EFFECT OF REWETTING AND DRYING ON SELECTED PHYSICAL PROPERTIES OF ASONTEM COWPEA VARIETY

BY

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DECLARATION

I, JONATHAN AMPAH, author of this thesis titled 'Effect of Rewetting and Drying on Selected Physical Properties of Asontem Cowpea Variety', do hereby declare that apart from the references of other people's work which has been duly acknowledged, the research work presented in this thesis was done entirely by me in the Department of Agricultural Engineering, Kwame Nkrumah University of Science and Technology, from August 2009 to August 2011.

This work has never been presented in whole or in part for any other degree in this university or elsewhere.

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ABSTRACT

This study assessed the effect of rewetting and drying on some selected physical properties of asontem cowpea at eight selected moisture contents namely, 8.07, 11.45, 17.20 and 22.54% w.b. for rewetting; and 9.58, 11.50, 15.13 and 19.00% w.b. for drying. The length, width, thickness, geometric mean diameter, surface area, volume, 1000 grain mass, bulk density, true density, porosity, filling angle of repose and the static coefficient of friction increased with increasing moisture content during rewetting. In the moisture content range of 8.07% w.b. to 22.54% w.b., the length, width and thickness increased non-linearly from 7.00 to 7.29mm, 6.27 to 6.33mm and 4.54 to 4.69mm respectively. The geometric mean diameter, surface area, volume and 1000 grain mass increased from 5.83 to 5.99mm, 107.03 to 113.09mm^2, 104.45 to 113.45mm^3 and 120.15 to 130.58g respectively; while bulk density and true density decreased non-linearly from 752.95 to 682.93kg/m^3 and 1219.90 to 1161.39 kg/m^3. Porosity increased linearly from 38.13% to 41.16%. The filling angle of repose increased non-linearly from 27.81 to 32.31; whiles the coefficient of static friction also increased non-linearly from 0.29 to 0.41, 0.30 to 0.45 and 0.25 to 0.32 for plywood, mild steel and rubber respectively. Sphericity decreased from 83.7% to 82.6% with increasing moisture content. The result obtained for drying showed that with decreasing moisture content, length, width and thickness dimensions as well as 1000 grain mass and filling angle of repose decreased from 8.16mm to 7.11, 6.36mm to 6.28, 4.77mm to 4.61, 132.85g to 120.93g and 29.35^0 to 27.92^0 respectively. The geometric mean diameter, surface area and volume decreased from 5.89 to 6.27mm, 109.46 to 123.87mm^2, and 108.02 to 130.23mm^{3}respectively; while bulk density and true density increased non-linearly from 710.93 to 663.12kg/m^3 and 1185.92 to 1063.80 kg/m^3; porosity increased non-linearly from 37.55 to 39.98%. However, the values of static coefficient of friction for plywood, mild steel and rubber appeared to increase in

the moisture content range of 11.50 and 15.13% wb and then decreased at 19.00% wb. The overall result of this study shows that linear dimensions increased non-linearly with increasing moisture content during rewetting and decreased with decreasing moisture content during drying. The filling angle of repose and the coefficient of static friction also increased non-linearly with increasing moisture content. Plywood offered the highest coefficient of friction during drying followed by mild steel and rubber. However, for rewetting, mild steel offered the highest coefficient of friction followed closely by plywood then rubber.

DEDICATION

This project is dedicated to my loving parents Mr. & Mrs. Jonathan Ampah Snr. and Vida Ampah and to Rodger.

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CHAPTER ONE

1.1 Background to the Study

Cereals and legumes are important sources of functional ingredients which are potential components for many processed foods.

Cowpeas are one of the most important food legume crops in the semi-arid tropics covering Asia, Africa, southern Europe, and Central and South America. A drought-tolerant and warm-weather crop, cowpeas are well-adapted to the drier regions of the tropics, where other food legumes do not perform well. It also has the useful ability to fix atmospheric nitrogen through its root nodules, and it grows well in poor soils with more than 85% sand and with less than 0.2% organic matter and low levels of phosphorus (Scott, 2008).

