (2010) reported a decrease in the compressive stress of cross laminated solid wood panels in the moisture range of 10 to 13%. Delwiche (2000) found a decrease in maximum compressive stress as wheat kernel moisture content increased in the range of 3 to 28 % (d.b). Comparing the compressive stress values recorded in this study with other authors' results, it was lower than the 36 MPa reported by Shitanda *et al*. (2002) for compressive stress of long grain rice at moisture content of 15% (w.b) and 25.7 MPa for compressive stress of wheat at 14% (d.b) (Delwiche, 2000)

$$\sigma_{max} = 3.3215\exp(-0.108\text{M}) \quad (8)$$

$$\varepsilon_{max} = -0.0003\text{M} + 0.011 \quad (9)$$

The increasing trend may have been caused by the interactions between the starch and protein matrix in the cocoa beans. This inherent property of the cocoa bean may have decreased the toughness of the beans as the moisture content increased (Dobraszczyk, 1994).

5.3.4 Young's Modulus and Crushing Energy

The variation of young's modulus as a function of bean moisture content is shown in Figure 5-3. An increase in moisture content decreased the Young's modulus linearly with a negative slope. The Young's modulus decreased from 1300 MPa to 205 MPa as the moisture content increased from 7 % to 22% (w.b).

The experimental values recorded were highly correlated with R^2 of 0.955. The regression equation between cocoa bean moisture content and Youngs modulus was as shown in eq [10]. Published results by Delwiche (2000) suggest a decrease in Young's modulus as wheat kernel moisture content increases in the range of 3 to 28 % (d.b).

$$E = -67.099M + 1708.8 \tag{10}$$

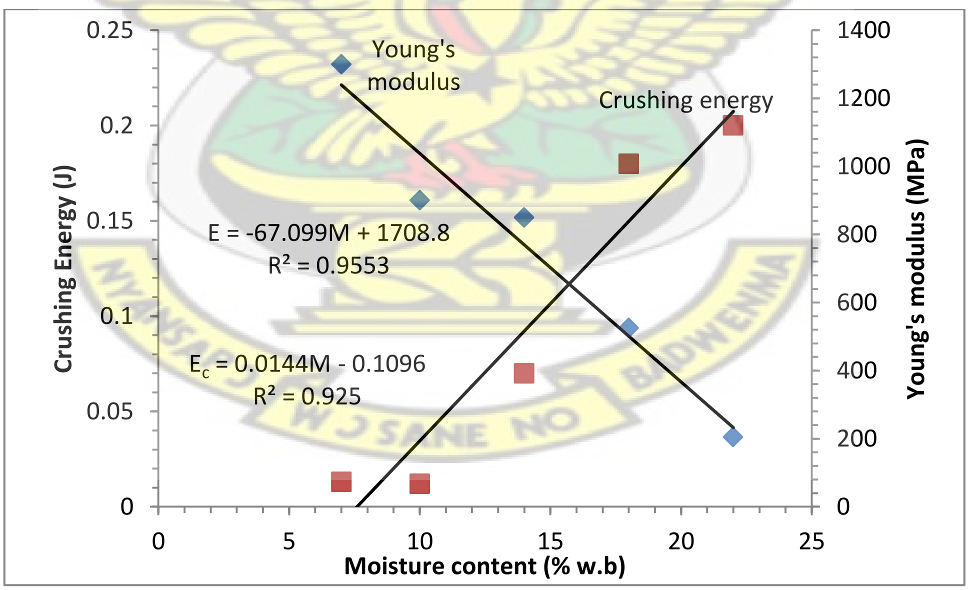

Figure 5-3: Variation of Young's Modulus and Crushing Energy against Bean Moisture Content

The inverse relationship between cocoa bean hardness and moisture content arising from the cleaving action of water as it diffuses through the intermolecular spaces of the bean, may have caused swelling and weakening of the cohesive forces, which resulted in the lowering of the compressive stress and strain. This further explains the reduction in Young's modulus as the moisture content was increased due to their closeness of relativity in measurement.

The energy requirement for crushing (E_c) of cocoa bean as a function of bean moisture content is displayed in Figure 5-3. When the cocoa bean moisture content was increased, more energy was required for compression of the bean in the lateral compression direction. The crushing energy increased from 0.013 J to 0.2 J when the moisture content increased from 7% to 22% (w.b). The regression between E and moisture content followed a linear function with a positive slope. Data for energy requirement were highly related to moisture content with coefficient of determination, R^2 of 0.925 Eq [11]:

$$E_c = 0.0144M - 0.1096 \quad (8)$$

Intuitively, the crushing energy was expected to reduce considering the explanation above but was not the case. On the contrary, there was an increase in crushing energy as moisture content increased. This trend may have been due to the increase in bean coat plasticity as moisture content was increased (Mabille, 2001). Dziki (2008) observed an increase in crushing energy for whole wheat kernel from 78 to 178 kJ/kg within a moisture content range of 10 to 20%. Similarly, Khan *et al*. (2010) found a linear function relationship between energy requirements and stem diameter to laterally compressed hemp stalk with R^2 values ranging from 0.71 to 0.82.

5.4 CONCLUSION

The present study has demonstrated that moisture content affect the cocoa bean compressive properties. The displacement at maximum load, Young's modulus, crushing energy, and the compressive strain generally have a more linear response between them and moisture content than the compressive stress, which had an exponential function with moisture content. The displacement at maximum load and crushing energy of the cocoa beans increased with increase in moisture content. However, the compressive stress, Young's modulus, and the compressive strain decreased with moisture content.

5.5 REFERENCES

Akaaimo, D. I. and Raji, A. O. (2006). Some Physical and Engineering properties of Prosopis Africana seed. *Journal of Biosystems Engineering*. 95: 197-205

Anass, A. B. (2006). Mechanical Properties of Cocoa Beans. BSc. Thesis, Department of Agricultural Engineering, KNUST, Kumasi.

Appiah, M. R. (2004). Impact of cocoa research innovations on poverty alleviation in Ghana, Ghana Academy of Arts and Sciences Publication

Aviara, N. A., Gwandzang, M. I. and Hague, M. A. (1999). Physical properties of guna seeds. *Journal of Agricultural Engineering Research*. 73: 105–111.

Awua, P. K. (2002). The success story of cocoa processing and chocolate manufacturing in Ghana – the success story that demolished a myth, David Jamieson & Associates Ltd., Saffron Walden, Essex.

Bart-Plange, A. and Baryeh, E.A. (2003). The physical properties of Category B cocoa Beans. *Journal of Food Engineering.* 20(1): 219-227.

Beckett, S. T. (2009). Industrial chocolate manufacture and use. John Wiley & Sons, Ltd, Chichester.

Burubai, W., Akor, A. J., Igoni, A. H. and Puyate, Y .T. (2007). Effect of loading rate and pre-heating time on the strength properties of African nutmeg (Monodora myristica). *International Agrophysics*. 21: 317-322.

Corrêa, P. C., Schwanz da Silva, F., Jaren, C., Afonso Júnior, P. C. and Arana, I. (2007). Physical and mechanical properties in rice processing. *Journal of Food Engineering.* 79(1): 137-142

Delwiche, S. R. (2000). Wheat endosperm compressive strength as affected by moisture. *Transaction of ASAE*. 43 (2): 365-373.

Deshpande, S. D., Bal, S. and Ojha, T. P. (1993). Physical properties of soybean. *Journal of Agricultural Engineering Research*. 56: 89–98.

De Vuyst, L., Camu, N., De Winter, T., Vandemeulebroecke, K., De Perre, V.V., Vancanneyt, M., De Vos, P. and Cleenwerck, I. (2008). Validation of the (GTG)5-rep-PCR fingerprinting technique for rapid classification and identification of acetic acid bacteria, with a focus on isolates from Ghanaian fermented cocoa beans. *International Journal of Food Microbiology.* 125: 79-90.

Dobraszczyk, B. J. (1994). Fracture mechanics of vitreous and mealy wheat endosperm. *Journal of Cereal Science.* 19(3): 273-282.

Dziki, D. (2008). The crushing of wheat kernel and its consequences on the grinding process. *Powder Technology*, 185: 181-186.

FAOSTAT (2005). Faostat database. Food and Agriculture Organisation. Also available at www.fao.org/es/ess/top/commodity.html?lang=en&item=125&year=2005 Internet was surfed on October ,2011.

Food Storage Manual (1995). World Food Programme, NRI Publishers.

Gereke, T. and Niemz, P. (2010). Mositure-induced stresses in spruce cross-laminates. *Engineering Structures*. 32: 600-606.

Irtwange, S. V. and Igbeka, J. C. (2002). Some physical properties of two African yam bean (Sphenostylis stenocarpa) accessions and their interrelations with moisture content. *Applied Engineering in Agriculture.* 18(5): 567–576

Khan, M. M. R., Chen, Y., Lague, C., Landry, H., Peng, Q. and Zhong, W. (2010). Compressive properties of hemp (Cannabis sativa L.) stalks. *Bisostystems Engineering*. 106: 315-323.

Khazaei J. and Mann, D. D. (2004). Effects of temperature and loading characteristics on mechanical and stress-relaxation properties of sea buckthorn berries, Part 1, Compression tests. Agricultural Engineering International: The CIGR Journal of Scientific Research Development, Manuscript FP 03: 011.

Kutte, M. T. (2001). Reactivation and performance evaluation of the threshing unit of a combined harvester for stationary threshing of rice.Unpublished M Eng Thesis, Federal University of Technology, Yola, Nigeria

Lefeber, T., Gobert, W., Vrancken, G. Camu, N. and Vuyst, L. D. (2011). Dynamics and species diversity of communities of lactic acid bacteria and acetic acid bacteria during spontaneous cocoa bean fermentation in vessel. *Food Microbiology.* 28: 457-464.

Mabille, F., Grilet, J. and Abecassis, J. (2001). Mechanical properties of wheat seed coats. *Cereal Chemistry.* 78 (3): 231–235.

Mamman, E., Umar, B. and Aviara, N. (2005). Effect of Moisture content and Loading Orientation on the Mechanical Properties of *Balanites Aegyptiaca* Nuts. The CIGR Ejournal Manuscript FP 04015. 7: 1-5.

Mohsenin, N. N. (1987). Physical Properties of Plant and Animal Materials: Structure, Physical Characteristics and Mechanical Properties. Updated and Revised Edition. Gordon and Breach Science Publishers, New York.

Moshenin, N.N. (1980). Physical Properties of Plant and Animal Materials. Gordon and Breach Science Publishers, New York.

Nutrition data.com (2011). USDA National nutrition database for national reference.

Ntiamoah, A. and Afrane, G. (2008). Environmental impacts of cocoa production and processing in Ghana: life cycle assessment approah, Journal of Cleaner Production,16 (16): 1735-1740

Okyere, E. (2005). Compression Properties of Shea Nut as a Function of Moisture Content. BSc Thesis. Faculty of Agriculture, K.N.U.S.T. Kumasi.

Rybiñski, W., B. Szot, R. Rusinek, and Bocianowski, J. (2009). Estimation of geometric and mechanical properties of seeds of Polish cultivars and lines representing selected species of pulse crops, *Int. Agrophysics. 23: 257-267*

Shitanda, D. Nishiyama, Y. and Koide, S. (2002). Compressive strength properties of rough rice considering variation of contact area. . 53: 53-58.

Singh, K. K. and Goswani, T. K. (1996). Physical properties of cumin seed. *Journal of Agricultural Engineering Research.* 64: 93–98.

Thompson, S. S., Miller, K. B. and Lopez, A. S. (2007). Cocoa and coffee. In: Doyle, M.P., Beuchat, L.R., Montville, T.J. (Eds.), Food Microbiology: Fundamentals and Frontiers. ASM Press, Washington, pp. 721-733.

CHAPTER SIX

6.0 COMPRESSIVE STRENGTH OF SHEA KERNEL WITH MOISTURE CONTENT VARIATION

Published as Bart-Plange, A., Addo, A., Akowuah, J .O and Ampah, J. (2012). ***Canadian Journal of Pure and Applied Sciences (CJPAS***), ***6(3): 2113-2119,*** **www.cjpas.net. ISSN NO.: 1920-3853**

KNUST

ABSTRACT

The effect of moisture content on the compressive properties of shea kernels was studied, so as to help engineers design appropriate machines that can be used to crack them. The effects of moisture content and loading on compressive stress, compressive strain, Young's modulus and crushing energy were examined. Compressive stress, compressive strain and Young's modulus decreased with increase in moisture content for shea kernel. For the shea kernel, compressive stress decreased from 2 MPa at 5% moisture content to 0.8 MPa at 23% moisture content. The compressive strain for shea kernel decreased from 0.0085 at 5% moisture content to 0.002mm/mm. Young's modulus for shea kernel decreased from 2000 MPa at 5% moisture content to 100 MPa at 24% moisture content. Crushing energy and displacement at maximum load on the other hand increased with moisture content. Displacement at maximum load increased linearly from 1.00 to 1.80 mm while crushing energy increased non-linearly from 0.005 to 0.13 mJ in the moisture content range of 5% at 24% w.b. The results provide useful data to be used by engineers in the design of suitable shea kernel cracking and crushing machines.

6.1 INTRODUCTION

Shea nut hails from the *Sapotaceae* family. The commonly known varieties include *Vitellaria paradoxa* (*Butryospermum parkii*) and *Vitellaria nilotica.* Shea nut is obtained from the shea tree, and is grown mostly throughout West and Central Africa; in the semiarid Sahel from Senegal to Ethiopia (Aremu and Nwannewuihe, 2011). Shea nut contains reasonably high amounts of oleic acids from which the shea butter (fat) is obtained. Shea butter is one of the basic raw materials for most food, cosmetics, soaps as well as the pharmaceutical industries (Boateng, 1992; Thioune *et al*., 2000) and it is sometimes used as a substitute for cocoa butter (Bekure *et al*., 1997). Shea nut serves as a main source of livelihood for the rural women and children in northern Ghana who are engaged in its gathering (Fobil, 2002). The kernel is obtained from the nut (Figure 6-1) by cracking with stones or mortar and pestle. Traditional methods of extraction of shea butter from the kernel involve a series of operations which includes steeping, roasting, pounding or grinding and boiling (Aviara *et al.,* 2005).

Figure 6-1: Shea Nut and Shea Kernel

Shea butter is marketed as being effective at treating the following conditions: burns, eczema, rashes, severely dry skin, dark spots, skin discolouration, chapped lips, stretch marks, wrinkles and provides natural UV sun protection (Boateng, 1992).

The knowledge of mechanical properties provides the basis for avoiding failure in engineering applications. From an engineering point of view, information and data on the mechanical properties of shea nut and kernel are necessary in the mechanization of various unit operations involved in their post-harvest processing. It also helps in the development of optimization parameters for efficient and effective processing equipment (Burubai *et al.*, 2007). Compressive and other engineering properties are important in many problems associated with the design of machines and the analysis of the behaviour of the product during unit operations such as drying, cleaning, sorting, crushing, and milling (Akaaimo and Raji, 2006). The solutions to problems of these processes involve knowledge of the compressive and other engineering properties (Irtwange and Igbeka, 2002). This was supported by Kutte (2001) that in the design of any agricultural handling and processing machine, properties of the crop must be taken into account. There is increasing interest in shea butter and its uses in industries with an increment in handling and processing of shea nut and kernel. However the present methods of handling and processing are both laborious and time consuming (Aviara *et al.*, 2005). There is therefore the need for development of improved methods of processing. For effective and proper design and manufacture of systems and equipment in handling shea kernel through such processes as cleaning, grading, drying, size reduction and many others, the engineering properties of shea kernel such as the compressive properties must be known. In the mechanization of the unit operations involved in the shea industry, the compressive properties of the kernels play an essential role in the design of optimized shea kernel bean processing machines.

Compressive properties including rupture force, deformation, compressive strain and stress, Young's modulus, and crushing energy used for the shea nut and kernel are useful information in designing shea nut kernel grinding machines. Studies have shown that compressive properties are influenced by a number of factors such as the cultivar or variety, temperature, and moisture content of the product under consideration (Delwiche, 2000; Shitanda *et al*., 2002). The rupture force indicates the minimum force required for shelling nuts and grinding kernels (Sirissomboon *et al*., 2007; Galedar *et al*., 2009). The deformation at rupture point can be used for the determination of the gap size between the surfaces in compressing the bean for shelling. Processing of shea nut is greatly related to the external forces exerted on each kernel between the grinding or crushing surfaces. Therefore, a study of the correlation between the forces on a single shea nut kernel is needed for a better understanding of milling shea kernel.

Several researchers have studied the mechanical properties of various food and biological materials (Altuntas and Karadag, 2006) for sainfoin seed; (Khan *et al*., 2010) for industrial hemp stalks; (Shitanda *et al*., 2002; Corrêa *et al*., 2007) for rough rice; (Rybiński *et al*., 2009) for pulse seeds; (Khazaei and Mann, 2004) for sea buckthorn berries; (Kalkan and Kara, 2011) for wheat; (Galedar *et al*., 2009) for pistachio nuts and kernel; (Isik and Unal (2007) for white speckled red kidney bean,

Food and biological materials are hygroscopic and absorb moisture under humid conditions until they reach equilibrium with the surroundings. The hydroscopicity of shea kernel affects its physical and mechanical properties and a range of moisture content exists within which optimum performance is achieved. Therefore, the effect of moisture content on the mechanical properties of cash crops like shea nut and kernel grown in Ghana is of importance in the design of handling, processing and storage equipment. Negligible information is available on compressive properties of such cash crops grown in Ghana. Some information exist on the Physical and thermal properties of shea nut and kernel (Aremu and Nwannewuihe, 2011).

Therefore, the objective of this research was to investigate the effect of moisture content on the compressive properties (deformation at rupture point, compressive stress and strain, Young's modulus, and crushing energy) of sheanut kernel that are relevant for the design of processing equipment.

6.2 MATERIALS AND METHODS

6.2.1 Preparation of Sample

The shea nuts used in the study were purchased from a local market at Bole in the Northern region of Ghana in October 2010. The samples were cleaned by removing foreign materials and damaged kernels. Sheanut kernel samples had all the quality checks performed and ready for local and export markets. Both samples were conditioned to four moisture content levels of 12.59, 22.41, 31.55 and 43.84% on wet basis. The samples were sealed in separate polythene bags and kept in a refrigerator at 5°C for five days to ensure uniform moisture distribution. The amount of distilled water added was calculated using equation (1) (Balasubramanian, 2001; Bart-Plange and Baryeh, 2003).

$$M_w = \frac{M_i(m_f - m_i)}{100 - m_f} \qquad (1)$$

Where,

M_w is the mass of distilled water (g),

M_i is the initial mass of sample (g),

m_f is the final moisture content of sample (%w.b.) and

m_i is the initial moisture content of sample (%w.b.).

Prior to using the kernels, they were taken out of the refrigerator and allowed to warm up to room temperature. Similar approaches have been used by Aviara *et al*. (1999) for guna seed, Deshpande *et al*. (1993) for soybean, and Singh and Goswami (1996) for cumin seed. After conditioning the samples to the desired moisture levels of 7, 10, 14, 18 and 22%, the dimensional properties were determined for four replicates and the mean values calculated.

6.2.2 Determination of principal dimensions

The average size was determined based on 100 randomly selected seeds. To determine the average size of the seed, a sample of 100 seeds were randomly picked and the three principal dimensions namely, length *(a)*, width, *(b)* and thickness *(c)* axes were measured using a micrometer screw gauge with an accuracy of 0.01mm. The width and thickness were measured perpendicular to the major axis. The geometric mean diameter *(Dg)* or equivalent diameter *(De)* as used by some researchers was calculated using the following relationship (Mohsenin, 1978):

$$D_g = (abc)^{1/3} \quad (2)$$

The Sphericity index (∅) was calculated using the following formula (Mohsenin, 1987):

$$\emptyset = \frac{(abc)^{1/3}}{a} \quad (3)$$

6.2.3 Determination of compressive properties

The compression test was conducted on the shea kernel at four moisture content levels (5%, 12%, 18, 24% w.b) using the Instron Universal Testing Machine (IUTM) furnished with a micro-computer. Prior to the compression test, the linear dimensions and the sphericity of the shea kernel were measured. During a compressive test, the shea kernel was placed laterally on the stable up platform and was compressed with a motion probe at a constant speed until the specimen fractured (Figure 6-2). The data acquisition system of the IUTM generated the rupture load and the displacement automatically during the compression. The load-displacement curve was used to derive the compressive properties of the shea kernel. The maximum compressive load, the load at which the kernel fractured was determined by the ratio of peak load of the displacement curve. The maximum compressive stress, strain, and crushing energy were determined using the following equations:

$$\sigma_{max} = \frac{P_{max}}{dL} \quad (4)$$

$$\varepsilon_{max} = \frac{\delta l}{l} \quad (5)$$

$$E_c = \frac{P}{2} \times \Delta D \quad (6)$$

Where,

σ_{max} is the maximum compressive stress in MPa, P_{max} is the maximum load in N, d is the mean diameter in mm, and L is the mean length in mm. ε_{max} is maximum compressive strain in mm/mm, l is the mean width of the specimen in mm, ΔD is the displacement interval in mm, E_c is the crushing energy in J and dL is the change in length.

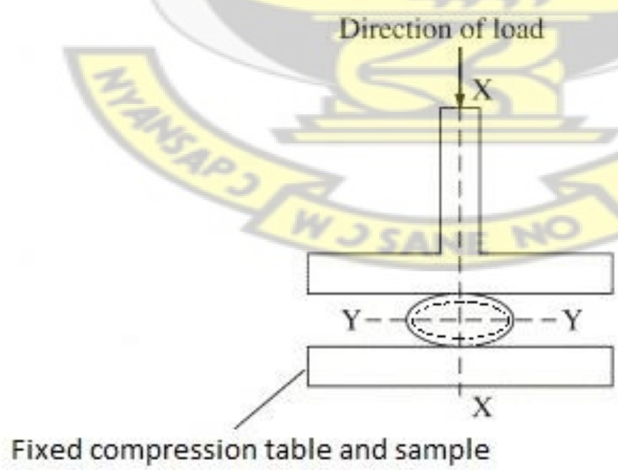

Figure 6-2: Lateral Compression of Shea Kernel

An analysis of variance (ANOVA) was performed to examine the effects of experimental factors and their interactions using SPSS 2007. Means of treatments were compared using Fisher's least significant difference. Regression analysis was performed on the data to examine the trends of compressive properties in relation to the kernel moisture content with MS excel. A significant level of probability $p < 0.05$ was used for all analysis. All measurements were replicated four times.