Based on the available information from FAO and personal correspondence with scientists in different countries, it is estimated that globally cowpea is cultivated on about 14.5 million hectares with an annual production of over 4.5 million tonnes (Singh *et al*., 2002).

Cowpea is a *dicotyledonea* belonging to the order *Fabales*, family *Fabaceae*, subfamily *Faboideae*, tube *Phaseolinae*, genus *Vigna* and section *Catiang* (Verdcourt, 1970). Some of the popularly grown varieties in Ghana are *Soronko, Asontem, Amantin, Asetenepa, Vallenge, Red Nkwanta*, *New era* and *Ayiyi.*

The protein in cowpea seed is rich in amino acids, lysine and tryptophan, compared to cereal grains; however, it is deficient in methionine and cystine when compared to animal proteins.

Therefore, cowpea seed is valued as a nutritional supplement to cereals and an extender of animal proteins (Prota, 2003).

Cowpea is now grown by millions of smallholder farmers throughout Africa where some two hundred million children, women, and men consume cowpea often, even daily, when it is available. Cowpea is widely known as the crop of the poor because its green pods and leaves are the earliest food available before cereals mature thereby serving as "insurance" against food shortages during the "hunger season". The canopies of cowpea and soybean cover the soil and protect it from recurrent erosion, add nitrogen from the atmosphere and the in-situ decay of root residues enrich the soil with nutrients (Coulibaly *et al.*, 2009).

In many areas of the world, the cowpea is the only available high quality legume hay for livestock feed. Cowpea may be used green or as dry fodder. It is also used as a green manure crop, a nitrogen fixing crop, or for erosion control (Davis *et al*., 1991).

1.2 Problem Statement and Justification

Little is known about the basic physical characteristics of biomaterials. Such basic information is important not only to engineers but also to food scientists, processors, plant breeders and other scientists who may find new uses for them (Mohsenin, 1970).

The design of handling and processing machinery of grains and seeds relies a great deal on the physical characteristics of grains. The physical characteristics are also affected by parameters such as the drying time and moisture content. These physical properties are important in the design of storage and processing equipment. Physical properties are important factors in solving problems associated with the design of machines or analysis of the behaviour of the product during agricultural processes such as planting, harvesting, handling, threshing, sorting and drying. For the maximum performance of storage and processing equipment, moisture content of agricultural materials must be at or within a certain moisture range. Therefore, knowledge about the physical properties of cowpeas at varying moisture contents is important in the design and construction of such equipment.

Shape and size dimensions are important in screening solids to separate foreign material and in sorting and sizing of fruits and vegetables. Size and shape determine how many fruits can be packed in shipping containers or plastic bags of a given size (Stroshine and Hamann, 1995). The determination of dimensional characteristics of milled rice quality parameters by image processing techniques will enable regular monitoring of milling operation in an objective manner and thus enable the operator to quickly react within a few minutes to changes in material properties (Yadav and Jindal, 2001 cited in Varnamkhasti *et al*., 2007).

When plant material such as forage are chopped by harvesting machinery and when cereal grain and oilseeds are ground in mills, the distribution of particle sizes must be known in order to achieve desirable properties without unnecessary expenditure of energy. Particle sizes of food materials such as powdered milk must be large enough to allow agglomeration and yet small enough to allow rapid dissolution during reconstitution (Stroshine and Hamann, 1995).

Recognizing the physical and mechanical properties of agricultural produce has always been at the center of attention and interest to agricultural researchers; this is especially in relation with designing of machineries and equipment which are used during harvest, transport, storing, and processing of agricultural products. Among the physical properties of agricultural products, dimensions, mass, volume, projected area, and surface area have the most importance in grading systems. Therefore, dimensional grading of products decreases the packaging and transportation costs and allows usage of proper packaging models (Peleg, 1958).