6.3 RESULTS AND DISCUSSION

6.3.1 Size and shape dimensions

Table 6-1 shows the mean major diameter, intermediate diameter, and the minor diameter as well as the effective mean diameter and sphericity of the shea kernel specimen used for the compression test at moisture contents of 4.78 ± 0.28% and 24.17 ± 0.12%. It was observed that the major diameter, intermediate diameter, and the minor diameter had values of 24.17 ± 3.20 mm, 17.55 ± 2.00 mm and 14.95 ± 1.54 mm at moisture content of 4.78 ± 0.28% while at moisture content of 24.17 ± 0.12%, the mean values of the major diameter, intermediate diameter and minor diameter were observed to be 24.65 mm, 18.11 mm and 15.46 mm respectively. The geometric mean diameter and sphericity had mean values of 18.48 mm and 0.769 respectively at moisture content of 4.78 ± 0.28% and 19.01 mm and 0.775 respectively at 24.17 ± 0.12% moisture content.

Table 6-1: Mean Dimensions of the Shea Kernel Specimen Used for the Compression Test

Moisture content (% w.b)	Mean Length mm	Mean width mm	Mean thickness mm	Mean effective diameter (mm)	Sphericity
5	24.17	17.55	14.95	18.48	0.769
24	24.65	18.11	15.46	19.01	0.775

KNUST

6.3.2 Displacement at maximum load

From Figure 6-3 it is clearly shown that as the moisture content increases, displacements at maximum load for shea kernel increases. Displacement at maximum load increased linearly from 1.00mm at 5% moisture content to 1.80mm at 18% moisture content.

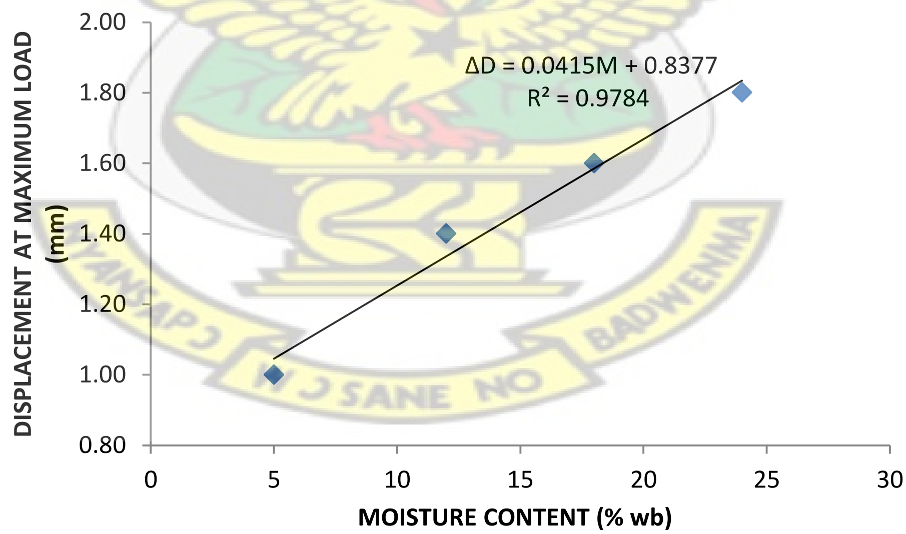

Figure 6-3: Relationship Between Displacement at Maximum Load and Moisture Content

The relationship between displacement at maximum load and moisture content for kernel can be represented by:

$$\Delta D = 0.0415M + 0.8377 \qquad R^2 = 0.9784 \qquad (7)$$

6.3.3 Compressive stress

The relationship between stress and moisture content can be found in Figure 6-4. Compressive stress decreased linearly from 2MPa at 5% moisture content to 0.8MPa at 23%. The decrease in compressive stress with moisture content is due to the fact that, as the kernels absorb moisture, they become softer; their cells swell and increase in surface area. When this happens, forces acting perpendicularly to these surfaces would be minimum leading to reduction in stress. Compressive stress was found to have the following relations with moisture content:

$$\sigma_{max} = -0.062M + 2.2897 \qquad R^2 = 0.9958 \qquad (8)$$

Similar decreasing trend was observed with moisture increase in the determination of the strength of barley kernels under uni-axial compression (Bargale *et al*., 1995), compression strength of cotyledon of three cultivars of whole snap bean (Phaseolus vulgaris L.) (Bay *et al*., 1996), for aegyptiaca nut (Mamman *et al*., 2005) , Compressive force for Filbert Nut and Kernel (Pliestic *et al*. 2006), for African nutmeg (Burubai *et al*., 2007) compressive strength of barley grains that were quasi-statically loaded in horizontal and vertical orientations (Tavakoli *et al*., 2009), wheat grains (Gorji *et al*., 2010), for Sc 704 corn variety (Seifi and Alimardani, 2010) mechanical strength of brown rice (Bagheri *et al*., 2011).

6.3.4 Compressive strain

The relationship between compressive strain and moisture content for shea kernel is found in Figure 6-4. The compressive strain for shea kernel decreases from 0.0085 MPa at 5% moisture content to 0.002 MPa at 24% moisture content. The relationship between compressive strain and moisture content is given by:

$$\epsilon_{max} = -0.0003M + 0.0106 \qquad R^2 = 0.9642 \tag{9}$$

KNUST

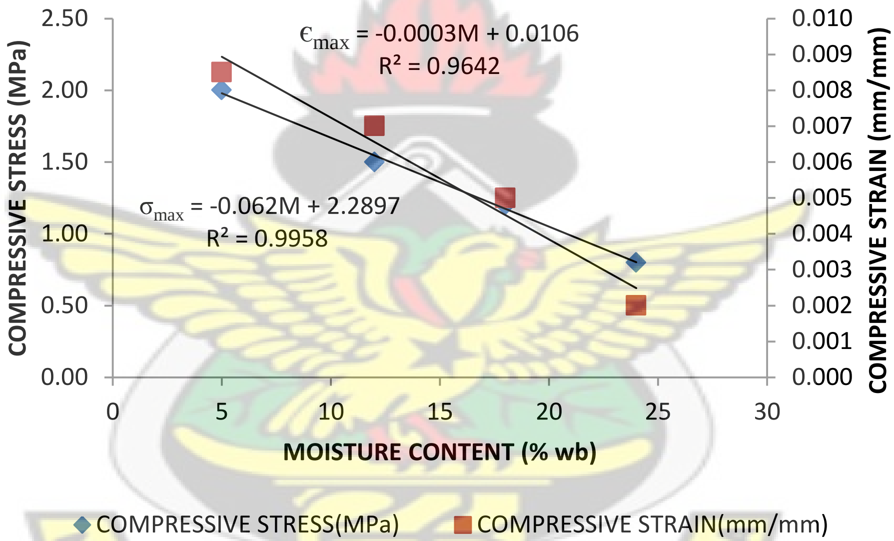

Figure 6-4: Relationship Between Compressive Stress, Compressive Strain and Moisture Content

6.3.5 Young's modulus

Figure 6-5 indicates that Young's Modulus for shea kernel decreased non-linearly from 2000 MPa at 5% moisture content to 100 MPa at 24% moisture content. The relationship between Young's modulus and moisture content decreased sharply. The relationship between Young's modulus and moisture content may be expressed by the following regression equations:

$$Y_m = -7.308M^2 + 117.72M + 1536.7 \qquad R^2 = 0.9576 \tag{10}$$

The values of modulus of elasticity of wheat kernels ranging from 486 to 1631 MPa were found by Sayyah and Minaei (2004) to correlate inversely with moisture content. According to Sayyah and Minaei (2004) a range of 230 to 4100 MPa has been reported by different authors for the modulus of elasticity with a mean standard error of 172 MPa (Mohsenin, 1978; Arnold and Robert, 1969; Bargale *et al.*,1995; Sayyah and Minaei, 2004). The results of this study fell within this range.

Other researchers such as Mamman *et al.* (2005) for aegyptiaca nut, Burubai *et al.* (2007) for African nutmeg seedcoat, Hemery *et al.* (2010) for wheat bran, Abbaspour-Fard *et al.* (2012) for pumpkin seed found Young's modulus to decrease with moisture content increase.

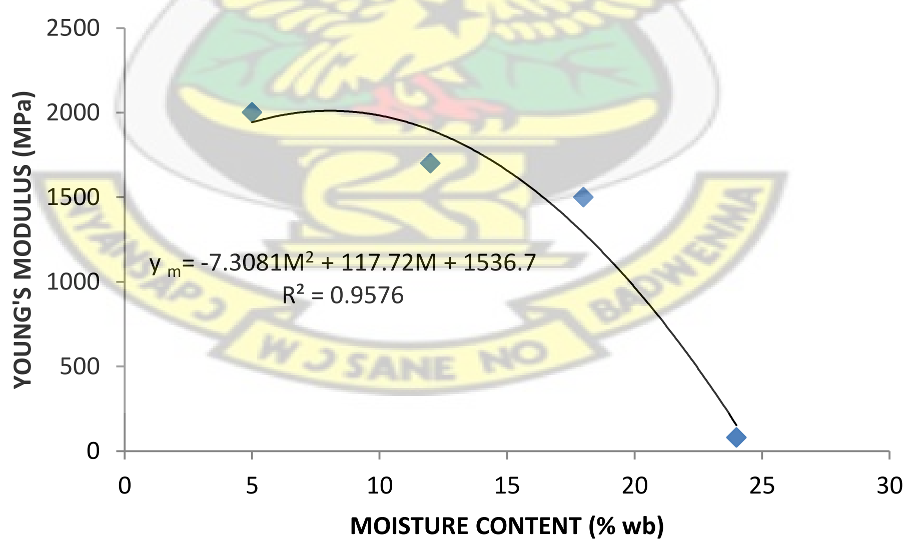

Figure 6-5: Relationship Between Young's Modulus and Moisture Content

6.3.6 Crushing energy

The relationship between crushing energy and moisture content is shown in Figure 6-6. Crushing energy increased non-linearly with moisture content from 0.005J at 5% moisture content to 0.13J at 24% moisture content. The reason for the increase in crushing energy is that, as the moisture increases, cohesive forces within the kernels increase and as a result, their resistance to cracking also increases. This would reduce compressive efficiency with time and the energy required also increases leading to increased cost of cracking.

KNUST

$$E_c = 0.0002M^2 + 0.0001M + 0.0008 \qquad R^2 = 0.9925 \qquad (11)$$

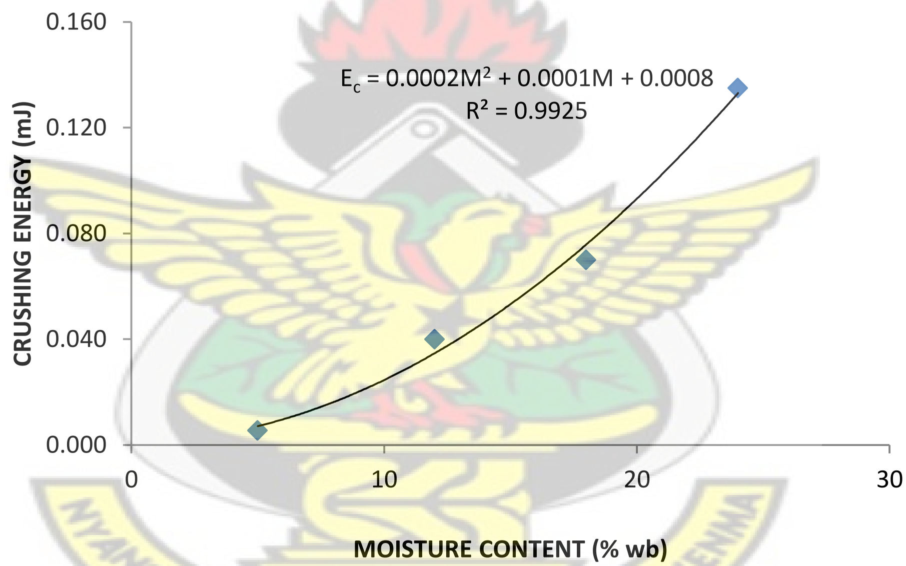

Figure 6-6: Relationship between Crushing Energy and Moisture Content

In a similar research by Saiedirad *et al*. (2008) involving small, medium, and large cumin seeds, the energy absorbed at seed rupture increased from 1.8 to 8.6 mJ and 7.6 to 14.6 mJ with increase in moisture content from 5.7% to 15% d.b. for quasi-statically loaded vertical and horizontal orientations, respectively. This increasing trend was similarly observed by other researchers including Burubai *et al*. (2007) for African nutmeg, Tavakoli *et al*. (2009) for barley grains, Gorji *et al*. (2010) for wheat grains, Seifi and Alimardani (2010) for Sc 704 corn variety and Tarighi *et al*. (2011) for corn grains. However, other researcher have found the crushing energy to decrease with decreasing moisture content (Mamman *et al.*, 2005) for aegyptiaca nut ; Unal *et al*. (2008) for mung beans; Zareiforoush *et al*. (2010) for two paddy rice varieties; Kalkan and Kara. (2011) for popcorn kernels; Alhijahani and Khodael (2011) for strawberry fruit. Bargale et al. (1995) in an early study found the energy required to cause rupture in the barley kernel to increase initially and then decreased with moisture content increase.

6.3.7 Engineering implications

In a bid to mechanize the various unit operations involved in the post-harvest processing of shea kernel, information and data on the behaviour of these strength properties as a function of moisture is needed. These data when utlised fully will not only save energy but will promote the design and development of effective and efficient process machines.

6.4 CONCLUSIONS AND RECOMMENDATION

The investigation of compressive properties of shea kernel revealed the following:

Compressive stress and compressive strain decreased from 2 MPa to 0.8 MPa and from 0.0085 to 0.002 mm/mm with increasing moisture content from 5% at 23% resdpectively.

Young's Modulus decreased from 2000 MPa at 5% moisture content to 100 MPa at 24% content.

Displacement at maximum load increased linearly from 1.00 to 1.80 mm while crushing energy increased non-linearly from 0.005 to 0.13 mJ in the moisture content range of 5% at 24% w.b.

6.5 REFERENCES

Abbaspour-Fard, M. H., Khodabakhshian, R. Emadi, B. and Sadrnia, H. (2012). Evaluation the Effects of Some Relevant Parameters on ElasticModulus of Pumpkin Seed and Its Kernel. International Journal of Biomaterials .Volume 2012, Article ID 271650, 6 pages.

Akaaimo, D. I. and Raji, A. O. (2006). Some physical and engineering properties of *Prosopis africana* seed. *Biosystems Engineering*. 95(2): 197–205.

Alhijahani, H. S. and Khodael, J. (2011). Some physical properties of strawberry (Kurdistan variety). *World Applied Science Journal*. 13(2): 206-212.

Altuntas, E. and Karadag, Y. (2006). Some physical and mechanical properties of sainfoin (Onobrychis sativa Lam.), grasspea (Lathyrus sativus L.) and bitter vetch (Vicia ervilia L.) seeds. *Journal of Applied Sciences*. 6 (6): 1373–1379.

Arnold, P. C. and Robert, A. W. (1969). Fundamental Aspects of Load-deformation Behaviour of Wheat Grains. *Transactions of ASAE.* 12: 104 -108.

Aremu, A. K. and Nwannewuihe, H. U. (2011). Specific heat of ground fresh sheanut kernel (*Butyrospernum paradoxum*) as affected by particle size, moisture content and temperature. *Journal of Emerging Trends in Engineering and Applied Sciences*. (JETEAS) 2(1): 177-183.

Aviara, N. A., Gwandzang, M. I. and Hague, M. A. (1999). Physical properties of guna seeds. *Journal of Agricultural Engineering Research*. 73: 105–111.

Aviara, N. A., Oluwole, F. A. and Haque, M. A. 2005. Effect of moisture content on some physical properties of sheanut (*Butyrospernum paradoxum*). *International Agrophysics.* 19: 193-198.

Bagheri, I., Dehpour, M. B., Payman, S. H. and Zareiforoush, H. (2011). Rupture strength of brown rice varieties as affected by moisture content and loading rate. *Australian Journal of Crop Science*. 5(10): 1239-1246.

Balasubramanian, D. (2001). Physical properties of raw cashew Nut. *Journal of Agricultural Engineering Research.* 78(3): 291 – 297.

Bargale, P. C., Irudayaraj, J. and Marquist, B. (1995). Studies on Rheological Behaviour of Canola and Wheat. *Journal of Agric. Engineering Research*. 61: 267 – 274.

Bart-Plange, A. and Baryeh, E. A. (2003). The physical properties of category B cocoa beans. *Journal of Food Engineering.* 60 (3): 219-227.

Bay, A. P. M., Bourne, M. C. and Taylor A. G. (1996). Effect of moisture content on compressive strength of whole snap bean (*Phaseolus vulgaris* L.) seeds and separated cotyledons. *International Journal of Food Science & Technology*. 31(4): 327–331.

Bekure, Z., Donlan, M., Gordon, Y. and Thomson, J. (1997). "Local to Global. The International market for Shea butter." Presented to United Nations Development Fund for Women.

Boateng, G. A. (1992). Production Manual for improved Shea butter processing technology (Ghana Regional appropriate Technological service, Ghana).

Burubai, W., Ako, A. J. Igoni, A. H. and Uyate, Y. T. (2007). Effects of Temperature and Moisture Content on the Strength Properties of African Nutmeg (Monodora Myristica). *Bulgarian Journal of Agricultural Science.* 13 (2007): 703-712

Corrêa, P. C., Schwanz da Silva, F., Jaren, C., Afonso Júnior, P. C. and Arana, I. (2007). Physical and mechanical properties in rice processing. *Journal of Food Engineering.* 79(1): 137-142.

Delwiche, S. R. (2000). Wheat endosperm compressive strength as affected by moisture. *Transaction of ASAE.* 43 (2): 365-373.

Deshpande, S. D., Bal, S. and Ojha, T. P. (1993). Physical properties of soybean. *Journal of Agricultural Engineering Research*. (56): 89-98.

Deshpande, S. D., Bal, S., and Ojha, T. P. (1996). Bulk thermal conductivity and diffusivity of soy bean. *Journal of Food Process Preservation*. 20: 177-189.

Fobil, J. N. (2002). Research and development of the shea tree and its products www.solutions-site.org [Accessed September 8 2007].

Galedar, M. N., Mohtasebi, S. S., Tabatabaeefar, A., Jafari, A. and Fadaei, H. (2009). Mechanical properties of pistachio nut and its kernel under compression loading. *Journal of Food Engineering*. 95: 499-504.

Gereke, T. and Niemz, P. (2010). Mositure-induced stresses in spruce cross-laminates. *Engineering Structures*. 32: 600-606.

Gorji, A. Rajabipour, A. and Tavakoli, H. (2010). Fracture resistance of wheat grain as a function of moisture content, loading rate and grain orientation. *Australian Journal of Crop Science*. 4(6): 448-452.

Hemery, Y. M., Mabille, F., Martelli, M. R. and Rouau, X. (2010). Influence of water content and negative temperatures on the mechanicalproperties of wheat bran and its constitutive layers. *Journal of Food Engineering*. 98(3): 360–369.

Irtwange, S. V. and Igbeka, J. C. (2002). Some physical properties of two African yam bean (Sphenostylis stenocarpa) accessions and their interrelations with moisture content. *Applied Engineering in Agriculture*. 18(5): 567–576.

Isik, E. and Unal, H. (2007). Moisture-dependent physical properties of white speckled red kidney bean grains. *Journal of Food Engineering*. 82 (2): 209–216.

Kalkan, F. and Kara, M. (2011). Handling, Frictional, and technological properties of wheat as affected by moisture and cultivar. *Powder Technology*. 213: 116-122.

Khan, M. M. R., Chen, Y., Lague, C., Landry, H., Peng, Q. and Zhong, W. (2010). Compressive properties of Hemp (Cannabis sativa L.) stalks. *Bisostystems Engineering*. 106: 315-323.

Khazaei, J. and Mann, D. D.(2004). Effect of temperature and loading characteristics on Mechanical and stress relxation properties of sea buckthorn berries. Agricultural Engineering International. Vol 6.

Kutte M.T., 2001. Reactivation and performance evaluation of the threshing unit of a combined harvester for stationary threshing of rice. Unpublished M Eng Thesis, Federal University of Technology, Yola, Nigeria.

Mamman, E., Umar, B. and Aviara, N. (2005). Effect of Moisture content and Loading Orientation on the Mechanical Properties of *Balanites Aegyptiaca* Nuts. The CIGR Ejournal Manuscript FP 04015. Vol. VII. 1-5.

Moshenin, N. N. (1978). Physical Properties of Plant and Animal Materials. Gordon and Breach Science Publishers, New York.

Pliestic, S. Dobricevic, N. Filipovic, D. and Gospodaric, Z. (2006). Physical Properties of Filbert Nut and Kernel. *Biosystems Engineering*. 93(2): 173–178.

Rybiñski, W., Szot, B., Rusinek, R. and Bocianowski, J. (2009). Estimation of geometric and mechanical properties of seeds of Polish cultivars and lines representing selected species of pulse crops, *Int. Agrophysics.* 23: 257-267.

Saiedirad, M. H., Tabatabaeefar, A., Borghei, A., Mirsalehi, M., Badii, F. and Ghasemi Varnamkhasti, M. (2008). Effects of moisture content, seed size, loading rate and seed orientation on force and energy required for fracturing cumin seed (Cuminum cyminum Linn.) under quasi-static loading. *Journal of Food Engineering*. 86: 565-572.

Shitanda, D., Nishiyama, Y. and Koide, S. (2002). Compressive strength properties of rough rice considering variation of contact area. *Journal of Food Engineering*. 53:53-58.

Seifi, M. R and Alimardani, R. (2010). The Moisture Content Effect on Some Physical and Mechanical Properties of Corn (Sc 704). *Journal of Agricultural Science*. 2(4): 125-134.

Singh K. K. and Goswami T. K. (1996). Physical properties of cumin seed. *Journal of Agricultural Engineering Research.* 64: 93-98.

Sirisomboon, P., Kitchaiya, P., Pholpho, T. and Mahuttanyavanitch, W. (2007). Physical and mechanical properties of Jatropha curcas L. Fruits, nuts and kernels. *Biosystems Engineering*. 97 (2): 201–207.

Tavakoli, H. Mohtasebi, S.S. Rajabipour, A. and Tavakoli, M. (2009). Effects of moisture content, loading rate, and grain orientation on fracture resistance of barley grain. *RES. AGR. ENG. 55*(3): 85–93

Tarighi, J., Mahmoudi, A., and Alavi, N. (2011). Some mechanical and physical properties of corn seed (Var. DCC 370). *African Journal of Agricultural Research*. 6(16): 3691-3699.

Thioune, O., Ahodikpe, D., Dieng, M., Diop, A. B., Ngom, S. and Lo, I. (2000). Inflammatory ointment from shea butter and hydro alcoholic extract of Khaya sengalensis barks (cailcederat) Dakar Med. 45(2): 113-6.

Unal, H., Esref, I., Nazmi, I. and Yucel, T. (2008). Geometric and Mechanical Properties of Mung Bean (*Vigna Radiata* L.) Grain: Effect of Moisture. *International Journal of Food Properties*. 11(3): 585-599.

KNUST

CHAPTER SEVEN

7.0 SOME MOISTURE DEPENDENT THERMAL PROPERTIES OF CASHEW KERNEL (*ANARCARDIUM OCCIDENTALE L.*)

Published as Bart-Plange, A., Addo, A., Mohammed-Kamil, A. P. and Kumi, F. (2012). ***Australian Journal of Agricultural Engineering. AJAE 3(2): 65-69 (2012).*** **ISSN NO.: 1836-9448**

KNUST

ABSTRACT

Thermal properties of crops are very important in the design of drying, processing and storage equipment. The availability of such relevant information on cashew nut will aid in the design and manufacture of equipment for postharvest operations. The thermal conductivity, specific heat capacity and thermal diffusivity of cashew kernel were evaluated as a function of moisture content. Specific heat was measured by the method of mixtures while the thermal conductivity was measured by the line heat source probe method. Thermal diffusivity was calculated from the experimental results obtained from specific heat, thermal conductivity and bulk density. The bulk density for nut and kernel decreased from 625.62 to 592.42 kg/m^3 and 559.60 to 505.06 kg/m^3 respectively with increasing moisture content from 5.0% to 9.0% w.b. Specific heat increased linearly from 1586 to1756 J/kgºC with increasing moisutre content. The thermal conductivity ranged from 0.2103 to 0.2296 W/mK and thermal diffusivity varied from 2.369×10^{-7} to 2.588×10^{-7} m^2/s. Specific heat, thermal conductivity and thermal diffusivity were found to increase linearly with increasing moisture content from 5.0 to 9.0% w.b.

Keywords: Cashew; thermal conductivity; thermal diffusivity; moisture content; specific heat.

7.1 INTRODUCTION

The cashew tree (*Anarcardium Occidentale* L.) is a native of Brazil and the Lower Amazons. It has been a valuable cash crop in the Americas, the West Indies, Madagascar, India and Malaysia (Frankel, 1991). The tree is now widely distributed throughout the tropics particularly in many parts of Africa and Asia. The five major producing countries are Vietman, India, Nigeria, Côte d'Ivoire and Brazil.

KNUST

Cashew nut is a high value edible nut and it ranks third among the edible tree nuts of the world with a current annual output of 28400 tonnes in Ghana (FAOSTAT, 2012). Nuts may be sold raw or as kernels and may be further processed into value-added products such as fried, roasted, or chocolate-coated kernels and confectioneries (Azam-Ali and Judge, 2001; Ogunsina and Bamgboye, 2007). Following the gradual increasing interest in cashew production in Ghana, there is the need to expand the production base of the crop so as to compete with the leading producing and exporting nations in Africa (Ojolo and Ogunsina, 2007). Knowledge of thermal properties of food and agricultural products, is essential for equipment design and prediction of heat transfer operations (Viviana *et al.,* 2008). Thermal properties of various foods and agricultural products have been studied by researchers such as Sherpherd and Bhardwaj (1985) for pigeon pea, Dutta *et al.* (1988) for gram, Aviara and Hague (2001) for shea nut kernel, Tansakul and Chaisawang (2007) for coconut milk and Nouri Jangi *et al.* (2011) for barley grains. A study conducted on thermal properties of straw mushroom by Tansakul and Chaisawang (2007) indicated that specific heat, thermal conductivity and thermal diffusivity increased with increase in moisture content. Moisture dependency of engineering properties of some cash and industrial crops have been studied by other researchers (Bart-Plange and Baryeh, 2003 for category B cocoa beans; Yalcin and Ozarslan, 2004 for vetch seed; Kinsley *et al*., 2005 for pomegranate seed; Yang and Zhao, 2001 for radish and alfalfa seeds; Gharibzahedi *et al*., 2011 for castor seed; Tarighi *et al*., 2011 for sunflower seeds. Engineering properties of other biological materials affected by moisture content have been found by other researchers (Aviara and Haque, 2001 for sheanut kernel; Baryeh, 2002 for millet; Erica *et al*., 2004 for safflower seed; Aydin, 2006 for peanut and kernel; Yalcin, 2006 for cowpea seed; Pliestic *et al.*, 2006 for filbert nut and kernel and Singh and Goswani, 2007 for cumin seed Sayed and Maryam, 2007 for kiwi fruit). Many researchers have worked on cashew nuts (Nathakaranakule and Prachayawarakorn, 1998; Balasubramanian (2001); Kurozawa *et al*., 2008; Ogunsina and Bamboye, 2007) but very little research work on variation of moisture content with thermal properties of cashew was found in the literature. The objective of the study was to determine the effect of moisture on the thermal properties of the cashew kernel.

7.2 MATERIALS AND METHODS

7.2.1 Materials

The materials that were used for the experiment included cashew nut samples, distilled water, digital electronic balance, calorimeter, DC power source, ammeter, voltmeter and a thermocouple.

7.2.2 Sample Preparation

The cashew nuts used in the study were purchased from a local market at Wenchi in the Brong Ahafo region of Ghana in December 2009. The cashew samples were processed at a local cashew processing company and manually cleaned to remove chaff. The initial moisture content of the samples was determined using a standard oven method at 105°C for 24 hours (Dursun et al., 2006). Other higher moisture contents of samples were obtained by adding calculated amounts of distilled water of mass given by equation (1) (Solomon and Zewdu, 2009, Ibrahim *et al*., 2006).

$$Q = \frac{W_i(M_f - M_i)}{100 - M_f} \quad (1)$$

Where,

Q mass of water to be added, kg

W_i initial mass of the sample, kg

M_i initial moisture content of the sample, % w.b.

M_f final moisture content of the sample, % w.b.

M_w mass of water, kg

The samples were sealed in separate polythene bags and kept in a refrigerator at 5°C for five days to ensure uniform moisture distribution throughout the sample. Before starting a test, the required quantity of seeds were taken out of the refrigerator and allowed to warm up to room temperature for about two hours (Nimkar and Chattopadhyay, 2001). The moisture content of cashew nut and kernel was investigated at four moisture levels of 5.0, 6.5, 8.0, and 9.0% w.b. These values are within the range of moisture contents encountered for cashew nut and kernel during postharvest operations.

7.2.3 Bulk Density Determination

The bulk density (ρ_b) of nuts and kernels was determined by pouring samples into a cylindrical container of known volume while striking excess samples off the brim without compacting the nuts and kernel (Zewdu and Solomon, 2008). The bulk density was then determined by dividing the mass of samples by the volume of the cylinder. All experiments were replicated four times at each moisture content level.

7.2.4 Determination of Thermal Properties

All experiments in this study were repeated four times at four levels of moisture content (5.0-9.0%), four levels of bulk density (505.06, 535.25, 539.84, 559.60 kgm^{-3}) and four temperature levels (35, 45, 55, 65 °C) for the cashew and kernel.

7.2.4.1 Determination of Specific Heat of Cashew Kernel

The method of mixtures has been the most common technique reported in the literature for measuring the specific heat (C_p) of agricultural and food materials (Singh and Goswani, 2000; Aviara and Haque, 2000; Razavi and Masoud, 2006; Nouri Jangi *et al.*, 2011). For the determination of specific heat in this study, the method of mixtures was used. Cashew kernel samples of known mass, temperature and moisture content were dropped into a copper calorimeter containing water of known mass and temperature. The calorimeter was well insulated so as to prevent heat loss to the room in which the experiment was performed. The mixture was stirred continuously using a glass rod stirrer. A digital thermometer was used to monitor the temperature of the mixture. The equilibrium (final) temperature was noted and the specific heat determined using equation (2) as used by Aviara and Haque (2001).

$$Cp = \frac{(McCc + MwCw)(Te - Tw)}{Ms(Ts - Te)} \quad (2)$$

Where,

C_p specific heat of sample, J/kg℃

C_c specific heat of calorimeter, J/kg℃

C_w specific heat of water, J/kg℃

M_w mass of water, kg

T_s initial temperature of sample, K

T_e equilibrium temperature, K

T_w initial temperature of water, K

7.2.4.2 Determination of Thermal Conductivity

The thermal conductivity (K) of the cashew kernel samples was determined using the line heat source method (Sweat *et al*., 1998). During the experiment, the samples at the desired moisture contents were placed in a cylinder at a particular bulk density. The plastic cylinder was sealed at the top and bottom with wooden plugs. A constant D.C. power source of 3V and a current of 1A was supplied to a Nichrome wire stretching between two ends of the plastic cylinder as the heat input source.The probe was inserted through the centre of the sample mass to take the temperature readings (Kurozawa *et al*., 2008). During the heating process, the temperature of the sample was recorded as a function of elapsed time at the interval of 30 seconds with the help of a digital time recorder.

Recorded temperature values were then plotted against the natural logarithm of elapsed time and subsequently thermal conductivity was calculated by using equations 3 and 4.

$$K = \frac{QIn(t_2 / t_1)}{4\pi(T_2 - T_1)} \tag{3}$$

$$Q_i = V\ I / L \tag{4}$$

Where,

K thermal conductivity, W/m K

Q_i heat input, W/m

V electrical voltage, volts

t_i initial time, s

t_2 final time, s

T_1 initial temperature, ℃

T_2 final temperature, ℃

7.2.4.3 Determination of Thermal Diffusivity

The thermal diffusivity (α_b) of the cashew kernel was calculated from experimental values of thermal conductivity, specific heat and bulk density using equation (5).

$$\alpha_b = \frac{K}{\rho_b Cp} \tag{5}$$

Where,

ρ_b bulk density, kg/m^3

C_p specific heat of sample, J/kg ℃

K thermal conductivity, W/m K

α_b thermal diffusivity, m^2/s

7.3 RESULTS AND DISCUSSION

7.3.1 Bulk Density

Figure 7-1 shows the variation of bulk density of cashew nut and kernel with moisture content. The values of bulk density of cashew nuts and cashew kernels decreased linearly from 625.62kgm^{-3} to 592.42kgm^{-3} and 559.60kgm^{-3} to 505.06kgm^{-3} respectively when the moisture content increased from 5.0% to 9.0% w.b. This decrease was mainly due to the fact that moisture gain in the sample was lower than accompanying volumetric expansion of the bulk (Solomon and Zewdu, 2009). Balasubramanian (2001) also found the bulk density of raw cashew to decrease with increasing moisture content. The negative linear relationship of bulk density with moisture content was also observed by Kibar *et al*. (2010) for rice, Seifi and Alimardani (2010) for corn and Gupta and Das (1997) for sunflower seed. Empirical equations were developed to describe the effect of moisture content on bulk density of cashew nuts and kernel.

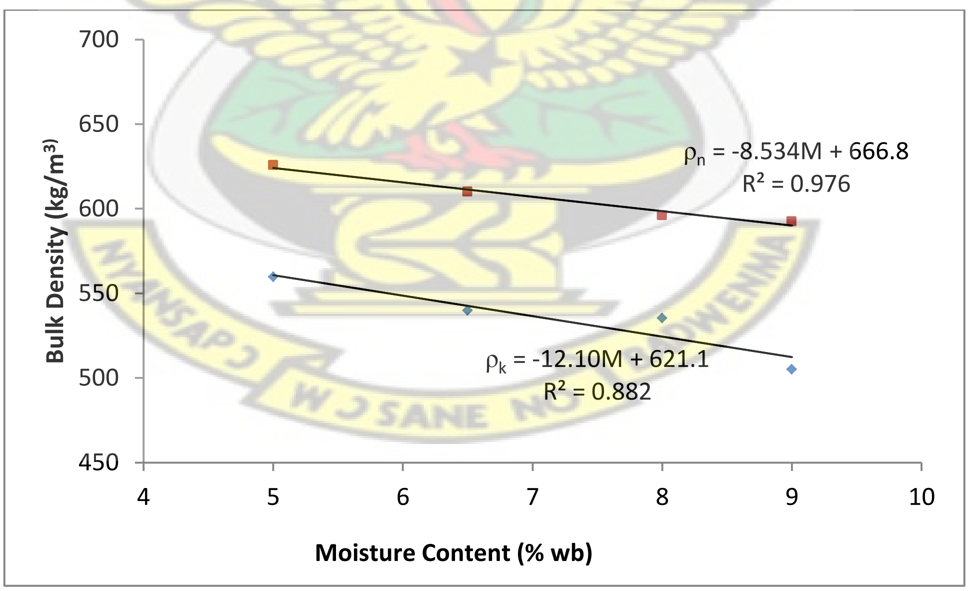

Figure 7-1: Effects of Moisture Content on Bulk Density of Cashew Nut/Kernel

7.3.2 Specific Heat

The variation of specific heat with moisture content is presented in Figure 7-2. The specific heat varied from 1586 $kJkg^{-1}ºC^{-1}$ to 1756 $kJkg^{-1}°C^{-1}$ in the moisture content range of 5.0 to 9.0%w.b. The specific heat increased linearly with increasing moisture content. The increasing trend in specific heat with moisture content correlates with work done by other researchers. Nathakaranakule and Prachayawarakorn (1998) also found a similar linear variation between the specific heat of cashew nuts and moisture content. Hsu *et al*. (1991) reported that the specific heat of pistachios varied from 1.1 to 2.1 kJ/kgK within the moisture content range of 9.5-39% w.b.

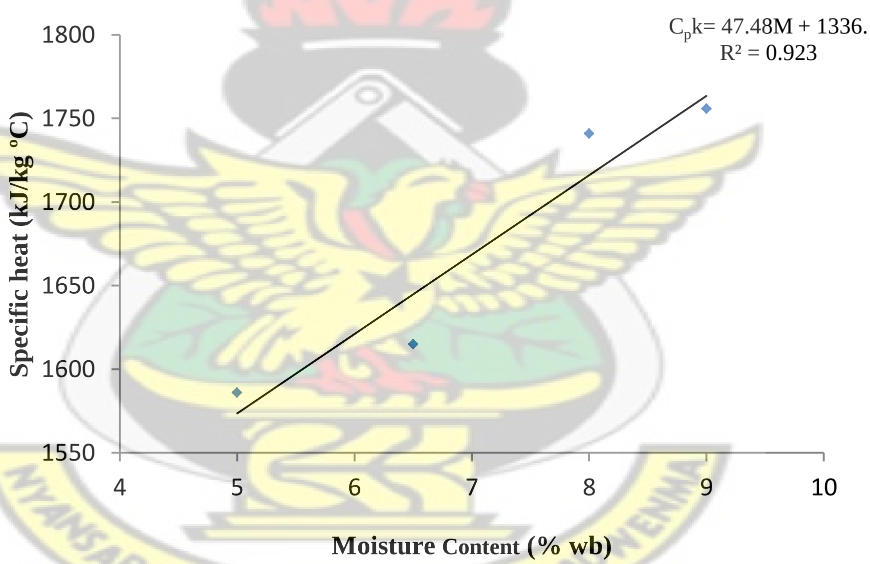

Figure 7-2: Moisture Content Variation on Specific Heat of Cashew Nut/Kernel

Chandrasekar and Viswanathan (1999) studied the thermal properties of two varieties of coffee beans in the moisture content range of 9.9-30.05% w.b. and showed that specific heat increased linearly from 0.78 to 2.36 kJ/kgK with increasing moisture content. However, other studies have reported non-linear relationships of some food and agricultural products (Murata *et al*., 1995 for rice; Tang *et al*., 1995 for lentil seeds; Chakraborty and Johnson, 1999 for tobacco).

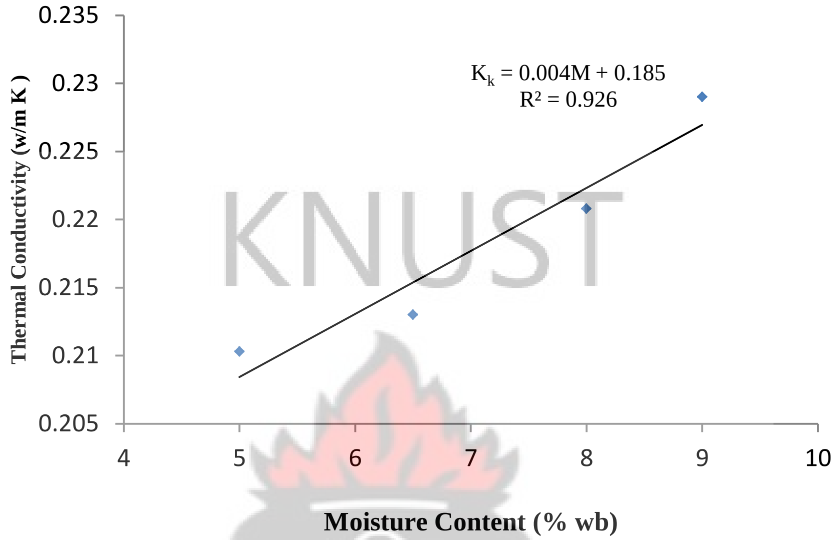

Figure 7-3: Variations of Moisture Content on Thermal Conductivity of Cashew Kernel

7.3.3 Thermal Conductivity

The variation of thermal conductivity with moisture content is shown in Figure 7-3. The thermal conductivity of cashew kernel varied from 0.2103 to 0.2296 W/m K with increasing moisture content in the range of 5.0-9.0% w.b. Other researchers such as Perusulla *et al*. (2010) for banana, Bart-Plange *et al*. (2009) for cowpea and maize, Nwabanne (2009) for cassava and Singh and Goswami (2000) for cumin seed also reported the existence of a linear relationship between thermal conductivity and moisture content. Kurozawa *et al*. (2008) found thermal conductivity to increase from 0.57 to 0.61 W/m °C with temperature in the range of 25 to 45 ^{o}C for cashew apple.

7.3.4 Thermal Diffusivity

Figure 7-4 shows the existence of a linear relationship between thermal diffusivity and moisture content. Thermal diffusivity increased linearly from 2.369×10^{-7} to 2.588×10^{-7} m^2/s with increasing moisture content in the range of 5.0% to 9.0% w.b. Hobani and Al-Askar (2000), found the thermal diffusivity of khudary and sufri dates to increase linearly with increasing moisture content. The average thermal diffusivity for nosrat and kavir varieties of barley grains was found to be 14.67×10^{-8} and 15.70×10^{-8} m^2/s respectively (Nouri Jangi *et al*., 2011). Other researchers such as Aviara and Haque (2001), Tansakul and Lumyong (2008), Shyamal *et al*. (1994) also reported a linear relationship between thermal diffusivity and moisture content for sheanut kernel, straw mushroom and wheat respectively.

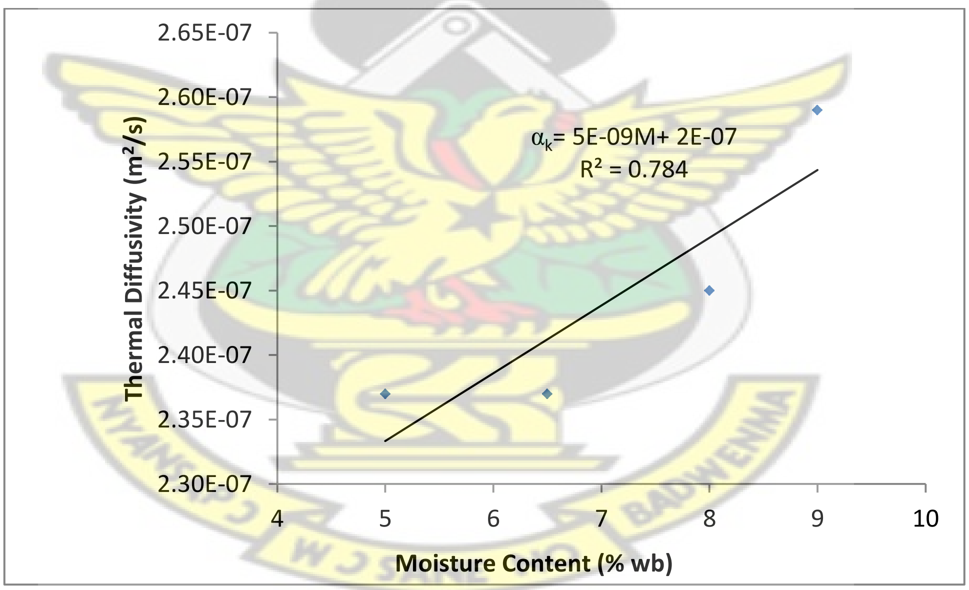

Figure 7-4: Variations of Moisture Content on Thermal Diffusivity of Cashew Kernel

7.4 CONCLUSIONS

For the moisture content range between 5.0% w.b. and 9.0% w.b., all the thermal properties studied were found to be moisture dependent.