According to Kabas *et al*. (2007) the function of many types of machines is influenced decisively by the size and shape of the fruit participating, and so in order to study a given process the fruit should be described accurately. Based on this, several researchers have determined the physical and mechanical properties of different agricultural products as a function of moisture content in order to design equipment for the handling, conveying, separation, drying, aeration, storing and processing of cowpea seeds. These include researchers such as Baryeh (2000) for bambara groundnuts; Bart-Plange *et al*. (2005) for maize; Varnamkhasti *et al*. (2007) for rice and Kiliçkan *et al*. (2010) for spinach seed.

Postharvest operations for cowpea generally consist of cleaning, sorting and grading. In Ghana these operations are often done on small-scale and manually. Currently, the seeds are extracted manually by breaking the pod and removing the seeds. These methods of handling and processing seeds are not only time and energy consuming, but also inefficient as they come with some chaff. Lack of standard principles for grading, packaging and consumers preferences has led to problems in storage and marketing.

The physical properties of some varieties of cowpeas in Ghana have been found for ‘asetenapa’ and ‘adom’. However, no work appears to have been done on the physical properties of ‘asontem’. Since these properties are pre-requisites for the design of equipment for cleaning, handling and other postharvest operations, it is essential to determine them. This study will evaluate various physical properties of the ‘asontem’ cowpea variety for different moisture contents during rewetting and drying. The study will therefore examine size and shape properties, porosity, 1000 grain mass, bulk density, true density, angle of repose and coefficient of static friction for the 'asontem' variety during rewetting and drying.

1.3 Aim and Specific Objectives

The main aim of this project was to determine the effect of rewetting and drying on linear dimensions, geometric mean diameter, sphericity, surface area, volume, 1000 grain mass, bulk density, true density, porosity, angle of repose and static coefficient of friction of Asontem cowpea variety

The specific objectives of this study were

- To determine the effect of rewetting on the linear dimensions, geometric mean diameter, sphericity, surface area, 1000 grain mass, bulk density, true density, porosity, angle of repose and static coefficient of friction on Asontem cowpea variety
- To determine the effect of drying on the linear dimensions, geometric mean diameter, sphericity, surface area, 1000 grain mass, bulk density, true density, porosity, angle of repose and static coefficient of friction on Asontem cowpea variety

CHAPTER TWO

2.0 LITERATURE REVIEW

2.1 Introduction

Processing of cereals and legumes often requires that the seeds be hydrated first to facilitate operations such as cooking or canning. Thus, absorption of water to these materials is of both theoretical and practical interest to processing industries (Hsu, 1983).

Recent scientific developments have improved the handling and processing of bio-materials through mechanical, thermal, electrical, optical and other techniques (Mohsenin, 1970).

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

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. 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 (Tavakoli *et al.*, 2009).

Cowpea is one of the staple foods in Ghana and information on its physical properties is useful in its storage and processing. Information on the physical properties is necessary in producing handling and processing machinery.

2.2 Taxonomy and Physiology of Cowpea

Cowpea (*Vignaunguiculata* L. Walp.), an annual legume, is also commonly referred to as southern pea, blackeye pea, crowder pea, lubia, niebe, coupe or frijole. Cowpea originated in Africa and is widely grown in Africa, Latin America, Southeast Asia and in the southern United States. It is chiefly used as a grain crop, for animal fodder or as a vegetable. The history of cowpea dates to ancient West African cereal farming, 5 to 6 thousand years ago, where it was closely associated with the cultivation of sorghum and pearl millet (Davis *et al.*, 1991).

Cowpea, as a diverse specie, is divided into three groups based on morphological characteristics. The three species are: *Vigna unguiculata* which is considered as the most primitive and most common in Asia; *Vigna sesquipedalis*, which is known as snake beans and commonly grown in the Far East and then *Vigna sinensis*, commonly found growing in Africa. This has similar growth habits like *Vigna unguiculata* but has larger pods which can reach a length of 30cm (Brittingham, 1946).