Bulk density for nut and kernel decreased from 625.62 kg/m^3 to 592.42 kg/m^3 and 559.60 to 505.06 kg/m^3 respectively as moisture content increased from 5.0% to 9.0% w.b.

The specific heat of the cashew kernel increased from 1586 J/kgK to 1756 J/kgK with increase in temperature from 35°C to 65°C and moisture content from 5.0% to 9.0% w.b. .

Thermal conductivity increased from 0.2103W/mK to 0.2296 W/mK which increased linearly with moisture content from 5.0% w.b. to 9.0% w.b. Thermal diffusivity values increased linearly from 2.369×10^{-7} to 2.588×10^{-7} m^2/s with increases in moisture content from 5.0 to 9.0% w.b.

7.5 REFERENCES

Aviara N. A. and Haque, M. A. (2001) Moisture dependence of thermal properties of sheanut kernel. *Journal of Food Engineering*. 47: 109-113.

Aydin, C. (2006). Some engineering properties of peanut and kernel. *Journal of Food Engineering.* 79: 810-816.

Azam-Ali, S. H. and Judge, E. C. (2001). Small-Scale cashewnut processing.Schumacher Centre for Technology & Develoment, BourtonDunsmore, Rugby. Wickshire,110p.

Balasubrahumanian, D. (2001) Physical properties of raw cashew nut. *Journal of Agricultural Engineering Research.* 78(3): 291-297.

Bart-Plange, A. and Baryeh, E. A. (2003). The physical properties of category B cocoa beans. *Journal of Food Engineering*. 60:219-227.

Bart-Plange A., Asare V. and Addo A. (2009). Thermal conductivity of maize and cowpea. Journal of Engineering and Technology. 2-3: 6-11.

Baryeh, E. A. (2002). Physical properties of millet. *Journal of Food Engineering*. 51:36- 46.

Chakraborty, S. M. and Johnson, W. H. (1999). Specific heat of flue cured tobacco bydifferential scanning calorimeter. *Transactions of ASAE*. 15(5): 928-931.

Chandrasekar, V. and Visvanathan, R. (1999). Physical and thermal properties of coffee. *Journal of Agricultural Engineering Research.* 73: 227-234.

Dutta, S. K., Nema, V. K. and Bhardwaj, R. K. (1988). Thermal properties of gram. *Journal of Agricultural Engineering Research*. 39:269-275.

Erica, B., Cuniberti, A. and Susana, M. (2004). Moisture dependent physical and compression properties of safflower seed. *Journal of Food Engineering.* 2: 134-140.

Frankel, H. (1991). Engineering properties of foods. ASAE, Michigan, 407p.

FAOSTAT (2012). Production quantities by country (tonnes) (Average 1992 - 2010) Available at: http://faostat3.fao.org/home/index.html#VISUALIZE [Accessed 10 May, 2012].

Gharibzahedi, S. M. T., Seyed, M. M. and Ghahderijani, M. (2011). A survey on moisture-dependent physical properties of castor seed (Ricinu communis L.). *Aust J Crop Sci.* 5(1): 1-7.

Gupta R. K. and Das S. K. (1997). Physical properties of sunflower seeds. *Journal of Agricultural Engineering Research,* 66: 1- 8.

Hobani, A. I. and Al-Askar, S. R. (2000). Effective thermal properties of dates Res. Bult., No. (92), Agric. Res. Center, King Saud Univ., pp. (5-20)

Hsu, M. H., Mannapperuma, J. D. and Singh, R. P. (1991). Physical and thermal properties of pistachios. *Journal of Agricultural Engineering Research*. 49: 311- 321.

Ibrahim, Y, Coskun, M.B. and Özarskun, K. (2006). Physical properties of sweet corn (Zeamayssaccharata sturt) seed. *Journal of Food Engineering*. 74: 523- 528.

Kibar, H., Ozturk, T. and Esen, B. (2010). The Effect of moisture content on physical and mechanical properties of rice (Oryza sativa L.). *Spanish Journal of Agric. Research*. 8(3): 741-749.

Kingsley, A.R.P., Singh, D.B., Manikantan, M.R. and Jain, R.K. (2005). Moisture dependent physical properties of dried pomegranate (Amardana). . *Journal of Food Engineering*. 75:492-496.

Kurozawa, L.W., Park, K. J. and Azonbel, P. M. (2008). Thermal conductivity and thermal diffusivity of papaya (Carica papaya,L.) and Cashew apple (Anacardium occidentale L.). *Braz. Journal of Food Tech.* 11:78-85.

Murata, S., Tagawa, A. and Ishibashi, S. (1995).The effect of moisture content and temperature on specificheat of cereal grains measured by DSC. *Journal of Japanese Society of Agric. Machinery*. 46(6): 547-554.

Nathakaranakule, A. and Prachayawarakorn, S. (1998). Determination of physical properties of cashew nuts. J. Kasetsart 32(2): 171-186.

Nimkar, P. M. and Chattopadhyay, P. K. (2001). Some physical properties of green gram. *Journal of Agricultural Engineering Research*. 80(2):183- 189.

Nouri Jangi, A. Mortazavi, S.A., Tavakoli, M., Ghanbari, H., Tavakolipour, A. and Haghayegh, G.H. (2011) Comparison of mechanical and thermal properties between two varieties of barley (*Hordeum vulgare* L.) grains. *Aust. Journal of Agric. Engineering*. 2(5):132-139.

Nwabanne J.T. (2009). Drying characteristics and engineering properties of fermented ground cassava. *African Journal of Biotechnology.* 8(5): 873-876.

Ogunsina, B.S. and Bamgboye, A.I. (2007). Effects of pre-Shelling treatment on the physical Properties of cashew nut(Anacardium Occidentale), Inst. Agrophysics. Polish Academy of Science. 21: 385-389.

Ojolo, S.J. and Ogunsina, B.S. (2007). Development of a cashew nut cracking device. Agric. Eng. Int.:The CIGR E J,Manuscript Vo. IX.

Perusulla, C. A., Viviana, C. and Mends, L.A. (2010). Development of a linear heat source probe and determination of banana thermal conductivity. *Journal of Food Engineering*. 12(6).

Pliestic, S., Dobricevic, N., Filipovic, D. and Gosodaric, Z. (2006). Physical properties of filbert nut and kernel. *Biosystems Engineering*. 93(2): 173-178.

Razavi, H. and Bahrani, S. (2007). A model for predicting the effects of moisture on the modulus ofelasticity of soybeans. *Transactions of ASAE.* 24 (5): 1338-1341.

Sayed, M.A.R. and Maryam, B.P. (2007). Some physical and mechanical properties of kiwi fruit. *Int. Journal of Food Engineering.* 3(6): 56-75.

Seifi, M.R. and Alimardani, R. (2010). Comparison of moisture-dependent physical and mechanical properties of two varieties of corn (Sc 704 and Dc 370). *Aust. Journal of Agric. Engineering*. 1(5): 170 -178.

Shepherd, H. and Bhardwaj, R.K. (1985). Thermal properties of pigeon pea. Cereal Foods World.31: 466-470.

Shyamal, D. K., Chakraverty, A. and Benerjee, H. D. (1994). Thermal properties of raw, parboiled and debrnned parboiled wheat and wheat bulgur. *Journal of Food Engineering*. 49: 195-201.

Singh, K. K. and Goswami, T. K. (2000). Thermal properties of cumin seed. *Journal of Food Engineering*. 45:181–187.

Solomon, W. K. and Zewdu, A. D. (2009). Moisture dependent physical properties of Niger (Guiconia abyssinica Cass) seed. *Ind. Crops and Prod*uction. 29: 165-170.

Sweat, V. E., Haugh, C. G., and Stadelman, W. J. (1998) Thermal conductivity of chicken ... International Communication in *Heat and Mass Transfer.* 25: 733–741

Sweat, V. E. and Haugh, C. G. (2006). Thermal conductivity probe for small food samples. *Transactions of.ASAE.* 17(1): 56-58.

Tang, J., Yannacopoulos, Y. and Kasap, S. O. (1995). Specific heat capacity of lentil seed by DSC.*Transactions of.ASAE*. 34(2): 517-522.

KNUST

Tarighi, J., Mahmoudi, A. and Rad, M. K. (2011). Moisture dependent engineering properties of sunflower (var. Armaviriski). *Aust Journal of Agric Engineering*. 2(2): 40- 44.

Tansakul, P. and Chaisawang, P. (2007). Thermophysical properties of coconut milk. *Journal of Food Engineering*. 73: 276-280.

Tansakul, A. and Lumyong, R. (2008). Thermal properties of straw mushroom. *Journal of Food Engineering*. 87: 91-98.

Viviana, C. M., Antonio, G. B., Leandro, de L. and Dos Santos, C. (2008). Apparent thermal diffusivity estimation of the banana during drying using inverse method. *Journal of Food Engineering*. 85: 569-579.

Yalcin, I. and Özarlan, C. (2004). Physical properties of vetch seed, *Biosystems Engineering*. 89(4): 507-512.

Yalcin, I. (2006). Physical properties of cowpea (Vigna sinensis l.) seed. *Journal of Food Engineering*. 79: 57-62.

Yang, J. and Zhao, J. (2001). Thermal properties of radish and alfalfa seeds. *Journal of Food Process Engineering*. 24: 291-313.

Zewdu, A. D. and Solomon, W. K. (2007). Moisture dependent physical properties of tef seed. *Biosystems Engineering*. 96 (1): 57-63.

KNUST

CHAPTER EIGHT

8.0 EFFECT OF MOISTURE, BULK DENSITY AND TEMPERATURE ON THERMAL CONDUCTIVITY OF GROUND COCOA BEANS AND GROUND SHEANUT KERNELS

Published as Bart-Plange, A., Addo, A., Amponsah, S. K. and Ampah, J. (2012). ***Global Journal of Science Frontier Research (GJSFR). Volume 12 Issue 8 Version 1.0 July 2012.***
ISSN NO.: 2249-4626

ABSTRACT

Thermal conductivity is an important engineering parameter in the design of food processing equipment. It predicts or controls the heat flux in food during processing such as cooking, frying, freezing, sterilization, drying or pasteurization. The thermal conductivity of ground cocoa beans and ground sheanut kernels with varying moisture content, bulk density and temperature was studied using the transient heat transfer method. The thermal conductivity increased linearly for ground cocoa beans sample from 0.0243 to 0.0311 W/^{o}Cm and for ground sheanut kernels from 0.0165 to 0.0458 W/^{o}Cm in the moisture content range of 12.59 to 43.84 %w.b. at a constant bulk density of 295 kg/m^3. For bulk density range of 430 to 525 kg/m^3, thermal conductivity of ground cocoa beans and ground sheanut kernel increased linearly from 0.0265 to 0.0324 W/^{o}Cm and 0.0209 to 0.0252 W/^{o}Cm respectively when moisture content was at 16 %w.b Thermal conductivity of ground sheanut kernel and ground cocoa beans increased significantly ($p<0.05$) from 0.0233 to 0.0382 W/^{o}Cm and 0.0261 to 0.0397 W/^{o}Cm respectively as temperature increased from 35 to 55 ^{o}C. Effect of moisture, bulk density and temperature on thermal conductivity of sheanut kernel and cocoa bean were found to be significant ($p>0.05$).

Keywords: Thermal conductivity, shea nut, kernels, cocoa beans, moisture content, bulk density, temperature.

8.1 INTRODUCTION

Shea nut and Cocoa are important oil producing crops in Ghana. Sheanut hails from the *Sapotaceae* family. The commonly known varieties include *Vitellaria paradoxa* (*Butryospermum parkii*) and *Vitellaria nilotica.* Shea nut is obtained from the shea tree, and is grown mostly throughout West and Central Africa; in the semi-arid Sahel from Senegal to Ethiopia (Aremu and Nwannewuihe, 2011). Shea nut contains reasonably high amounts of oleic acids from which the shea butter (fat) is obtained. Shea butter is one of the basic raw materials for most food, cosmetics, soap as well as the pharmaceutical industries (Thioune *et al*., 2000) and it is sometimes used as a substitute for cocoa butter (Bekure *et al*., 1997).

Cocoa (*Theobroma Cacao*) is an ancient crop of the lowland tropical forest, which originated from the Southern and Central America (Lefeber *et al*., 2011). In West Africa, cocoa is one of the most important cash crops. Globally, Ghana's cocoa bean production is ranked second in the world after her western neighbour Côte d'Ivoire (FAOSTAT, 2005). Ghana is recognized as the world leader in premium quality cocoa beans production. Cocoa serves as the major source of revenue for the provision of socio-economic infrastructure in the country. In terms of employment, the industry employs about 60% of the national agricultural labour force in the country (Appiah, 2004 cited in Ntiamoah and Afrane, 2008). For these farmers, cocoa contributes about 70 -100% of their annual household incomes (COCOBOD, 2004 cited in Ntiamoah and Afrane, 2008). Cocoa seeds are the source of commercial cocoa beans and cocoa products include cocoa liquor, cocoa butter, cocoa cake and cocoa powder as well as chocolate. Cocoa powder is essentially used as flavour in biscuits, ice cream and cakes and is consumed by most beverage industries. Besides the traditional uses in chocolate manufacture and confectionery, cocoa butter, like shea butter, is also used in the manufacture of cosmetics. It is also a folk remedy for burns, cough, dry lips, fever, malaria, rheumatism and wounds. Studies show that the cocoa bean contains flavonoids with antioxidant properties that can reduce blood clot and the risk of stroke and cardiovascular attacks (ICCO, 2011).

The thermal conductivity of materials can be influenced by a number of factors such as the moisture content of the material, porosity and fibre orientation of the material (Stroshine and Hamann, 1994; Mohsenin, 1990). Thermal conductivity of food and biological materials increase with increase in moisture content and density (Opoku *et al*., 2006 for hay; Muramatsu *et al*., 2006 for brown rice, Aviara *et al*., 2008 for guna seeds and Perusella *et al*., 2010 for banana). Thermal conductivity data is needed for calculating energy demand for the design of equipment and optimization of thermal processing of foods (Polley *et al*., 1980). It controls the heat flux in food during processing such as cooking, frying, freezing, sterilization, drying or pasteurization. In the determination of thermal conductivity of food materials, the commonly employed methods are the transient and the steady-state methods (Mohsenin, 1980). Besides processing and preservation, thermal conductivity and other properties such as specific heat and thermal diffusivity also affect sensory quality of foods as well as energy saving during processing (Opoku *et al*., 2006). It is not uncommon to see farmers dry their produce without taking into consideration the quantity of heat needed to accomplish the drying process which in turn affects the market value of the end product. This is because such information on thermal conductivity of local agricultural products is either unavailable or inadequate.

The objective of this study therefore, was to determine the thermal conductivity of ground sheanut kernel and ground cocoa beans and investigate their dependence on moisture content, bulk density and temperature using the transient heat method.

8.2 MATERIALS AND METHODS

8.2.1 Sample Preparation

The shea nuts used in the study were purchased from a local market at Bole in the Northern region of Ghana in October 2010 while the cocoa beans were obtained the Kuapa Kokoo Depot in Kumasi in the Ashanti region of Ghana. The samples were cleaned by removing foreign materials and damaged kernels or beans. The sheanut kernel and cocoa beans used had all the quality checks performed and ready for local and export markets. Both sets of samples were conditioned to four moisture content levels of 12.59, 22.41, 31.55 and 43.84% wet basis. The samples were sealed in separate polythene bags and kept in a refrigerator at 5°C for five days to ensure uniform moisture distribution. Distilled water was then added to the samples: The amount of distilled water added was calculated using equation (1) (Balasubramanian, 2001):

$$M_w = \frac{M_i(m_f - m_i)}{100 - m_f} \qquad (1)$$

Where,

M_w is the mass of distilled water (g),

M_i is the initial mass of sample (g),

m_f is the final moisture content of sample (%w.b.) and

m_i is the initial moisture content of sample (%w.b.).

For bulk density variation, samples were milled in a laboratory hammer mill to a particle size of two millimetres using a set of screens. Varying bulk densities of 322, 346, 381 and 410 kg/m^3 were obtained by compressing in a cylinder with known weights at a constant moisture content using standard procedures (AOAC, 2002).

8.2.2 Experimental Setup

The setup for the thermal conductivity measurements is as shown in Figure 8-1. The thermal conductivity apparatus is a set-up consisting of an aluminium cylinder, which was used as sample holder, with a heating coil stretching between two insulated ends of the cylinder. A thermocouple was fitted through the top end of the cylinder for temperature readings in the sample. Heat (Q) was supplied by a constant direct current power source with current and voltage of 1A and 3V respectively throughout the experiment. In the set-up, there was an ammeter to take current readings, voltmeter to take voltage readings and a rheostat to vary resistance in the circuit in order to achieve the desired current.

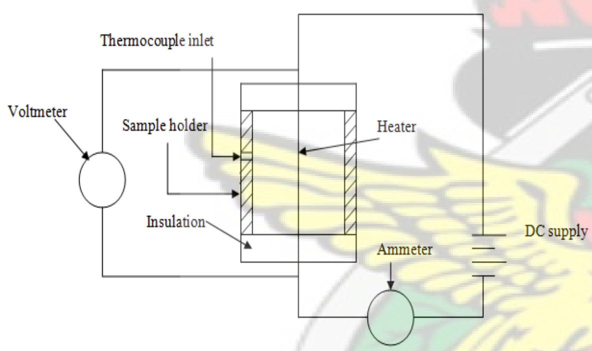

Figure 8-1: Schematic Diagram of the Thermal Conductivity Measuring Apparatus

The conditioned samples were placed in the aluminium sample cylinder in the set-up. The sample temperature at the centre of the cylinder was checked by means of a thermocouple, the current was adjusted to one ampere and a voltage of three volts was used. Temperature readings were taken at regular time interval of one minute for 40 minutes for each sample experimented. Thermal conductivity was determined at five sample temperatures of 35, 40, 45, 50 and 55°C, which is typically used for crop drying.

8.2.3 Thermal Conductivity Determination

Thermal conductivity (k) was determined using equation (2) (Tabil, 1999).

$$k = \frac{Q}{4\pi(t_2 - t_1)} \ln \frac{\theta_2}{\theta_1} \qquad (2)$$

Where,

Q = VI (V is the supplied voltage, I is input current, Q heat source per meter of the line source)

k = thermal conductivity of the medium (W/°Cm)

t_1 is initial temperature (°C)

t_2 is final temperature (°C)

ϑ_1 is initial time (min)

ϑ_2 is final time (min)

The thermal conductivity values of the ground shea nut kernel and ground cocoa beans were determined by calculating the slopes of the graphs of temperature changes against time ratio on a semi-logarithmic graph. The experiment was replicated four times at each moisture content. Bulk density and temperature level and thermal conductivity were recorded in each case.

8.2.4 Statistical Analysis

The experimental design used was the completely randomized design (CRD) with single factor analysis of variance (ANOVA) for all data and analyzed with Minitab Version 15. Statistical significance was carried out using Tukey and Fisher's approach at $p<0.05$.

8.3 RESULTS AND DISCUSSION

8.3.1 Effect of Moisture Content

Figure 8-2 shows the linear variation of thermal conductivity of ground shea nut kernel and ground cocoa beans with moisture content at constant bulk density (295 kg/m^3). Thermal conductivity of ground shea nut kernel and ground cocoa beans increased significantly ($p<0.05$) from 0.0165 to 0.0458 W/°Cm and 0.0243 to 0.0311 W/°Cm respectively with increasing moisture content from12.59 to 43.84 % w.b.

KNUST

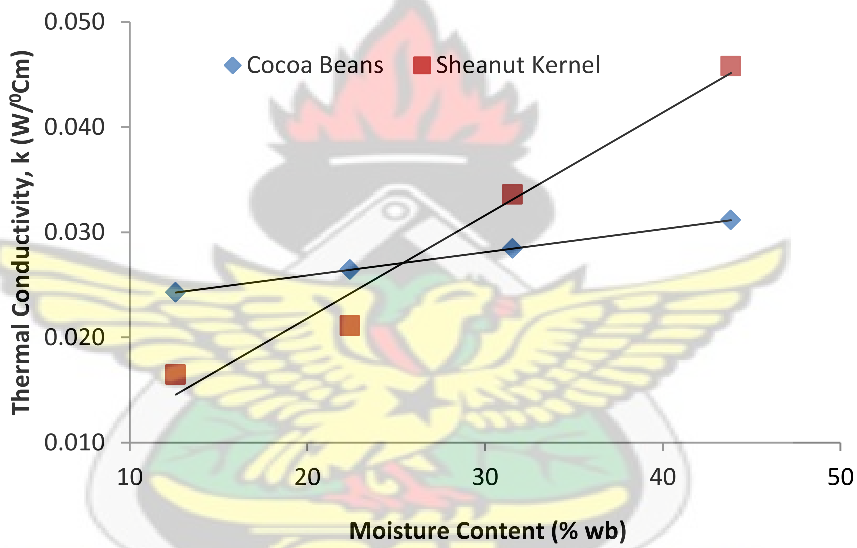

Figure 8-2: Thermal Conductivity as a Function of Moisture Content

Similar trend was observed in the thermal conductivity of soybean (Deshpande *et al*., 1996), cumin seed (Singh and Goswami, 2000), sheanut kernel (Aviara and Haque, 2001), borage seed (Yang *et al*., 2002), millet grains (Subramanian and Viswanathan, 2003), rough rice (Yang *et al*., 2003), brown rice (Muramatsu *et al*, 2006), maize and cowpea (Bart-Plange *et al*., 2009) and guna seed (Aviara *et al*., 2008).

The increase in thermal conductivity with moisture content can be attributed to the fact that an increase in moisture content of the sample increases the amount of water molecules available to fill the pores within the sample thus increasing the ability of the sample to conduct more heat.

The relationship between the thermal conductivity of ground shea nut kernel (k_{sk}) and ground cocoa beans (k_{cb}) and moisture content (*M)* can be expressed using equations (3) and (4) respectively.

KNUST

$k_{sk} = 0.097M + 0.002, \qquad R^2 = 0.974 \qquad (3)$

$k_{cb} = 0.022M + 0.021, \qquad R^2 = 1 \qquad (4)$

Equations (3) and (4) depict that thermal conductivity of ground sheanut kernel and ground cocoa beans have a linear relationship with moisture content. This agrees with what was reported by Aviara and Haque (2001) on shea nut kernel. Studies by other researchers also found thermal conductivity to increase with increasing moisture content (Sweat, 1974; Rao and Rizvi, 1986; Mohsenin, 1990; Tansakul and Lumyong, 2008; Meghwal and Goswami, 2011).

8.3.2 Effect of Bulk Density

The variation of thermal conductivity of ground shea nut kernel and ground cocoa beans with bulk density at constant moisture content (16 %w.b.) is shown in Figure 8-3.

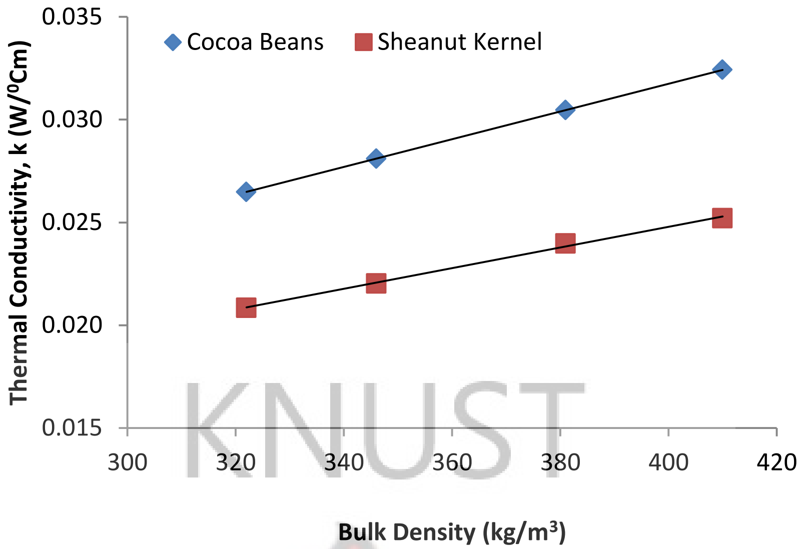

Figure 8-3: Thermal Conductivity as a Function of Bulk Density

The thermal conductivity of ground shea nut kernel and cocoa beans increased linearly and significantly ($p<0.05$) from 0.0209 to 0.0252 W/°Cm and 0.0265 to 0.0324 W/°Cm respectively as bulk density increased from 322 to 410 kg/m^3. This trend was similarly observed by other researchers including Taiwo *et al*. (1996) for cowpea, Aviara and Haque (2001) for shea nut kernel, Bart-Plange *et al*. (2009) for maize and cowpea and Meghwal and Goswami (2011) for black pepper. Moreover, it was observed that the thermal conductivity of ground shea nut kernel was generally lower than ground cocoa beans with increase in bulk density. The increase in thermal conductivity with bulk density can best be explained by making reference to the conduction ability of the sample particles in relation to the pores between them. Increasing the bulk density means increasing the number of particles in a constant volume thus decreasing the pore volume which leads to increased heat conduction ability of the sample.

The linear relationship between the thermal conductivity of ground shea nut kernel (k_{sk}) and ground cocoa beans (k_{cb}) and bulk density (ρ) may be expressed using equations (5) and (6) respectively.

$$k_{sk} = 5\times10^{-5}\rho + 0.004, \qquad R^2 = 0.997 \tag{5}$$

$$k_{cb} = 7\times10^{-5}\rho + 0.004, \qquad R^2 = 1 \tag{6}$$

8.3.3 Effect of Temperature

Figure 8-4 describes the variation of thermal conductivity with increasing temperature at constant moisture content and bulk density. At constant moisture content of 20.5% w.b. and constant bulk density of 420 kg/m^3, the thermal conductivity of ground shea nut kernel and ground cocoa beans increased significantly ($p<0.05$) from 0.0233 to 0.0382 W/^{o}Cm and 0.0261 to 0.0397 W/^{o}Cm respectively as temperature increased from 35 to 55 ^{o}C.

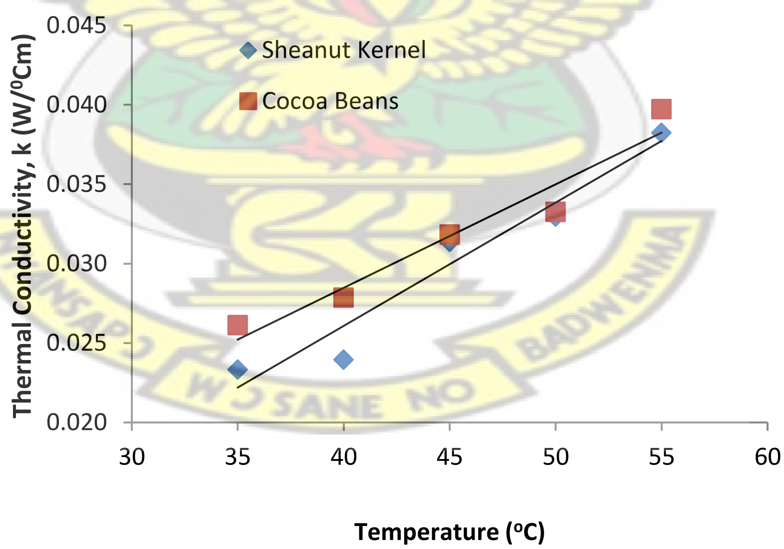

Figure 8-4: Thermal Conductivity as a Function of Temperature

The linear relationship between the thermal conductivity of ground sheanut kernel (k_{sk}) and ground cocoa beans (k_{cb}) and temperature (^oC) can be expressed using equations (7) and (8) respectively.

$$K_{sk =} = 0.0008T - 0.005 \quad R^2 = 0.9446 \tag{7}$$

$$K_{cb} = 0.0007T + 0.0024 \quad R^2 = 0.9434 \tag{8}$$

KNUST

Aviara and Haque (2001) and Bart-Plange *et al*. (2009) observed an increase in thermal conductivity with temperature for shea nut kernel and maize and cowpea respectively. Kurozawa *et al.* (2008) found thermal conductivity to increase from 0.57 to 0.61 W/m °C with temperature in the range of 25 to 45^{o}C for cashew apple. Mahmoodi and Hosein (2008) also found thermal conductivity of pomegranates to increase linearly from 0.6106 to 0.6372 W/m°C with increase in temperature from 26.5 to 45°C.

8.4 CONCLUSIONS

Investigations on the thermal conductivity of ground shea nut kernel and ground cocoa beans revealed the following:

Thermal conductivity of ground sheanut kernel and ground cocoa beans increased significantly ($p<0.05$) from 0.0165 to 0.0458 W/°Cm and 0.0243 to 0.0311 W/°Cm respectively with increasing moisture content from12.59 to 43.84 %w.b. at constant bulk density. A linear relationship was found to exist between thermal conductivity and moisture content.

Thermal conductivity of ground shea nut kernel and cocoa beans increased significantly ($p<0.05$) from 0.0209 to 0.0252 W/°Cm and 0.0265 to 0.0324 W/°Cm respectively as bulk density increased from 322 to 410 kg/m^3 at constant moisture content. A linear regression best describes the relationship between thermal conductivity and bulk density.

At a constant moisture content of 20.5 %w.b. and constant bulk density of 420 kg/m^3, the thermal conductivity of ground sheanut kernel and ground cocoa beans increased significantly ($p<0.05$) from 0.0233 to 0.0382 W/^{o}Cm and 0.0261 to 0.0397 W/^{o}Cm respectively as temperature increased from 35 - 55 ^{o}C.

8.5 REFERENCES

AOAC. (2002). Official Methods of Analysis, 17th Ed. Association of Official Analytical Chemists, Gaithersburg, Maryland, USA.

Appiah, M. R. (2004). Impact of cocoa research innovations on poverty alleviation in Ghana. Ghana Academy of Arts and Sciences Publication cited in Ntiamoah, A. and Afrane, G. (2008). Environmental impacts of cocoa production and processing in Ghana: life cycle assessment approach, *Journal of Cleaner Production*. 16(16): 1735-1740.

Aremu, A. K. and Nwannewuihe, H. U. (2011). Specific heat of ground fresh sheanut kernel (*Butyrospernum paradoxum*) as affected by particle size, moisture content and temperature. *Journal of Emerging Trends in Engineering and Applied Sciences*, (JETEAS) 2 (1): 177-183.

Aviara, N. A. and Haque, M. A. (2001). Moisture dependence of thermal properties of sheanut kernel. *Journal of Food Engineering.* 47: 109-113.

Aviara, N. A., Haque, M. A. and Ogunjimi, L. A. O. (2008). Thermal properties of Guna Seed. Institute of Agrophysics, Polish Academy of Sciences. 22: 291-297.

Balasubramanian, D. (2001). Physical Properties of Raw Cashew Nut. *Journal of Agricultural Engineering Research*. 78(3): 291 – 297.

Bart-Plange, A., Asare, V. and Addo, A. (2009). Thermal conductivity of maize and cowpea. *Journal of Engineering and Technology*. 2(3): 6-11.

Bekure, Z., Donlan, M., Gordon, Y. and Thomson, J. (1997). "Local to Global. The International market for Shea butter." Presented to United Nations Development Fund for Women.

COCOBOD (2004). Socio-economic study. Final report [MASDAR]. Ghana Cocoa Board cited in Ntiamoah, A. and Afrane, G. (2008). Environmental impacts of cocoa production and processing in Ghana: life cycle assessment approah, *Journal of Cleaner Production*. 16(16): 1735-1740.

Deshpande, S. D., Bal, S., and Ojha, T. P. (1996). Bulk thermal conductivity and diffusivity of soy bean. *Journal of Food Process Preservation*. 20: 177-189.

FAOSTAT (2005). Faostat database. Food and Agriculture Organisation.[Accessed 10 October, 2011]. Available online: www.fao.org/es/ess/top/commodity.html?lang=en&item=125&year=2005.

ICCO. (2011). Available at www.icco.org. [Accessed September 1 2011].

Kurozawa, L. W., Park, K. J. and Azonbel, P. M. (2008). Thermal conductivity and thermal diffusivity of papaya (Carica papaya,L.) and Cashew apple (Anacardium occidentale L.). *Braz. Journal of Food Tech*. 11: 78-85.

Lefeber, T., Gobert, W., Vrancken, G. Camu, N. and Vuyst, L. D. (2011). Dynamics and species diversity of communities of lactic acid bacteria and acetic acid bacteria during spontaneous cocoa bean fermentation in vessel. *Food Microbiology*. 28: 457-464.

Mahmood, M. and Hosein, K. M. (2008). Determination and Comparison of Thermal Conductivity of Iranian Pomegranate Varieties. 18th National Congress on food technology, Mashhyad, IR, Iran, 15-16 October , 2008.

Meghwal, M. and Goswami, T. K. (2011). Thermal properties of black pepper and its volatile oil. *International Journal of Advanced Biotechnology and Research*. 2(3): 334-344.

Mohsenin, N. N. (1980). Thermal Properties of Foods and Agricultural Materials. pp 83–121, Gordon and Breach, New York.

Mohsenin, N. N. (1990). Thermal properties of foods and agricultural materials. New York: Gordon and Breach.

Muramatsu, Y., Tagawa, A., Kasai, T., Takeya, K. and Fukushima, M. (2006). Prediction of thermal conductivity of kernels and packed bed of brown rice. *Journal of the Japanese Society of Agricultural Machinery,* 64(1): 70–76.

Ntiamoah, A and Afrane, G. (2008). Environmental impacts of cocoa production and processing in Ghana: life cycle assessment approah, *Journal of Cleaner Production*, 16(16): 1735-1740.

Opoku, A., Tabil, L. G., Crerar, B. and Shaw, M. D. 2006. Thermal conductivity and thermal diffusivity of timothy hay. *Canadian Biosystem Engineering*. 48: 3.1-3.7

Perusulla, C. A., Viviana, C., Mends, L. A. (2010). Development of a linear heat source probe and determination of banana thermal conductivity. *International Journal of Food Engineering 6(5).*

Polley, S. I., Synder, O. P. and Kotnour, F. (1980). A compilation of thermal properties of foods. *Food Technology.* 34(11): 76–78.

Rao, M. A. and Rizvi, S. S. H. (1986). Engineering properties of foods. New York: Marcel Dekker.

Singh, K. K. and Goswami, T. K. (2000). Thermal properties of cumin seed. *Journal of Food Engineering.* 45: 181-187.

Stroshine, R. and Hamann, D. D. (1994). Physical Properties of Agricultural Materials and Food Products. 1994. Course manual, Purdue University, USA.

Subramanian, S. and Viswanathan, R. (2003). Thermal properties of minor millet grains and flours. *Biosystems Engineering*. 84: 289-296.

Sweat, V. E. (1974). Experimental values of thermal conductivity of selected fruits and vegetables. *Journal of Food Science*. 39: 1080-1091.

Tabil, L. G. (1999). Specific heat of agricultural and food materials. Research report, Department of Agricultural and Bio-resource Engineering, University of Saskatchewan, Canada. p 7.

Taiwo, K. A., Akanbi, C. T. and Ajibola O. O. (1996). Thermal properties of ground and hydrated cowpea. *Journal of Food Engineering*.. 29: 249-256.

Tansakul, A. and Lumyong, R. (2008). Thermal Properties of Straw Mushroom. *Journal of Food Engineering*. 87:91-98.

Thioune, O., Ahodikpe, D., Dieng, M., Diop, A. B., Ngom, S. and Lo, I. (2000). Inflammatory ointment from shea butter and hydro alcoholic extract of Khaya sengalensis barks (cailcederat) Dakar Med. 45(2): 113-6.

Yang, W., Sokhansanj, S., Tang, J. and Winter, P. (2002). Determination of thermal conductivity, specific heat and thermal diffusivity of borage seeds. *Biosystems Engineering.* 82: 169-176.

Yang, W., Siebenmorgen, T. J., Thielen, T. P. H and Cnossen, A. G. (2003). Effect of glass transition on thermal conductivity of rough rice. *Biosystems Engineering*. 84(2): 193-20

CHAPTER NINE

9.0 GENERAL DISCUSSION

9.1 Introduction

Food materials vary significantly in composition, microstructure and their physical properties. These include particle size, shape, colour, hygroscopicity, cohesion, flowability, density, compressibility, mechanical strength and thermal properties (Mohsenin, 1987). There are simple standard methods to determine such properties and the outcome of their determination may strongly depend on the test conditions. The relationship between the measured parameters and the dependent factors as well as the test conditions is critical for proper interpretation of acquired data. The design and adoption of any technology for production and processing of crops at all levels of the value chain require specific characteristics of the crop involved. Properties of different crops may differ and therefore equipment adjustment and or modification is required for a particular operation if efficiency is the desired end result. For instance, a jab planter used for seeding different grains would need seed plate modifications for different seeds to achieve desired results and therefore dimensional and shape properties of granular food materials may be required. According to Peleg (1983) modification of particle size distribution, for example, can result in simultaneous change in bulk density, flowability and appearance. Moreover, the particle sample preparation method used can have a profound effect on the physical properties, and the same applies to handling and storage conditions. Therefore, the distinction between engineering properties of different grains and granular materials is fundamental although a certain degree of overlap is unavoidable.

This thesis focused on physical, thermal and compressive properties of selected cash crops grown in Ghana. The crops in focus are cocoa, shea and cashew which are export crops that have the potential of expanding Ghana's GDP. The effects of variation of moisture which affect the engineering properties of food and biological materials such as those considered in the studies were investigated and presented in Chapters 3 to 8.

In Chapters 3 and 4, physical properties of cocoa beans and cashew kernels have been presented and highlighted with moisture content changes indicating how the properties studied change with moisture. Compressive properties of cashew kernels, cocoa beans and shea kernels are presented in Chapters 4, 5 and 6. Thermal properties of ground cashew kernels, cocoa beans and shea kernels are then discussed in Chapters 7 and 8.

9.2 Physical properties

Size characterization and moisture effect have been considered in this study. Cocoa bean and cashew kernel weight were also studied as particle weight has a dominant effect on the bulk properties and flowability of granular materials. In most granular food materials, the relative dominance of gravitational and surface forces can change, primarily, as a result of moisture sorption, loss or redistribution, and/or heating or cooling (Peleg, 1978). Hydrostatic pressure which is related to the density of granular products, which may be produced in storage, can vary significantly with moisture absorption. When individual particles are put together in storage the contact area between them increase which then could increase the strength exerted for example on silo walls. Granular food materials such as cocoa should be considered as dynamic systems where bulk density and angle of repose change significantly with time, especially when moisture exchange and temperature are concerned.

Some of the important physical properties of cocoa beans and cashew kernels are reported and discussed in Chapters 3 and 4. Moisture influence on the selected physical properties has been established in the moisture range recommended for postharvest operations. Because of the irregular and inhomogeneous nature of the grains, linear as well as non linear relationships involving moisture content variation and the properties studied have been found.

The relationship between physical properties of two categories of cocoa beans were evaluated as a function of moisture content within the moisture content range of 5.67 - 25.04% on wet basis. Some of the selected properties studied showed linear relationships with moisture variation while others exhibited non linear trends. Studies on bean weight were considered for cocoa beans and this is reported in Chapter 3. Effect of moisture on bean weight, which is significant in product quality characterization and international trade, was found to have an increasing linear trend (Table 9-1).

Table 9-1: Moisture Effect on some Selected Properties of Cocoa Beans and Cashew Kernels.

	Cocoa beans	Cashew kernels
1000 bean mass	Increased linearly	Increased linearly
Bulk density	Decreased linearly	Decreased linearly

The variation of bulk density of cocoa beans and cashew kernel with moisture content has been found in this study to have a linearly decreasing trend with increasing moisture content (Table 9-1). The decreasing trend of bulk density with increasing moisture content has also been reported by Deshpande *et al*. (1993) for soybean within the moisture range of 8% db to 25% db; Tunde-Akintunde and Akintunde (2007) for beniseed in the moisture range of 3.5% db and 25.0% db; Ozturk *et al.* (2009) for new common bean cv. 'Elkoca-05' within the moisture range of 7.50% db and 19.85% db. On the other hand, an increase in bulk density as moisture content increases was reported by Joshi *et al*. (1993) for pumpkin seeds and Suthar and Das (1996) for karingda seeds. These discrepancies could be due to the cell structure, volume and mass increase characteristics of the grains and seeds as moisture content increases.

The bulk density at an average moisture content of 8.6% which is close to storage moisture content for the small and large size cocoa beans was found to range from 559.60 to 699.9 kg/m^3. This corresponds to what is reported in literature (Wood and Lass, 2001). The average bulk density for cashew at 5% moisture content wb was 505 kg/m^3. In this study, bulk density of cocoa beans has been found to be higher than that of cashew kernels. This distinction between different grains and granular materials is fundamental although a certain degree of overlap is unavoidable since it helps in the analysis of quality, product weight, moisture effect and flowability of the products.

9.3 Compressive properties

The importance of compressive strength of food grains in processes such as milling and grinding cannot be overemphasized. Mechanical compressibility can be determined by compressing a specimen with a Universal Testing Machine and recording its apparent stress-strain relationship.

Results of moisture effect on compressive properties of cocoa beans, cashew kernel and shea nut investigated into are discussed in Chapters 3, 4 and 5.

The maximum compressive load, maximum displacement, stress, strain, and Young's modulus studied for cashew kernel were found to increase linearly from 0.445 to 0.574 kN, 7.760 to 8.008 mm, 2.225 to 2.872 MPa, 0.777 to 0.801 mm/mm and 4.666 to 9.853 MPa respectively in the moisture content range of 5 - 9%.

The compressive properties of premium quality cocoa beans from Ghana, considering the effect of moisture content in the moisture range of 7% to 22 % (w.b) were also studied. The results of the study demonstrated that the displacement at maximum load or the deformation and the crushing energy had more positive linear function with moisture content and increased from 0.80 to 1.87 mm and from 13.0 to 200 mJ respectively. The compressive strain and Young's Modulus decreased significantly in linear relationship with very high correlation coefficient within the moisture content range considered, which increased from 0.009 to 0.0045 mm/mm, and 1300 to 205 MPa respectively. The compressive stresss, however, decreased exponentially with increasing moisture content from 1.5 to 0.3 MPa. The increase in deformation and subsequent decrease in compressive stress and strain of the cocoa bean, as the moisture content increased, shows that the energy absorption capability of wet cocoa bean is higher than the dry ones leading to higher mechanical strength to rupture during the lateral compressive loading. These findings provide useful information for food, agricultural engineers and others in the design of suitable cocoa beans crackers.

In the case of shea kernels, the effects of moisture content and loading on compressive stress, compressive strain, Young's Modulus and crushing energy were also examined. Compressive stress, compressive strain and Young's Modulus decreased with increase in moisture content for shea kernels. Compressive stress and strain decreased linearly from 2.0 to 0.8 MPa and 0.0085 at to 0.002 mm/mm as moisture content increased from 5% w.b. to 24% w.b. respectively. Young's Modulus decreased non-linearly from 2000 MPa at 5% moisture content to 100 MPa at 24% moisture content. Crushing energy on the other hand increased non-linearly from 0.005 to 0.13 mJ in the moisture content range of 5% to 24% w.b. The results provide useful data to confirm what other researchers have found for other grains and seeds which could be used in the design of suitable shea kernel cracking and crushing machines. Variation of moisture with the compressive properties studied are presented in Table 9-2.