2.2.1 Production

The worldwide area cultivated with cowpea in 2008 was estimated to be 11.8 million ha. Production in Africa represents about 91% of the global production. West Africa, with 10.7 million ha, accounts for most of Africa’s production, with Nigeria and Niger being the leading cowpea growing countries. Worldwide, cowpeas rank among the top five food fibre crops because they can tolerate poor and dry soils. Based on Food and Agricultural Organisation (FAO) data, annual cowpea production has increased from about 0.87 million tonnes in 1961 to 1.2 million tons in 1981 to 2.4 million tons in 1991. The bulk of cowpea production comes from the drier regions of northern Nigeria (5 million ha and 2.3 million tons), Niger Republic

(3 million ha and 0.4 million tons) and North East Brazil (about 1.9 million ha and 0.7 tons). In spite of its importance and wide cultivation, the overall productivity of cowpea is very low with average yield particularly in Africa ranging from 100 to 400 kg/ha (Singh *et al.*, 2002).

2.2.2 Structure and Chemical Composition of Cowpea Seeds

Cowpea grain contains about 22% protein and constitutes a major source of protein for resource-poor rural and urban people. It is estimated that cowpea supplies about 40% of the daily protein requirements to most of the people in Nigeria (Muleba *et al*. 1997).

Cowpeas are relatively small dicotyledonous seeds ranging in size from 2 to 28.4 g per 100 seeds. The dimensions are reported to range from 2 to 12mm in length, 6.6mm in width and 4.9mm in thickness (Davis *et al.*, 1991).

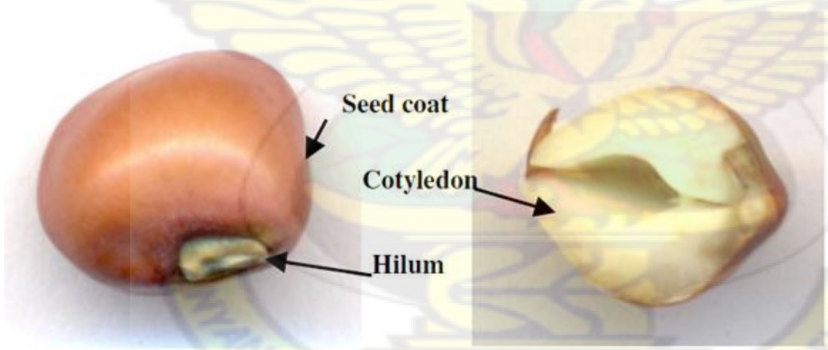

Figure 1 Morphology of cowpea seed showing seed coat, cotyledon and hilum (University of Pretoria publication, 2003)

According to Davis *et al*. (1991), It has been proposed that the shape of cowpea seeds is dependent on the development process in the pod; kidney shaped seeds develop when there is no restriction during development within the pod. However, globular shaped seeds develop where there is limited space.

The seed coat percentage in relation to the whole seed ranges from 1.5 to 16% (Akinyele *et al.*, 1986; Olapade *et al.*, 2002).

Table1 Chemical composition of whole cowpea seeds (Longe, 1980)

Constituents	Percentage(%)	Sugars	Percentage(%)
Moisture	10.4	Glucose	0.2
Crude Protein	28.0	Fructose	0.4
Fat extract	1.9	Sucrose	1.6
Ash	3.8	Raffinose	0.7
Crude fibre	3.1	Stachyose	2.7
Starch	40.6	Verbascose	3.6

Source: University of Pretoria publication (2003)

Table 2 The nutrient content of mature cowpea seed (average of eight varieties)

Nutrient	Percentage (%)
Protein	24.8%
Fat	1.9%
Fibre	6.3%
Carbohydrate	63.6%
Thiamine	0.00074%
Riboflavin	0.00042%
Niacin	0.00281%

Source: Bressani R. cited in Davis *et al.*, 1991

2.2.3 Growth Habits

Cowpea is a warm-season, annual, herbaceous legume. Plant types are often categorized as erect, semi-erect, prostrate (trailing), or climbing. Growth habit ranges from indeterminate to fairly determinate with the non-vining types tending to be more determinate. Cowpea generally is strongly taprooted (Davis *et al*., 1991).