Table 9-2: Compressive Properties and their Moisture Effect for Cocoa, Cashew and Shea

	Cocoa beans	Cashew nuts	Shea kernel
Compressive stress	Linear decrease	Linear increase	Linear decrease
Compressive strain	Linear decrease	Linear increase	Linear decrease
Young's Modulus	Linear decrease	Linear increase	Non-linear decrease
Crushing energy	Linear increase	Linear increase	Non-linear increase

The values found in this study are consistent with the results obtained by Sayyah and Minaei (2004) who found Young's modulus of wheat kernels to range from 486 to 1631 MPa and to correlate inversely with increasing moisture. According to Afkari Sayyah and Minaei (2004) a range of 230 to 4100 MPa has been reported by different authors for the modulus of elasticity with a mean standard error of 172 MPa (Mohsenin, 1978; Arnold and Robert, 1969; Bargale *et al.*, 1995, Afkari Sayyah and Minaei, 2004). The results of this study fall within this range.

Other researchers such as Mamman *et al.* (2005) for aegyptiaca nut, Burubai *et al.* (2007) for African nutmeg seed, Hemery *et al.* (2010) for wheat bran, Abbaspour-Fard *et al.* (2012) for pumpkin seed also found Young's modulus to decrease with moisture content increase.

In a similar research by Saiedirad *et al.* (2008) involving small, medium, and large cumin seeds, the energy absorbed at seed rupture increased from 1.8 to 8.6 mJ and 7.6 to 14.6 mJ with increase in moisture content from 5.7% to 15% d.b. for quasi-statically loaded vertical and horizontal orientations, respectively. This increasing trend was similarly observed by other researchers including Burubai *et al*. (2007) for African nutmeg, Tavakoli *et al*. (2009) for barley grains, Gorji *et al*. (2010) for wheat grains, Seifi and Alimardani (2010) for Sc 704 corn variety and Tarighi *et al*. (2011) for corn grains.

Researcher have found the crushing energy to decrease with decreasing moisture content (Mamman *et al*., 2005 for aegyptiaca nut; Unal *et al*., 2008 for mung beans; Zareiforoush *et al*., 2010 for two paddy rice varieties; Kalkan and Kara, 2011 for popcorn kernels; Alhijahani and Khodael 2011 for strawberry fruit). Bargale et al. (1995) in an early study found the energy required to cause rupture in the barley kernel to increase initially and then decreased with moisture content increase which implies that moisture content range is an important consideration.

9.4 Thermal properties

During processing and storage, many agricultural materials and food products are either heated or cooled. Grains and seeds are dried prior to storage, canned foods are sterilized by heating and cereal products such as bread and crackers are baked. Cooling, cooking, baking, roasting, pasteurization, freezing and dehydration all involve heat transfer and the design of such processes requires a knowledge of the thermal properties of the materials involved (Stroshine and Hamann, 1995).

Several processes involve diffusion of water into or out of agricultural materials and the transfer of heat into food products and grains during drying is accompanied by simultaneous diffusion of water through the product to the surrounding air (Stroshine and Hamann, 1995).

Attempts have been made to optimize the drying process and to minimize internal cracking during drying of grains and seeds with the aid of mathematical and numerical drying models but according to researchers including Mohsenin (1980) such modelling requires knowledge of both the mass transfer properties of the material and the effects of heat and moisture on changes in volume. Thermal conductivity is an important engineering parameter in the design of food processing equipment as it predicts or controls the heat flux in food during processing such as cooking, frying, freezing, sterilization, drying or pasteurization.

KNUST

The thermal conductivity of ground cocoa beans, ground shea and cashew kernels with varying moisture content, bulk density and temperature was studied and this is discussed in Chapters 7 and 8. In the determination of the conductivity of food materials, the commonly employed methods are the transient and the steady-state methods (Mohsenin, 1980) and so in these studies, the transient state method was used which is appropriate for food materials and has been used by several researchers. Important data on thermal conductivity as affected by moisture content changes have been generated for the crops studied.

Thermal conductivity increased linearly for ground cocoa beans sample from 0.0243 to 0.0311 W/^{o}Cm and for ground shea kernels from 0.0165 to 0.0458 W/^{o}Cm in the moisture content range of 12.59 to 43.84 % w.b. at a constant bulk density of 295 kg/m^3.

The relationship between the thermal conductivity of ground shea kernel and ground cocoa beans and moisture content have been discussed in Chapters 7 and 8. Equations generated depict that thermal conductivity of ground cashew kernels, cocoa beans and shea kernels have a linear increasing relationship with moisture content. Similar trend was observed in the thermal conductivity of soybean (Deshpande *et al*., 1996), cumin seed (Singh and Goswami, 2000), sheanut kernel (Aviara and Haque, 2001), borage seed (Yang *et al*., 2002), millet grains (Subramanian and Viswanathan, 2003), rough rice (Yang *et al*., 2003), brown rice (Muramatsu *et al*., 2006), maize and cowpea (Bart-Plange *et al*., 2009) and guna seed (Aviara *et al*., 2008).

The increase in thermal conductivity with moisture content can be attributed to the fact that an increase in moisture content of the sample increases the amount of water molecules available to fill the pores within the sample thus increasing the ability of the sample to conduct more heat.

The variation of thermal conductivity of ground shea kernels and ground cocoa beans with other properties such as bulk density and temperature were also studied at constant moisture content. It was found that thermal conductivity increased linearly and significantly ($p<0.05$) with bulk density and temperature.

For bulk density range of 430 to 525 kg/m^3, thermal conductivity of ground cocoa beans and ground sheanut kernel increased linearly from 0.0265 to 0.0324 W/^{o}Cm and 0.0209 to 0.0252 W/^{o}Cm respectively when moisture content was at 16 %w.b. Thermal conductivity of ground sheanut kernel and ground cocoa beans increased significantly ($p<0.05$) from 0.0233 to 0.0382 W/^{o}Cm and 0.0261 to 0.0397 W/^{o}Cm respectively as temperature increased from 35 to 55^{o}C. Specific heat, thermal conductivity and thermal diffusivity for ground cashew kernel were investigated into and found to increase linearly from 1586 to1756 J/kg^{o}C, 0.2103 to 0.2296 W/mK and 2.369×10^{-7} to 2.588×10^{-7} m^2/s with increasing moisture content from 5.0 to 9.0% w.b. Effect of moisture on the thermal properties were found to be significant ($p>0.05$).

9.5 Engineering implications

In a bid to mechanize the various unit operations involved in the post-harvest processing of shea kernel, information and data on the behaviour of these strength properties as a function of moisture is needed. The utlisation of the data generated would save energy and promote the design and development of appropriate, effective and efficient process machines.

Besides processing and preservation, thermal conductivity and other properties such as specific heat and thermal diffusivity also affect the sensory quality of foods as well as energy saving during processing (Opoku *et al*., 2006). It is not uncommon to see farmers dry their produce without taking into consideration the quantity of heat needed to accomplish the drying process which in turn affects the market value of the end product. This is because such information on thermal conductivity of local agricultural products is either unavailable or inadequate. The data provided on thermal conductivity could be used for the analysis of drying of the crops studied.

CHAPTER TEN

10.0 CONCLUSION AND RECOMMENDATIONS

10.1 Conclusions

The relationship between all the physical, thermal and compressive properties studied and moisture content were found to be significant ($p>0.05$) for cocoa, cashew and sheanut and kernel.

KNUST

10.1.1 Physical properties

The results of moisture variation on selected physical properties for cocoa bean and cashew kernel samples such as 1000-bean mass, true density, porosity, emptying angle of repose, static coefficient of friction showed increasing trends with linear relationships while bulk density variation was found to decrease linearly with moisture content increase.

10.1.2 Compressive properties

The compressive stress, strain, and Young's modulus for the cashew kernel increased from 0.214 to 1.214 MPa, 0.355 to 0.472 mm/mm, and from 2.446 to 6.416 MPa respectively as moisture content increased from 5.0 to 9.0% wb.

The compressive strain and Young's Modulus for cocoa beans decreased significantly in linear relationship with moisture from 0.009 to 0.0045, and from 1300 MPa to 205 MPa respectively as moisture content increased from 7 to 22% wb. The compressive stress, however, decreased exponentially with increasing moisture content from 1.5 MPa to 0.3 MPa while the crushing energy had more positive linear function with moisture content and increased from 0.013 J to 0.2 J.

For the shea kernel, compressive stress decreased from 2 MPa at 5% moisture content to 0.8 MPa at 23% wb moisture content. The compressive strain for shea kernel decreased from 0.0085 at 5% moisture content to 0.002 mm/mm. Young's modulus for shea kernel decreased from 2000 MPa at 5% moisture content to 100 MPa at 24% content. Crushing energy increased non-linearly from 0.005 to 0.13mJ in the moisture content range of 5% at 24% w.b. The results provide useful data to be used by engineers in the design of suitable shea kernel cracking and crushing machines.

10.1.3 Thermal properties

The thermal conductivity of ground cocoa beans and ground shea kernels were found to increase linearly with increasing moisture content. The thermal conductivity increased linearly for ground cocoa beans sample from 0.0243 to 0.0311 W/^{o}Cm and for ground sheanut kernels from 0.0165 to 0.0458 W/^{o}Cm in the moisture content range of 12.59 to 43.84% w.b. at a constant bulk density of 295 kg/m^3. Specific heat, thermal conductivity and thermal diffusivity for ground cashew kernel were found to increase linearly from 1586 to 1756 J/kgºC., 0.2103 to 0.2296 W/mK and 2.369×10^{-7} to 2.588×10^{-7} m^2/s with increasing moisture content from 5.0 to 9.0% w.b.

10.2 Recommendations and future work

This study has brought out some issues which will need further investigation:

The chemical composition of the grains is among the important factor that may affect engineering properties of food materials and should be determined in future work as it is believed will affect properties considered.

In this study ground grain samples were used for the determination of thermal properties. Analysis of thermal properties using whole grain samples should be the focus of future work. The line heat source method was used for the determination of thermal properties. Future work should consider the use of the steady state method as well to ascertain the variation that may exist between the two methods.

The determination of the compressive properties focused on uniaxial compression in horizontal loading so further research looking at other axis and comparing the effects of vertical loading as well is necessary. The relationship between porosity, particle density and compressive properties should be given attention.

Linear and nonlinear moisture relationships with the properties studied have been established which need to be investigated for other crops grown in Ghana to enable a database of engineering properties for Ghanaian crops to be established for farmers, processors, food scientist and agricultural engineers.

REFERENCES

Abalone, R., Cassinera, A., Gastón, A. and Lara, M. A. (2004). Some physical properties of Amaranth seeds. *Biosystems Engineering*. 89(1): 109-117.

Abatania, L., Gyasi, K. O., Coulibaly, O., Adeoti, R. and A.B. Salifu. (2000). Adoption and impact of improved cowpea technologies in Ghana cited in Asafo-Adjei, B., Atuahen, A. G. and Singh, B. B. (2005) Registration of Asontem cowpea. International Institute of Tropical Agriculture. *Crop Science Journal*. (45):26-49.

Abbaspour-Fard, M. H., Khodabakhshian, R., Emadi, B. and Sadrnia, H. (2012). Evaluation the Effects of Some Relevant Parameters on ElasticModulus of Pumpkin Seed and Its Kernel. *International Journal of Biomaterials.* Volume 2012, Article ID 271650, 6 pages.

Abbot, J. A. and Massie, D. R. (1995). Non-destructive dynamic force/deformation measurement of kiwifruit firmness. *Transactions of ASAE*. 93: 6025

Acquaye, D., Smith, M., Letchamo, W., Angers, P. and Simon, J. (2001). Agribusiness in Sustainable Natural African Plant Products. ASNAPP-SB-10-2001.

Adegbulugbe, T. and Olujimi, O. (2009). Evaluation of varietal and moisture content effect of some cowpea varieties on their bulk densities, particle density and porosity. http//www.ajol.info/journals/ nifoj

Ahmadi H., Fathollahzadeh, H. and Mobli, H. (2009). Postharvest physical and mechanical properties of apricot fruits, pits and kernels (C.V. Sonnati Salmas) cultivated in Iran. *Pak J. Nut.* 8(3): 264-268.

Ahmadi, H., Mollazade, K., Khorshidi, J., Mohtasebi S. S. and Rajabipour A. (2010) Some physical and mechanical properties of funnel seeds. *African Journal of Biotechnology.* 9(5):. 648-655.

Akaaimo, D. I. and Raji, A. O. (2006). Some physical and engineering properties of prosopis Africana seed. *Biosystems Engineering*. 95(2): 197-205.

Akinci, I., Ozdemir, F., Topuz, A., Kabas O. and Canakci, M. (2004) Some Physical and Nutritional Properties of Juniperus drupacea fruits. *Journal of Food Engineering*. 65: 325–331.

Alhijahani , H. S. and Khodael, J. (2011). Some physical properties of strawberry (Kurdistan variety). *World Applied Science Journal*. 13(2): 206-212

Altuntas E. and Yildiz M. (2007). Effect of moisture content on some physical and mechanical properties of faba bean (*Viciafaba* L.) grains. *Journal of Food Engineering Research*. 78: 174-183.

Altuntas, E. and Karadag, Y. (2006). Some physical and mechanical properties of sainfoin (Onobrychis sativa Lam.), grasspea (Lathyrus sativus L.) and bitter vetch (Vicia ervilia L.) seeds. *Journal of Applied Sciences*. 6 (6): 1373–1379.

Ampah, J. Bart-Plange, A. and Dzisi, K. A. (2012). Effect of rewetting on selected physical properties of *'Asontem'* Cowpea Variety. *ARPN Journal of Engineering and Applied Science*. 7(5): 389-395.

Ampawan, T.; and Rotjarek, L. (2008). Thermal properties of straw mushroom. *Journal of food Engineering*. 87, 91-98.

Anass, A. B. (2006). Mechanical properties of cocoa beans. BSc. Thesis, Department of Agricultural Engineering, KNUST, Kumasi.

Andrighetti, L., Bassi, G. F., Capella P., Franca, F. M. C., and Vannini, G. (1998). The world cashew economy. Inchiostroblu, Italy.

AOAC. (2002). Official Methods of Analysis, 17th Ed. Association of Official Analytical Chemists, Gaithersburg, Maryland, USA.

Appiah, M. R. (2004). Impact of cocoa research innovations on poverty alleviation in Ghana. Ghana Academy of Arts and Sciences Publication cited in Ntiamoah, A. and Afrane, G. (2008). Environmental impacts of cocoa production and processing in Ghana: life cycle assessment approach, *Journal of Cleaner Production*. 16(16): 1735-1740.

Aremu, A. K. and Nwannewuihe, H. U. (2011). Specific heat of ground fresh sheanut kernel (*Butyrospernum paradoxum*) as affected by particle size, moisture content and temperature. *Journal of Emerging Trends in Engineering and Applied Sciences*. 2(1): 177-183.

Arnold, P. C. and Robert, A. W. (1969). Fundamental aspects of load-deformation behaviour of wheat grains. *Transactions of ASAE*. 12: 104 -108.

Asiedu, J. J. (1989). Processing tropical crops. A technological approach. The Macmillan Press, London and Basingstoke. 266 p.

Aviara, N. A. and Haque, M. A. (2001). Moisture dependence of thermal properties of sheanut and kernel. *Journal of food Engineering*. 47: 109-113.

Aviara, N. A., Oluwole, F. A. and Haque, M. A. (2005). Effects of moisture content on some physical properties of sheanut (*Butyrospernum paradoxum*). *International Agrophysics.* 19: 193-198.

Aviara, N. A., Gwandzang, M. I. and Hague, M. A. (1999). Physical properties of guna seeds. *Journal of Agricultural Engineering Research*. 73: 105–111.

Aviara, N. A., Haque, M. A. and Ogunjimi, L. A. O. (2008). Thermal properties of guna seeds. Institute of Agrophysics, Polish Academy of Sciences. 22: 291-297.

Awua, P.K. (2002). The success story of cocoa processing and chocolate manufacturing in Ghana – the success story that demolished a myth, David Jamieson & Associates Ltd., Saffron Walden, Essex.

Aydın C. (2002). Physical properties of hazel nuts. *Biosystem Engineering*. 82(3): 297-303.

Aydin, C. (2006). Some engineering properties of peanut and kernel. *Journal of food Engineering*. 79: 810-816.

Aydin, C., Ogut, H. and Konak, M. (2002). Some physical properties of Turkish Mahaleb. *Biosystems Engineering, 82 (2): 231-234.*

Azam-Ali, S. H. and Judge, E. C. (2001). Small-Scale cashew nut processing. Schumacher Centre for Technology & Develoment, BourtonDunsmore, Rugby. Warwickshire, UK,110p.

Azam-Ali, S. H. and Judge, E. C. (2004). Small-scale cashew nut processing. FAO Publication, Rugby, Warwickshire, UK.

Bagheri, I., Dehpour, M. B., Payman, S. H. and Zareiforoush, H. (2011). Rupture strength of brown rice varieties as affected by moisture content and loading rate. *Australian Journal of Crop Science*. 5(10): 1239-1246.

Bahnasawy, A. H. (2007). Some physical and mechanical properties of garlic. *International Journal of Food Engineering*. 3(5): 51-87.

Balasubramanian, D. (2001). Physical properties of raw cashew Nut. *Journal of Agricultural Engineering Research*. 78(3): 291 – 297.

Bargale, P. C., Irudayaraj, J. and Marquist, B. (1995). Studies on rheological behaviour of canola and wheat. *Journal of Agricultural Engineering Research*. 61: 267 – 274.

Bart-Plange, A. and Baryeh, E. A, (2003). The physical properties of category B cocoa beans. *Journal of Food Engineering*. 60, 219-227.

Bart-Plange, A., Addo, A. and Dzisi, K. A. (2005) Effect of Rewetting and Drying on Selected Physical Properties of 'Obatanpa' Maize Variety. *Journal of the Ghana Institute of Engineers*. 3 (1): 12-15.

Bart-Plange, A., Addo, A. and Dzisi, K. A. (2006). Effects of drying and rewetting on some dimensional and mass properties of 'Dorke' maize variety. *Journal of Ghana Science Association*. 8(1): 89-96.

Bart-Plange, A., Asare, V. and Addo, A. (2009). Thermal conductivity of maize and cowpea. *Journal of Engineering and Technology*. 2(3): 6-11.

Baryeh E. A. (2001). Physical properties of bambara groundnuts. *Journal of Food Engineering*. 47(2001): 321-326.

Baryeh, E. A. (2002). Physical properties of millet. *Journal of Food Engineering*. 51, 36-46.

Baryeh, E. A. and Mangope, B. K. (2003). Some physical properties of QP 38 variety pigeon pea. *Journal of Food Engineering. 56, 59-65.*

Bay, A. P. M., Bourne, M. C. and Taylor, A. G. (1996). Effect of moisture content on compressive strength of whole snap bean (*Phaseolus vulgaris* L.) seeds and separated cotyledons. *International Journal of Food Science and Technology*. 31(4): 327–331.

Beckett, S. T. (2009). Industrial chocolate manufacture and use. John Wiley & Sons, Ltd, Chichester.

Bekure, Z., Donlan, M., Gordon, Y. and Thomson, J. (1997). "Local to Global. The International market for Shea butter." Presented to United Nations Development Fund for Women.

Boateng, G. A. (1997). Production manual for improved shea butter processing technology (Ghana Regional appropriate Technological service, Ghana).

Bouman, G., (1992). Grain Handling and Storage (Developments in Agricultural Engineering), 4: 19- 26.

Brown, A. H. (1989). The use of plants genetic resources. Syndicate Ltd. University of Cambridge, England.

Brown, R. (1996). Honduran cashew fruit drying. *Report on five dried food foods*. 325Pp.

Burubai, W., Ako, A. J., Igoni, A. H. and Uyate, Y. T. (2007). Effect of loading rate and pre-heating time on the strength properties of African nutmeg (Monodora myristica). *International Agrophysics.* 21: 317-322.

Carman, K. (1996). Some physical properties of lentil seeds. *Journal of Agricultural Engineering Research. 63: 87-92.*

Cenkowski, S., Zhang, Q. and Crerar, W. J. (1995). Effect of sorption hysteresis on the mechanical behaviour of canola. *Transactions of the ASAE.* 38(5): 1455 – 1460.

Chakraborty, S. M., and Johnson, W. H. (1999). Specific heat of flue cured tobacco by differential scanning calorimeter. *Transactions of the American Society of Agricultural Engineers*. 15(5): 928-931.

Chandrasekar, V. and Visvanathan, R. (1999). Physical and thermal properties of coffee. *Journal of Agricultural Engineering Research. 73: 227-234.*

Choi, Y., and Okoi, M. R. (1986). Effects of temperature and composition on the thermal properties of foods. In: Le Maguer, M.; Jelen P. (Eds), In: *Food Engineering and process Applications*. 1: 93-101.

Chukwu, O. (2010). Moisture-Sorption Study of Dried Date Fruits. *AU J.T.* 13(3): 175-180.

Cienfuegos-Jovellanos, E., Qinones, M. M., Muguerza, B., Moulay, L, Miguel, M and Aleixandre, A. (2009). Antihypertensive Effect of a Polyphenol-Rich Cocoa Powder Industrially Processed To Preserve the Original Flavonoids of the Cocoa Beans. *Journal of Agric. Food Chemistry*. 57 (14): 6156–6162.

COCOBOD. (2004). Socio-economic study. Final report [MASDAR]. Ghana Cocoa Board cited in Ntiamoah, A. and Afrane, G. (2008). Environmental impacts of cocoa production and processing in Ghana: life cycle assessment approah, *Journal of Cleaner Production*. 16(16): 1735-1740.

Cooper, K. A., Campos-Gimenez, E., Alvarez, D. J., Nagy, K., Donovan, J. L. and Williamson, G. (2007). Rapid reverse-phase ultra-performance liquid chromatography analysis of the major cocoa polyphenols and inter-relationship of their concentration in chocolate. *Journal Agric. Food Chemistry. 55:* 2841-2847.

Corrêa, P. C., Schwanz da Silva, F., Jaren, C., Afonso Júnior, P. C. and Arana, I. (2007). Physical and mechanical properties in rice processing. *Journal of Food engineering.* 79(1): 137-142.

Coşkuner, Y. and Karababa, E. (2007a). Physical properties of Coriander (*Coriandrum sativum* L.) seed. *Journal of Food Engineering*. 80: 408-416.

Coşkuner, Y. and Karababa, E. (2007b). Some physical properties of flaxseed (*Linum usitatissimum* L.). *Journal of Food Engineering*. 78: 1065-1073.

Coulter, J. (1989). The market of cashew nuts and cashew nut shell liquid. London, TDRI market note.

Davis, D. W., Oelke, E. A., Oplinger, E. S., Doll, J. D., Hanson, C. V. and Putnam, D. H. (1991). Alternative Field Crops Manual, Purdue. [Accessed 6 December 2010]. Available online: http://www.hort.purdue.edu/newcrop/afcm/cowpea.html.

Day, C. L. (1999). A device for measuring voids in porous materials. *Journal of Agricultural Engineering Research.* 45(1): 36-37.

Delwiche, S. R. (2000). Wheat endosperm compressive strength as affected by moisture. *Transaction of ASAE.* 43 (2): 365-373.

Demir, F., Doğan, H. Özcan, M. and Haydar, H. (2001). Nutritional and physical properties of hackberry (*Celtis australis* L.). *Journal of Food Engineering*. 50: 241-247.

Deshpande, S. D., Bal, S. and Ojha, T. P. (1993). Physical properties of soybean. *Journal of Agricultural Engineering Research*. (56): 89-98.

Deshpande, S. D., Bal, S. and Ojha, T. P. (1996). Bulk thermal conductivity and diffusivity of soy bean. *J. Food Process Preservation*. 20: 177-189.

Desmet, M., Lammertyn, J., Scheerlinck, N., Verlinden, B. E. and Nicolai, B. M. (2002). Determination of puncture injury susceptibility of tomatoes. *Postharvest Biology and Technology*. 15: 207-225.

De Vuyst, L., Camu, N., De Winter, T., Vandemeulebroecke, K., De Perre, V.V.,Vancanneyt, M., De Vos, P. and Cleenwerck, I. (2008). Validation of the (GTG)5-rep-PCR fingerprinting technique for rapid classification and identification of acetic acid bacteria, with a focus on isolates from Ghanaian fermented cocoa beans. 125, 79-90.

Dillon, M. and Griffith, C. (2001). How to Hazard Analysis Critical Control point. (HACCP): an illustrated guide. MD Associates, Grimsby.

Dobraszczyk, B. J. (1994). Fracture mechanics of vitreous and mealy wheat endosperm. *Journal Cereal Science.* 19(3): 273-282.

Dursun, I. Dursun, E., Tuğrul, K. M. (2006). Some physical properties of sugar beet seed. *Journal of Stored Products Research*. 43: 149-155.

Dutta, S. K., Nema, V. K. and Bhardwaj. R. K. (1988).Thermal properties of gram. *Journal of Agricultural Engineering Research*. 39: 269-275.

Dziki, D. (2008). The crushing of wheat kernel and its consequences on the grinding process. *Powder Technology*. 185: 181-186.

Erica, B., Cuniberti, A. and Susana, M. (2004). Moisture dependent physical and compression properties of safflower seed. *Journal of Food Engineering.* 2: 134-140.

Erica, B., Arnold, P. C., Huff, E. R. and Fridley, R. B. (2005). Moisture dependent physical and compression properties of safflower seeds. *Journal of Food Engineering*. 72: 134-140.

Errington, M. and Coulter, J. P. (1994). The international market for cashew products. *Overseas Development natural Resources Institute,* Chatham, Kent, UK.

Esref I. and Halil, Ü (2007). Moisture-dependent physical properties of white speckled red kidney bean grains. *Journal of Food Engineering*. 82: 209-216.

FAOSTAT (2004). Faostat database. Food and Agriculture Organisation. [Accessed 10 October, 2012]

FAOSTAT (2005). Faostat database. Food and Agriculture Organisation. [Accessed 10 October, 2012]. Available online:www.fao.org/es/ess/top/commodity.html?lang=en&item=125&year=2005.

FAOSTAT (2012). Faostat database. Food and Agriculture Organisation. [Accessed 10 October, 2012].

Fellows, P.; Hidellage, V.; and Judge, E. (1992). Making safe food. ITDG Publishing, London.

Fobil, J. N. (2002). Research and development of the shea tree and its products www.solutions-site.org [Accessed September 8 2007].

Fontana, A. J., J. Varith, J. Ikediala, J. Reyes, and B. Wacker. (1999). Thermal properties of selected foods using a dual needle heat-pulse sensor, ASAE Paper No. 996063, St. Joseph, MI: ASAE.

Frankel, H. (1991). Engineering properties of foods. *American Society of Agricultural Engineers* (ASAE). St. Joseph, Michigan, 407p.

Fraser, B. M., Verma, S. S. and Muir, W. E. (1978). Some physical properties of fababeans. Journal of Agricultural Engineering Research (30) 53–57 cited in Kabas, O., Yilmaz, E., Ozmerzi, A., Akinci, I. (2007). Some physical and nutritional properties of cowpea seed (Vigna sinensis L.). *Journal of Food Engineering*. 79: 1405–1409.

Galedar, M. N., Mohtasebi, S. S., Tabatabaeefar, A., Jafari, A. and Fadaei, H. (2009). Mechanical properties of pistachio nut and its kernel under compression loading. *Journal of Food Engineering*. 95: 499-504.

Garcia, J. L., Ruiuz-Altisent, M., and Barreiro, P. (1995). Factors influencing mechanical properties and bruise susceptibility of apples and pears. *Journal of Agricultural Engineering*. *Research*. 61: 11-18.

Geankpolis, R. N. (1983). Crack formation in corn kernels subject to impact. *Transaction of American Society of Agricultural Engineers.* 24(4): 889-892.

Gereke, T. and Niemz, P. (2010). Mositure-induced stresses in spruce cross-laminates. Engineering Structures, 32: 600-606.

Gharibzahedi, S. M. T., Etemad, V., Mirarab-Razi, J. and Fos'hat M. (2010). Study on some engineering attributes of pine nut (Pinuspinea) to the design of processing equipment. (56) 3: 99-106.

Gharibzahedi, S. M. T., Mousavi, S. M., Moayedi A., Garavand, A. T. and Alizadeh, S. M. (2010). Moisture-dependent engineering properties of black cumin (*Nigella sativa* L.) seed. Agric. Eng. Int: CIGR. 12(1).

Gharibzahedi, S. M. T., Seyed, M. M. and Ghahderijani, M. (2011) A survey on moisture-dependent physical properties of castor seed (Ricinu communis L.) *Aust Journal of Crop Sc*ience. 5(1): 1-7.

Gibbon, K. C., Edison, A. R., Hayashi, H. D. and Hoseney, R. C. (1981). Processing Equipment for Agricultural products. Second Edition, AVI Publication company, Inc. Westport, Connecticut 294p

Gorji, A., Rajabipour, A. and Tavakoli, H. (2010). Fracture resistance of wheat grain as a function of moisture content, loading rate and grain orientation. *Australian Journal of Crop Science*.4(6): 448-452.

Grotte, M., Duprat, F., Loonis, D. and Petri, E. (2001). Mechanical properties of the skin and the flesh of apples. *International Journal of Food Properties*. 4: 149-161.

Gupta, R. K. and Das, S. K. (1997). Physical properties of sunflower seeds. *Journal of Agricultural Engineering Research. 66: 1- 8.*

Gupta R. K. and Das, S. K. (2006). Some physical properties of green gram. *Journal of food Engineering*. 66: 1-8.

Gupta, R. K. and Das, S. K. (1998). Friction coefficients of sunflower seeds and kernels on various structural surfaces. *Journal of Agricultural Engineering Research. 66: 1-8.*

Gürsoy, S. and Güzel, E. (2010). Determination of physical properties of some Agricultural Grains. *Research Journal of Applied sciences, Engineering and Technology.* 2(5): 492-498.

Hall, F. J. (1998). Cashew nut processing part II. *Trials of equipment in western Nigeria. Tropical Science.* 8(4).

Hammond, L., Anstee, G., Donkor, P. and Wumbediow, L. (1997). Handbook of Shea processing using a manual operated bridge press. Natural Resources Institute, England.

Hanlon, J. (2000). Power without responsibility: the World Bank and Mozambican cashew nut. *Review of African Economy*. 27(83).

Hartley, A. (2000). The cashew nut in Papua New Guinea. Department of primary industry.

Hemery, Y. M., Mabille, F., Martelli, M. R. and Rouau, X. (2010). Influence of water content and negative temperatures on the mechanicalproperties of wheat bran and its constitutive layers. *Journal of Food Engineering*. 98(3): 360–369.

Hobani, A. I. and Al-Askar, S. R. (2000). Effective thermal properties of dates. Res. Bult., Agric. Res. Center, King Saud Univ. 92: 5-20

Holland, M., Jindal V. K., Huff, E. R. and Holt, J. E. (1991). Physical and chemical properties of food. American Society of Agricultural Engineers. St Joseph, Michigan, 407p.

Hsu, M. H., Mannapperuma, J. D., and Singh, R. P. (1991). Physical and thermal properties of pistachios. *Journal of Agricultural Engineering Research*. 49: 311-321.

Hu, X. and Mallikarjunan, P. (2005). Thermal and dielectric properties of shucked oysters. Leb – Wissenschaft and Tech. Zurich. 38(5): 489-494.

Hwang, M. P., and Hayakawa, K. (1980). A specific heat calorimeter for foods. *Journal of Food Science*. 44: 435-438.

Ibrahim, Y., Coskun, M. B. and Özarskun, K. (2006). Physical properties of sweet corn (*Zea mays saccharata* sturt) seed. *Journal of Food Engineering*. 74: 523- 528.

ICCO, (2011). International Cocoa Organisation, http// www.icco.org. [Accessed September 1, 2011].

ICCO (2002). International Cocoa Organization. http://www.icco.org

Igbozulike, A. O. and Aremu, A. K. (2009). Moisture dependent physical properties of Garcinia kola seeds. *Journal of Agricultural Technology.* 5(2): 239-248.

Irtwange, S. V. and Igbeka, J. C. (2002). Some physical properties of two African yam bean (Sphenostylis stenocarpa) accessions and their interrelations with moisture content. *Applied Engineering in Agriculture.* 18(5): 567–576.

Isik, E. and Unal, H. (2007). Moisture-dependent physical properties of white speckled red kidney bean grains. *Journal of Food Engineering.* 82 (2): 209–216.

Izadifar, M. and Baik, O. D. (2007). Determination of thermal properties of the rhizome of podophyllum peltatum for drying and ethanol extraction. *Biosystems Engineering*. 97: 357-370.

Jaffee, S., and Morton, J. (1995). Marketing Africa's high value food: Comparative experiences of an emergent private sector. The World Bank. Washington D.C.

Jain, L., Hall, C. B., Holt, C. B., Hosmer, D. W. and Lomeshow, S. (2003). Firmness of pear fruit tissues according to cultivar and ripeness. *Journal of American Society of Horticultural Sciences*. 11: 663-665.

Jain, R. K. and Bal, S. (1997). Properties of pearl millet. *Journal of Agric. Engineering Research. 66: 85-91*.

Jain, R. K., and Kumar, S. (1999). Department of cashew nut Sheller. *Journal of Food Engineering*. 32: 339-245.

Jonfia-Essien, W. A. (2004). Cocoa: West Africa (Ghana). In R. Hodges and G. Farrell(Eds), Crop Post Harvest: Science and Technology volume 2 (pp 216-245). Blackwell Publishing, Oxford, UK.

Joshi, D. C., Das, S. K. and Mukherji, R. K. (1993). Physical properties of pumpkin seeds. *Journal of Agricultural Engineering Research*. 54: 219-229.

Juana, S. M., Aurolio, D. L., Salvado, N. G. and Jose, A. L. S. (2008). Some physical properties of roselle seeds as a function of moisture content. *Journal of Food Engineering*, 87: 391-397.

Kabas, O., Yilmaz, E., Ozmerzi, A. and Akinci, I. (2007). Some physical and nutritional properties of cowpea seed (*Vigna sinensis* L.). *Journal of Food Engineering*. 79: 1405-1409.

Kalkan, F. and Kara, M. (2011). Handling, frictional, and technological properties of wheat as affected by moisture and cultivar. *Powder Technology*. 213: 116-122.

Karababa, E. (2006). Physical properties of pop corn kernels. *Journal of Food Engineering*. 72: 100-197.

Karababa, E. and Coşkuner, Y. (2007). Some physical properties of flaxseed (*Linum usitatissimum* L.). *Journal of Food Engineering*. 78: 1065-1073.

Karimi, M., Kheiralipour, K., Tabatabaeefar, A., Khoubakht, G. M., Naderi, M. and Heidarbeigi, K. (2009) The Effect of Moisture Content on Physical Properties of Wheat. *Pakistan Journal of Nutrition*, 8 (1): 90-95.

Kashaninejad, M., Mortazavi, A. Safekordi, A. and. Tabil, L. G. (2005). Some physical properties of pistachio (*Pistacia vera* l.) nut and its kernel. *Journal of Food Engineering*. 72 (1): 30-38.

Kazarian, E. A. and Hall, C. W. (1965). Thermal properties of grains. *Transactions of the American Society of Agricultural Engineers*. 8(1): 33-48.

KNUST
W J SANE NO BADWE

Khan, M. M. R., Chen, Y., Lague, C., Landry, H., Peng, Q. and Zhong, W. (2010). Compressive properties of hemp (*Cannabis sativa L.)* stalks. *Bisostystems Engineering*. 106: 315-323.

Khazaei, J. and Mann, D. D. (2004). Effect of temperature and loading characteristics on Mechanical and stress relaxation properties of sea buckthorn berries. *Agricultural Engineering International*. Vol 6.

Kibar, H., Ozturk, T. and Esen B. (2010). The Effect of moisture content on physical and mechanical properties of rice (*Oryza sativa L*.). *Spanish Journal of Agric. Research*. 8(3): 741-749.

Kılıçkan, A., Üçer, N. and Yalçın, I. (2010) Some physical properties of spinach (Spinacia oleracea L.) seed. *African Journal of Biotechnology*. 9(5): 648-655.

Kingsley, A. R. P., Singh, D. B., Manikantan, M. R. and Jain R. K. (2005). Moisture dependent physical properties of dried pomegranate (Amardana). *Journal of Food Engineering*. 75: 492-496.

Klenin, N. I., Popov, I. F. and Sakun, V. A. (1986). Agricultural Machines, Theory of Operation, Computation of Controlling Parameters and the Conditions of Operation, first ed. Reka Printers Private Limited, New Delhi cited in Tavakoli, M., Tavakoli, H., Rajabipour, A., Ahmadi, H. and Gharib-Zahedi, S. M. T. (2009) Moisture-dependent physical properties of barley grains *International Journal of Agricultural and Biological Engineering*. 2(4).

Konak, M., Carman, K. and Aydin, C. (2002). Physical properties of chick pea seeds. *Biosystems Engineering*. 82(1): 73-78

Kurozawa, L. W., Park, K. J. and Azonbel, P. M. (2008). Thermal conductivity and thermal diffusivity of papaya (*Carica papaya, L*.) and Cashew apple (*Anacardium occidentale L*.). *Braz. Journal of Food Technology.* 11: 78-85.

Kutte, M. T. (2001). Reactivation and performance evaluation of the threshing unit of a combined harvester for stationary threshing of rice. Unpublished M Eng Thesis, Federal University of Technology, Yola, Nigeria

Lawton, P.J. (1980). Coefficients of friction between cereal grain and various silo wall materials. *J. Agric. Engg. Res.* (25): 75–86 cited in Varnamkhasti, M. G., Mobli, H. Jafari, A., Rafiee, S., Heidarysoltanabadi, M. and Kheiralipour, K. (2007) Some Engineering Properties of Paddy (var. sazandegi) *International Journal of Agriculture & Biology.* Available at http://www.fspublishers.org [Accessed 20 August 2010].

Lefeber, T., Gobert, W., Vrancken, G. Camu, N. and Vuyst, L. D. (2011). Dynamics and species diversity of communities of lactic acid bacteria and acetic acid bacteria during spontaneous cocoa bean fermentation in vessel. *Food Microbiology*. 28: 457-464.

Lewis, M. J. (1987). Physical properties of foods and food processing systems. VCH Publishers, Deerfield Beach, Florida. 465p.

Lewis, M. J. (2002). Measurement techniques for quality control of Agricultural products. *American Society of Agricultural Engineers*. St. Joseph. Michigan. 53p.

Mabille, F., Grilet, J. and Abecassis, J. (2001). Mechanical properties of wheat seed coats, *Cereal Chemistry.* 78 (3): 231–235.

Mahmood, M. and Hosein, K. M. (2008). Determination and Comparison of Thermal Conductivity of Iranian Pomegranate Varieties. 18th National Congress on food technology, Mashhyad, IR, Iran, 15-16 October , 2008.

Majdi, A. A. and Taha, M R. (2006). Effect of moisture content on some physical properties of green wheat. *Journal of Food Engineering.* 79: 1467-1473.

Maki, K. S., Bartsch, J. A., Pitt, R. E. and Leopold, A. C. (1994). Viscoelastic properties and the glassy state in soya beans. *Seed Science Research.* 4(1): 27-31.

Mamman, E. Umar, B. and Aviara, N. (2005). Effect of Moisture content and Loading Orientation on the Mechanical Properties of *Balanites Aegyptiaca* Nuts. The CIGR Ejournal Manuscript FP 04015. 7: 1-5.

Meghwal, M. and Goswami, T. K. (2011). Thermal properties of black pepper and its volatile oil. *International Journal of Advanced Biotechnology and Research.* 2(3): 334-344.

Milani, E., Sayed M., Razavy, A., Koocheki, A., Nikzadeh, V., Vahedi, N., MoeinFard, M. and Gholamhossein Pour A. (2007). Moisture dependent physical properties of cucurbit seeds. *Int. Agrophysics.* 21: 157-168.

Milani, A.P. (1993). *Determination of the Stored Products Properties for Silo Pressures and Flow Design*. Doctorate in structure engineering, Engineering School of Soa Carlos. University of Sao Paulo, Sao Carlos, SP, Brazil cited in Varnamkhasti, M. G., Mobli, H. Jafari, A., Rafiee, S., Heidarysoltanabadi, M. and Kheiralipour, K. (2007) Some Engineering Properties of Paddy (var. sazandegi) *International Journal of Agriculture & Biology.* Available at http://www.fspublishers.org [Accessed 20 August 2010].

Mohapatra, D. and Bal, S. (2004). Wear of rice in an abrasive milling operation, part2: Prediction of bulk temperature rise. *Bio-systems Eng.* (89): 101–8 cited in Varnamkhasti, M. G., Mobli, H. Jafari, A., Rafiee, S., Heidarysoltanabadi, M. and Kheiralipour, K. (2007) Some Engineering Properties of Paddy (var. sazandegi) International journal of agriculture & biology. Available at http://www.fspublishers.org [Accessed 20 August 2010].

Mohsenin, N. N. (1970). Physical properties of plant and animal materials. Gordon and Breach Science Publishers. New York cited in Üçer, N., Kiliçkan, A. and Yalçın B. (2010) Effects of moisture content on some physical properties of red pepper (*Capsicum annuum* L.) seed. African *Journal of Biotechnology*, 9(24): 3555-3562.

Mohsenin, N. N. (1978). Physical Properties of Plant and Animal Materials. 1st. edn. Gordon and Breach Publishing Co., New York.

Mohsenin, N. N. (1980). Thermal Properties of Foods and Agricultural Materials. pp 83–121, Gordon and Breach, New York.

Mohsenin, N. N. (1986). Physical Properties of Plant and Animal Materials, 2nd edition. Gordon and Breach Science Publishers, New York cited in Varnamkhasti, M. G., Mobli, H. Jafari, A., Rafiee, S., Heidarysoltanabadi, M. and Kheiralipour, K. (2007) Some Engineering Properties of Paddy (var. sazandegi) International journal of agriculture & biology. Available at http://www.fspublishers.org [Accessed 20 August 2010].

Mohsenin, N. N. (1987). Physical Properties of Plant and Animal Materials: Structure, Physical Characteristics and Mechanical Properties. Updated and Revised Edition. Gordon and Breach Science Publishers, New York.

Mohsenin, N. N. (1990). Thermal Properties of Foods and Agricultural Materials. New York: Gordon and Breach.

Moreyra, R. and Peleg, M. (1980). Compressive deformation patterns of selected food powders. J. Food Sci. 45: 864-868. [Description of the application of a Universal Testing Machine to determination of the properties of powders].

Muramatsu, Y., Tagawa, A., Kasai, T., Takeya, K., and Fukushima, M. (2006). Prediction of thermal conductivity of kernels and packed bed of brown rice. *Journal of the Japanese Society of Agricultural Machinery*. 64(1): 70–76

Murata, S., Tagawa, A. and Ishibashi, S. (1995).The effect of moisture content and temperature on specific heat of cereal grains measured by DSC. *Journal of the Japanese Society of Agricultural Machinery.* 46(6): 547-554.

Murthy, C. T. and Bhattacharya, S. (1998). Moisture dependent physical and uniaxial compression properties of black pepper. *Journal of Food Engineering*. 37: 193-205.