According to Davis *et al*. (1991), Cowpea pods are smooth, 6 to 10 inches long, cylindrical and generally somewhat curved. The seed coat can be either smooth or wrinkled and of various colours including white, cream, green, buff, red, brown, and black. Seed may also be speckled, mottled, or blotchy. Many are also referred to as 'eyed' (blackeye or pinkeye) where the white coloured hilum is surrounded by another colour.

Emergence is epigeal which makes cowpea more susceptible to seedling injury, since the plant does not regenerate buds below the cotyledonary node. The trifoliate leaves develop alternately. Leaves are smooth, dull to shiny, and rarely pubescent. Commonly, the terminal leaflet is longer and larger than the lateral leaflets. It generally is day neutral. Flowers are borne in multiple racemes of 8 to 20 in flower stalks (peduncles) that arise from the leaf axil. Two or three pods per peduncle are common and often four or more pods are carried on a single peduncle. The presence of these long peduncles is a distinguishing feature of cowpea and this characteristic also facilitates harvest. The open display of flowers above the foliage and the presence of floral nectaries contribute to the attraction of insects. Cowpea primarily is self-pollinating (Davis *et al*., 1991).

2.2.4 Environment Requirements

According to Davis *et al*. (1991), Cowpeas are grown under both irrigated and non-irrigated regimes. The crop responds positively to irrigation but will also produce well under dryland conditions. Cowpea is more drought resistant than common bean. Drought resistance is one reason that cowpea is such an important crop in many underdeveloped parts of the world. If irrigation is used, more vegetative growth and some delay in maturity may result. Application rates should ensure that the crop is not overwatered, especially in more northern latitudes, as this will suppress growth by lowering soil temperatures. The most critical moisture requiring period is just prior to and during bloom. Cowpea performs well on a wide variety of soils and soil conditions, but performs best on well-drained sandy loams or sandy soils where soil pH is in the range of 5.5 to 6.5.

2.2.5 Weed Control

Adequate weed control is necessary for good growth and high yields.

- Mechanical: Use of the rotary hoe and row cultivator in cowpea is similar to that of soybean. One or two rotary hoeings followed by timely cultivation should be done when no herbicides are used. One or more cultivations should also be done when herbicides are used (Davis *et al.*, 1991).
- Chemical: The term 'cowpea' is not found on most herbicide labels. Rather, the crop is referred to as black-eyed peas, southern peas, pinkeyed peas or crowder peas. Farmers planning on producing cowpeas should check with their State Agricultural Extension Service for advice on chemical weed control (Davis *et al.*, 1991).

2.2.6 Diseases and their Control

2.2.6.1 Root rot and Damping off

These diseases are caused by three different fungi. Symptoms vary and include rapid death of young succulent plants, discoloration of taproots, longitudinal cracks of the stems, stunting, wilting and poor yields. Complete control of root rot and damping off is difficult, and no variety is resistant to root rot. Persistent damp weather prior to development of the first true leaf and the crowding of seedlings due to poor seed spacing may increase damping off (Davis *et al.*, 1991).

Fungal and viral diseases can be reduced by:

- Treating high quality seed with fungicides labelled for cowpeas.
- Applying cowpea-labelled fungicides in the furrow.
- A four or five year rotation with other crops.
- Seeding into warm, well-prepared soils.
- Planting certified seed of resistant varieties.
- Controlling weeds.
- The removal of virus-affected plants.

2.2.6.2 Southern Blight

This is caused by a fungus that attacks roots and stems of cowpeas. The first visible symptom of southern blight is a progressive, yellowing and wilting of the foliage beginning on the lower leaves. The plant dies within a few days after the rust symptoms appear. A brownish vascular discoloration inside the stem may extend several inches above the soil line. During warm, moist conditions, the coarse, white mycelium of the fungus makes characteristic fan-shaped patterns of growth on the stem at the soil line. In this white-mat of the fungus, numerous smooth, round, light-tan to dark-brown mustard seed-like bodies called sclerotia are formed (Davis *et al.*, 1991).

2.2.6.3 Mosaic Virus

According to Davis *et al.*, (1991), a characteristic symptom of the mosaic virus disease is an intermixing of light and dark-brown areas. Infected plants usually are more dwarfed and bushy and yields are reduced. Mosaic diseases can also result in malformed pods. Plants infected during seedling stages may be barren and fail to produce. The best way to prevent large yield losses from virus diseases is to grow tolerant varieties.

2.2.6.4 Fusarium Wilt

Fusarium wilt usually causes the lower leaves on one side of the plant to turn yellow. Infected plants usually are stunted and wilted as the organism develops in the food and water conducting tissues. Brick red tissue can be observed in the stem when it is split lengthwise. The best control of Fusarium wilt is the use of resistant varieties (Davis *et al.*, 1991).

2.2.7 Insects and Other Predators and Their Control

Davis *et al.*, (1991), states that root-knot nematodes cause the root to appear knotted and galled. Above ground nematode symptoms appear as nutrient deficiencies, with stunting and often wilting because the root system is incapable of absorbing adequate amounts of water and nutrients. Nodules are attached to sides of roots, and galls are within the roots. Root-knot nematodes can also be harmful to the cowpea because root injuries make the plants much more susceptible to attack by fusarium wilt. Nematode populations can be reduced through crop rotation, fallowing, sanitation, weed control, and planting resistant varieties.

Cowpea curculio is a small weevil that causes blister-like spots on the surface of the pod. Aphids are small, green, soft-bodied insects that feed by piercing the plant tissue and withdrawing plant juices. Infestations of this pest develop on leaves and the fruiting stems. Their feeding, especially on the fruiting stem reduces the amount of plant nutrients available for pod and pea development. Infested foliage turns yellow and dies. Aphids excrete large quantities of a sugary substance called honey dew which supports the growth of sooty mould. Sooty mould, a fungus, is dark in colour, which reduces the amount of sunlight that reaches the leaf (Davis *et al.*, 1991).

2.2.8 Harvesting

Davis *et al.* (1991), states that cowpea can be harvested at three different stages of maturity: green snaps, green-mature, and dry. Depending on temperature, fresh-market (green-mature) peas are ready for harvest 16 to 17 days after bloom (60 to 90 days after planting). Most domestic cowpea production is mechanically harvested, however, hand harvested cowpeas suffer less damage and the harvest season may continue over a 1 to 3 week period. One person can hand harvest 12 to 20 bushels of cowpea pods per day.

Cowpea leaves are picked in a period from 4 weeks after emergence of the seedlings to the onset of flowering. The average seed yield in Ghana and Nigeria is 600kg/ha, Senegal is 110kg/ha, in Niger 470kg/ha and in the United States 900kg/ha. Immature fresh cowpea seeds have a limited shelf life if stored at ambient temperatures, but at 8℃ they can stay fresh for 8 days. Harvested pods must be dried to reduce the moisture content of the seeds for safe storage. Threshing by hand or with a conventional thresher is carried out on thoroughly dried pods (PROTA, 2003).

Seed quality is important for the seed market so care in harvest and post-harvest handling may be important to avoid cracked or split seed. Cowpea grown as a dried pea product can be directly combined using a platform head or a row crop head. The grain can be stored short term at around 12% moisture or less, with 8 to 9% recommended for long term storage. For some markets, the cowpeas must be harvested at a higher moisture, such as 18%, and trucked directly from the field to the processor (Quinn and Myers, 2002).

2.2.9 The Cowpea Trade

In West Africa, cowpea markets are part of an ancient trade that links the humid coastal agro-ecological zones with the semiarid interior. This ancient trade is based on the comparative advantage in food production characteristics of each zone (Coulibaly *et al*., 2009).