Mustafa, C. (2006). Physical properties of barbunia bean seed. *Journal of Food Engineering*. 80: 353-358.

Nayar, K. G. (1995). Cashew: a crop with unlimited potential. The cashew, Jan/Mar. Pp.45.

Nelson, S. O. and You, T. S. (1989). Microwave dielectric properties of corn and wheat kernels and soybeans at microwave frequencies. Trans. Am. Soc. Agric. Eng., (32): 242-249 cited in Karimi, M., Kheiralipour, K., Tabatabaeefar, A., Khoubakht, G. M., Naderi, M. and Heidarbeigi, K. (2009) The Effect of Moisture Content on Physical Properties of Wheat. *Pakistan Journal of Nutrition* 8 (1): 90-95.

Nimkar, P. M. and Chattopadhyay, P. K. (2001). Some physical properties og green gram. *Journal of Agric. Engineering Research. 80: 183-189*.

Nimkar, P. M., Dipali, S. and Renu, M. D. (2005). *Biosystems Engineering*. 91(2): 183-189.

Nouri Jangi, A., Mortazavil, S. A., Tavakoli, M., Ghanbari, H., Tavakolipour, A., Haghayegh, G. H. (2011) Comparison of mechanical and thermal properties between two varieties of barley (*Hordeum vulgare* L.) grains. *Aust. Journal of Agric. Engineering*. 2(5): 132-139.

Ntiamoah, A and Afrane, G. (2008). Environmental impacts of cocoa production and processing in Ghana: life cycle assessment approah, *Journal of Cleaner Production*, 16(16): 1735-1740

Nutrition data. Com. (2011). USDA National Nutrient Database for Standard Reference

Nwakonobi, T. U. and Onwualu, A. P. (2009). Effect of Moisture Content and Types of Structural Surfaces on Coefficient of Friction of Two Nigerian Food Grains: Sorghum (*Sorghum bicolor*) and Millet (*Pennisetum glaucum*) Agricultural Engineering International: the CIGR Ejournal. Manuscript 1152. Volume XI.

Ogunsina, B. S. and Bamgboye, A. I. (2007). Effects of pre-Shelling treatment on the physical Properties of cashew nut (*Anacardium Occidentale*). *Institute of Agro physics. Polish Academy of Science*. 21: 385-389.

Ogut, H. (1998). Some physical properties of white lupin. *Journal of Agricultural Engineering Research*. 69: 273–277.

Ohler, J. G. (1990). Cashew, Amsterdam, Department of Agricultural Research.

Ojolo, S J. and Ogunsina B. S. (2007). Development of a cashew nut cracking device. *Agricultural Engineering International: The CIGR Ejournal. Manuscript* PM 06 030. Vo. IX.

Okyere, E. (2005). Compression properties of shea nut as a function of moisture content. Unpublished BSc Thesis. Faculty of Agriculture, K.N.U.S.T. Kumasi.

Olajide, J.O. and J.C. Igbeka (2003). Some physical properties of groundnut kernels. *Journal of Food Engineering.* (58): 201–4 cited in Varnamkhasti, M. G., Mobli, H. Jafari, A., Rafiee, S., Heidarysoltanabadi, M. and Kheiralipour, K. (2007) Some Engineering Properties of Paddy (var. sazandegi). *International Journal of Agriculture & Biology.* Available at http://www.fspublishers.org [Accessed 20 August 2010].

Opoku, A., Tabil, L. G., Crerar, B. and Shaw, M. D. (2006). Thermal conductivity and thermal diffusivity of timothy hay. *Canadian Biosystems Engineering*. 48: 31-37.

Ozarslan, C. (2002). Physical properties of cotton seed. *Biosystems Engineering. 83 (2): 169-174.*

Özcan, M. and Aydin, C. (2001). Some physic-mechanic properties of terenbinth (*Pictacia terenbinthus* L.) fruits. *Journal of Food Engineering*. 53: 97-101.

Ozisik, M. N. (1993). Heat conduction. John Wiley & Sons, Mar 22, 1993 - Technology & Engineering – 692.

Ozturk, T. and Esen, B. (2008). Physical and Mechanical Properties of Barley. *Agricultura Tropica Et Subtropica*. 41(3): 117 —121.

Ozturk, T., Kara, M., Elkoca, E. and Ercisli, S. (2009). Physico-chemical grain properties of new common bean cv. ‘Elkoca-05’ *Scientific Research and Essay*. 4(2): 88-93.

Paksoy, M. and Aydin, C. (2004). Some physical properties of edible squash (*Cucurbita pepo L.) seeds. Journal of Food Engineering*. 65: 225-231.

Peleg, M. (1978). Flowability of food powders and methods for its evaluation. (A Review). J. Food /'roc. Eng. I. 303-328. [A concise survey of the principles behind powders flowability evaluation]

Peleg, M. (1983). Physical characteristics of food powders. In Physical Properties of Foods (eds. M. Peleg and E. B. Bagley), 293-324. Westport, CT: AVI Publishing Co. [A very brief review of what affects the properties of food powders].

Perusulla, C. A., Viviana, C. and Mends, L. A. (2010). Development of a line heat source probe and determination of banana thermal conductivity. *Journal of Food Engineering*. 12(6).

Pliestic, S., Dobricevic, N., Filipovic, D. and Gospodaric, Z. (2006). Physical Properties of Filbert Nut and Kernel. *Biosystems Engineering*. 93(2): 173–178.

Polley, S. I., Synder, O. P. and Kotnour, F. (1980). A compilation of thermal properties of foods. *Food Technology*. 34(11): 76–78.

Pradhan, R. C., Naik, S. N., Bhatnagar, N. and Vijay, V. K. (2008). Industrial crops and food products. Doi: 10. 1016/jindcrop. 07. 002.

PROTA Foundation, Plant Research of Tropical Africa 2 (2003). Netherland, Wageningen. p.550-556.

Rao, M. A. and Rizvi, S. S. H. (1986). Engineering properties of foods. New York: Marcel Dekker.

Razavi, H. and Bahrani, S. (2007). A model for predicting the effects of moisture on the modulus of elasticity of soybeans. *American Society of Agricultural Engineers*. 24(5): 1338-1341.

Reddy, B. S. and Chakraverty, A. (2004). Physical properties of raw and parboiled paddy. *Biosystems of Engineering*. 84(4): 461-466.

Richard, S. and Donald, H. (1995). Physical properties of Agricultural materials and food products. VCH publishers, Deefield Beach. Florida. 224p.

Rosengarten, P. (1984). Physical properties of plant and Animal materials. Second Edition, Gordon & Breach Science Publishers, New York. 891p.

Russel, D. C. (2001). Cashew nut processing. *F .A. O Agricultural services Bulletin*. No. 6. Rome.

Rybiñski, W., Szot, B., Rusinek, R. and Bocianowski, J. (2009). Estimation of geometric and mechanical properties of seeds of Polish cultivars and lines representing selected species of pulse crops, *Int. Agrophysics.* 23: 257-267.

Sacilik, K., Öztürk, R. and Keskin, R. (2003). Some physical properties of hemp seed. *Bios stems Engineering*. 86(2): 191-198.

Sahoo, P. K., and Srivastava, A. P. (2002). Physical properties of Okra seed. *Biosystems Engineering*. 83 (4): 441-448.

Saiedirad, M. H., Tabatabaeefar, A., Borghei, A., Mirsalehi, M., Badii, F. and Ghasemi Varnamkhasti, M. (2008). Effects of moisture content, seed size, loading rate and seed orientation on force and energy required for fracturing cumin seed (*Cuminum cyminum Linn*.) under quasi-static loading. *Journal of Food Engineering*, 86: 565-572.

Sayed, M. A. R. and Maryam, B. P. (2007). Some physical and mechanical properties of kiwi fruit. *International Journal of Food Engineering*. 3(6): 56-75.

Sayyah, A. H. and Minaei, S. (2004). Behaviour of Wheat Kernels under Quasistatic Loading and Its Relation to Grain Hardness. *Journal of Agric. Science and Technology.* 6: 11-19.

Scott, C. (2008). Sub-saharan africa news in brief: 25 march–9 april. *Scidev.net*. science and development network. Available at http://www.scidev.net/en/sub-suharan-africa/news/sub-saharan-africa-news-in-brief-25-march-9-april.html [Accessed 21 August 2010].

Seifi, M. R. and Alimardani, R. (2010). Comparison of moisture-dependent physical and mechanical properties of two varieties of corn (Sc 704 and Dc 370). *Australian Journal Agric. Engineering*. 1(5): 170 -178.

Seifi, M. R. and Alimardani, R. (2010). The Moisture Content Effect on Some Physical and Mechanical Properties of Corn (Sc 704). *Journal of Agricultural Science.* 2(4): 125-134.

Selvi, K. C., Pinar, Y. and Yesiloğlu, E. (2006). Some physical properties of linseed. *Biosystems Engineering*. 95(4): 607-612.

Sessiz, A., Esgici, R. and Kizil, S. (2006). Moisture-dependent physical properties of caper (*Capparis* ssp.) fruit. *Journal of Food Engineering*. 79: 1426-1431.

Shepherd, H, and Bhardwaj, R. K. (1985). Thermal properties of pigeon pea. *Cereal Foods World.* 31: 466-470.

Shepherd, H and Bhardwaj, R. J. (1986). Moisture dependent physical properties of pigeon pea. *Journal of Agric. Engineering Research.* 35: 227-234.

Shewfelt, J. A. (1999). Firmness changes of pear fruit before and after harvest with the acoustic impulse response technique. *Journal of Food Engineering*. 77: 181-191.

Shitanda, D., Nishiyama, Y. and Koide, S. (2002). Compressive strength properties of rough rice considering variation of contact area. *Journal of Food Engineering.* 53:53-58.

Shitanda, D., Nishiyama, Y. and Koide, S. (2001). Performance analysis of an impeller husker considering the physical and mechanical properties of paddy rice. *Journal of Agric. Engineering Research.* 79: 195–203.

Shyamal, D. K., Chakraverty, A. and Benerjee, H. D. (1994). Thermal properties of raw, parboiled and debrnned parboiled wheat and wheat bulgur. *Journal of Food Engineering.* 49: 195-201.

Singh, K. K. and Goswani, T.K. (2007). Thermal properties of cumin seed. *Journal of Food Engineering.* 45: 181-187.

Singh, K. K. and Goswami, T. K. (1996). Physical properties of cumin seed. *Journal of Agricultural Engineering Research.* (64): 93-98.

Singh, K. K. and Goswami, T. K. (2000). Thermal properties of cumin seed. *Journal of Food Engineering*. 45: 181-187.

Sirisomboon, P., Kitchaiya, P., Pholpho, T. and Mahuttanyavanitch, W. (2007). Physical and mechanical properties of Jatropha curcas L. Fruits, nuts and kernels. *Biosystems Engineering.* 97 (2): 201–207.

Sitkei, G. (1986). Mechanics of Agricultural Materials. *Journal of Biosystems Engineering.* 10(1): 13-20.

Solomon, W. K. and Zewdu, A. D. (2009). Moisture dependent physical properties of Niger (Guiconia abyssinica Cass.) seed. *Industrial Crops and Products*. 29:165-170.

Srivastava, A. K., Mahoney, W. T. and West, N. L. (1990). The effect of crop properties on combine performance. *Trans. ASAE* (33): 63–72 cited in Varnamkhasti, M. G., Mobli, H. Jafari, A., Rafiee, S., Heidarysoltanabadi, M. and Kheiralipour, K. (2007) Some Engineering Properties of Paddy (var. sazandegi) *International Journal of Agriculture & Biology*. Available at http://www.fspublishers.org [Accessed 20 August 2010].

Steinberg, F. M., Bearden, M. M. and Keen, C. L. (2003). Cocoa and chocolate flavonoids: implications for cardiovascular health. *Journal of the American Dietetic Association.* 103: 215–223.

Stroshine, R. and Hamann, D. (1995). Physical Properties of Agricultural Materials and Food Products. Course Manual, Purdue University, Indiana.

Stroshine, R. and Hamann, D. (1998). Physical Properties of Agricultural Materials and Food Products. Course Manual, Revised Edition, Purdue University, Indiana.

Subramanian, S. and Viswanathan, R. (2003). Thermal properties of minor millet grains and flours. *Biosystems Engineering.* 84: 289-296.

Suter, D. A., Agrawal, K. K. and Clary, B. L. (2000).Thermal properties of peanut pods, hulls, and kernels. *Transactions of the American Society of Agricultural Engineers.* 18(2): 370-375.

Suthar, S. H. and Das, S. K. (1996). Some physical properties of karingda [citrullus lanatus (thumb) mansf] seeds. J. Agric. Eng. Res. 65(1): 15- 22 cited in Üçer, N., Kiliçkan, A., and Yalçın B. (2010). Effects of moisture content on some physical properties of red pepper (*Capsicum annuum* L.) seed. *African Journal of Biotechnology*. 9(24): 3555-3562.

Sweat, V. E. (1974). Experimental values of thermal conductivity of selected fruits and vegetables. *Journal of Food Science.* 39: 1080-1091.

Sweat, V. E. and Haugh, C. G. (2006). Thermal conductivity probe for small food samples. *Transactions of the American Society of Agricultural Engineers*. 17(1): 56-58.

Tabatabaeefar, A. (2003). Moisture-dependent physical properties of wheat. Int Agrophysics; 17: 207－211 cited in Tavakoli, M., Tavakoli, H., Rajabipour, A., Ahmadi, H. and Gharib-Zahedi, S. M. T. (2009) Moisture-dependent physical properties of barley grains. *International Journal of Agricultural and Biological Engineering*. 2(4).

Tabil, L. G. (1999). Specific heat of agricultural and food materials. Research report, Department of Agricultural and Bio-resource Engineering, University of Saskatchewan, Canada. p 7.

Taiwo, K. A., Akanbi, C. T. and Ajibola O. O. (1996). Thermal properties of ground and hydrated cowpea. *Journal of Food Engineering*. 29: 249-256.

Tang, J., Yannacopoulos, Y. and Kasap, S. O. (1995). Specific heat capacity of lentil seed by DSC. *Transactions of the American Society of Agricultural Engineers.* 34(2): 517-522.

Tansakul, P. and Chaisawang, P. (2007). Thermophysical properties of coconut milk. *Journal of Food Engineering*.73: 276-280.

Tansakul, A. and Lumyong, R. (2008). Thermal properties of straw mushroom. *Journal of Food Engineering.* 87: 91-98.

Tarighi, J, Mahmoudi, A. and Rad, M. K. (2011). Moisture dependent engineering properties of sunflower (var. Armaviriski). *Australian Journal of Agricultural Engineering.* 2(2): 40- 44.

Tarighi, J., Mahmoudi, A. and Alavi, N. (2011). Some mechanical and physical properties of corn seed (Var. DCC 370). *African Journal of Agricultural Research.* 6(16):.3691-3699.

Tavakoli, H. Mohtasebi, S. S. Rajabipour, A. and Tavakoli, M. (2009). Effects of moisture content, loading rate, and grain orientation on fracture resistance of barley grain. *Res. Agr. Eng.*, *55*(3): 85–93.

Tavakoli, M., Tavakoli, H., Rajabipour, A., Ahmadi, H. and Gharib-Zahedi, S. M. T. (2009) Moisture-dependent physical properties of barley grains. *International Journal of Agricultural and Biological Engineering*, 2(4).

Thiex, N., and Van Erem, T. (1999). Comparisons of Karl Fischer method with oven methods for determination of water in forages and animal feeds. *Journal of AOAC*. 82: 799-808.

Thioune, O., Ahodikpe, D., Dieng, M., Diop, A. B., Ngom, S. and Lo, I. (2000). Inflammatory ointment from shea butter and hydro alcoholic extract of Khaya sengalensis barks (cailcederat) Dakar. *Med*. 45(2): 113-6.

Thompson, R. L., Fleming, H. P. and Hamann, D. D. (1992). Delineation of puncture forces for exocarp and mesocarp tissues in cucumber fruit. *Journal of Texture Studies*. 23: 169-184.

Thompson, R. A. and Isaac, G. W. (1967). Porosity determination of grains and seeds with comparison pycnometer. *Transactions of ASAE*. 10:693-696.

Thompson, S. S., Miller, K. B. and Lopez, A. S. (2007). Cocoa and coffee. In: Doyle, M.P., Beuchat, L.R., Montville, T.J. (Eds.), Food Microbiology: Fundamentals and Frontiers. ASM Press, Washington, pp. 721-733.

Timbers, G. E. (1995). Properties of rapeseed: Thermal conductivity and specific heat. *Canadian Agricultural Engineering*. 17: 81-84.

Transakul, P. and Chaisawang P. (2007). Thermophysical properties of coconut milk. *Journal of Food Engineering*. 73: 276-280.

Tunde-Akintunde, T. Y. and Akintunde, B. O. (2004). Some physical properties of sesame seed. *Bio-systems Eng*. (88): 127–9 cited in Varnamkhasti, M. G., Mobli, H. Jafari, A., Rafiee, S., Heidarysoltanabadi, M. and Kheiralipour, K. (2007) Some Engineering Properties of Paddy (var. sazandegi) *International Journal of Agriculture & Biology*. Available at http://www.fspublishers.org [Accessed 20 August 2010].

Tunde-Akintunde, T. Y. and Akintunde, B. O. (2007). Effect of moisture content and variety on selected properties of Beni seeds. Agricultural Engineering International: The CIGR-E journal. Manuscript FP 07 021. Vol. IX.

Üçer, N., Kılıçkan, A. and Yalçın, I. (2010). Effects of moisture content on some physical properties of red pepper (*Capsicum annuum* L.) seed. *African Journal of Biotechnology.* 9(24): 3555-3562.

Unal, H., Esref I., Nazmi, I. and Yucel, T. (2008). Geometric and Mechanical Properties of Mung Bean (*Vigna Radiata* L.) Grain: Effect of Moisture. *International Journal of Food Properties*. 11(3) 585-599.

Vaidehi, M. P. and Babu, R. M., (2000). Cashew apple and nut recipes with nutritive value. Bangalore, India Division of Rural Home Science, University of Agricultural Sciences.

Van-Woensel, J. R.; Lyons. Y. and Cowell, R. E. (1999). Viscosity and flow measurement. *Biosystems Engineering*. 45(3): 45-47.

Varnamkhasti, M. G., Mobli, H., Jafari, A., Rafiee, S., Heidarysoltanabadi, M. and Kheiralipour, K. (2007). Some Engineering Properties of Paddy (var. sazandegi). *International Journal of Agriculture & Biology.* Available at http://www.fspublishers.org [Accessed 20 August 2010].

Visvanathan, R., Palanisamy, P. T., Gothandapani, P. T. and Sreenarayanan, V. V. (1996). Physical properties of neen nut. *Journal of Agricultural Engineering Research.* 63: 19-26.

Viviana, C. M., Antonio, G. B., De Lima, L. and Dos Santos, C. (2008). Apparent thermal diffusivity estimation of the banana during drying using inverse method. *Journal of Food Engineering*. 85: 569-579.

Wallapapan, K., and Sweat, V. E. (1999). Thermal conductivity of defatted soy flour. *Transactions of American Society of Agricultural Engineers*. 25: 1440-1444.

Wang, B., Li D., Wang, L., Huang, Z., Zhang, L., Chen, X. D. and Mao, Z. (2007). Effect of moisture content on the physical properties of fibered flaxseed. *International Journal of Food Engineering.* 3(5).

Wang, J., Jiang, R. S. and Yu, Y. (2004). Relationship between dynamic resonance frequency and egg physical properties. *Food Research International*. 37: 45-50.

Wang, J., Tang, B. and Yang, Y. (2006). Firmness detection by excitation dynamic characteristics for peach. *Food Control.* 17: 353-358.

Winterhaler, H. H. (1991). Physical properties related to drying twenty food grains. Paper 80-353, *American Society of Agricultural Engineers*. St Joseph, Michigan.

Wood, G.A.R. and Lass, R.A. (2001). Cocoa (Tropical Agriculture). Wiley-Blackwell Ltd, 4th Edition.

Xu, S. (2005). Studies on the Mechanical properties of Vegetables. *The Journal of American Science*. 1(2): 61-64.

Yadav, B. K. and Jindal, V. K. (2001) Monitoring milling quality of rice by image analysis. Computational Agric. (33): 19–33 cited in Varnamkhasti, M. G., Mobli, H. Jafari, A., Rafiee, S., Heidarysoltanabadi, M. and Kheiralipour, K. (2007) Some Engineering Properties of Paddy (var. sazandegi) International journal of agriculture & biology. Available at http://www.fspublishers.org [Accessed 20 August 2010].

Yalcin, I. (2006). Physical properties of cowpea (Vigna sinensis l.) seed. *Journal of Food Engineering*. 79: 57-62.

Yalcin, I. and Özarlan, C., (2004). Physical properties of vetch seed. *Biosystems Engineering*, 889(4): 507-512.

Yang, J. and Zhao, Y. (2001). Thermal properties of radish and alfalfa seeds. *Journal of Food Process Engineering*. 24: 291-313.

Yang, W., Siebenmorgen, T. J., Thielen, T. P. H. and Cnossen, A. G. (2003). Effect of glass transition on thermal conductivity of rough rice. *Biosystems Engineering*. 84(2): 193-200.

KNUST

Yang, W., Sokhansanj, S., Tang, J. and Winter, P. (2002). Determination of thermal conductivity, specific heat and thermal diffusivity of borage seeds. *Biosystems Engineering*. 82: 169-176.

Zareiforoush, H., Komarizadeh, M. H. and Alizadeh. M. R. (2010). Mechanical Properties of Paddy Grains under Quasi-Static Compressive Loading. *New York Science Journal*. 3(7).

Zewdu, A. D. and Solomon, W. K. (2007). Moisture dependent physical properties of tef seed. *Biosystems Engineering*. 96(1): 57-63.

KNUST

NYANSAPƆ WɔSANE NO BADWENMA