These trade linkages can be illustrated with Ghana which though a cowpea producer still imports about 10 000 MT annually (Langyintuo 1999) of which about 30% are from Burkina Faso and the rest from Niger (Table 3). According to Langyintuo (1999), in Accra, the large, rough coated Nigerien cowpea (cowpea from Niger) sells for a premium, but they need to be marketed quickly because they do not store well in the humid coastal climate (Coulibaly and Lowenberg-DeBoer, 2000)

Table3 Official imports of cowpea into Ghana

Year	Total Imports (MT)	Burkina Faso Imports (MT)	Burkina Faso Imports (% of total)	Niger Imports (MT)	Niger Imports (% of total)
1992	2055.34	592.00	28.80	1463.34	71.20
1993	2460.80	637.92	24.16	2002.88	75.84
1994	11798.98	2898.95	24.57	8900.03	75.43
1995	13086.29	3295.95	25.19	9790.34	74.81
1996	6816.80	3077.79	45.15	3739.01	54.85
1997	N/A	N/A	N/A	N/A	N/A
1998	10167.18	3050.15	30.00	7117.03	70.00

Source: Langyintuo, 1999, cited in Coulibaly *et al*., 2009

Throughout West Africa, the value chain of cowpea starts with the production of cowpeas by small scale farmers; and in the Sahelian countries of Niger, Burkina Faso and Mali, and in the inland areas of coastal countries, farmers typically sell their marketable surplus grains to rural assemblers, who in turn sell to urban wholesalers directly or through commission agents. Commission agents sell grain on behalf of their clients (rural assemblers), and provide storage but do not take any price risk associated with the storage function. Commission fee paid to the commission agent by rural assemblers varies usually from country to country and is often about 2% of the wholesale price. In some West African countries including Nigeria, Ghana, Togo, Benin and Burkina Faso, grain traders have organized themselves into commodity-based associations to promote marketing of grain and put in place guidelines for grain pricing (Langyintuo *et al*., 2003). These commodity associations serve as a bridge between grain traders and government organizations.

In addition to consumer preferences, there are also other factors which influence cowpea consumption and hence marketing in West Africa. In Nigeria, the level of consumption of cowpea is determined by four major factors, including income level of consumers, taste of the product, market price of cowpea and its close substitutes, and population density of cities which are the major markets (Kormawa *et al*., 2000).

2.2.10 Processing

Harvested green cowpeas will "heat" resulting in spoilage unless kept cool. Post-harvest facilities have to provide shade and adequate ventilation on the way to the cooler. Cowpeas cooled below 45^{o} F may show chilling injury (Davis *et al*., 1991).

In Africa, particularly in Ghana, traditional milling and other processing practices are time and labour intensive, cumbersome and expose the product to losses and adulteration. Innovative technologies include decortications, fermentation, extrusion and improved domestic processing. New cowpea-based products include weaning mixes and blending, new formulation and fortification (Nyankori, 2002).

The only processing activities currently existing in Niger for processing of cowpea are artisanal operations, and are small in scale, producing cowpea fritters using cowpea semolina, which are generally eaten with rice. Modern commercial cowpea operations utilise adequate techniques for storage, based on drying followed by insecticide treatment where storage is for over 6 months (European Union, 2002).

2.2.11 Uses

The protein in cowpea seed is rich in amino acids, lysine and tryptophan, compared to cereal grains; however, it is deficient in methionine and cystine when compared to animal proteins.

Therefore, cowpea seed is valued as a nutritional supplement to cereals and an extender of animal proteins (PROTA, 2003).

Cowpea can be used at all stages of growth as a vegetable crop. The tender green leaves are an important food source in Africa and are prepared as a pot herb, like spinach. Cowpea leaves are served either boiled or fried and usually eaten with porridge. Immature green and still soft seed is cooked to a thick soup and used as relish. In Benin State, Nigeria, the seeds are eaten directly whilst the pod walls are dried and preserved for later use. Immature snapped pods are used in the same way as snapbeans, often being mixed with other foods. Green cowpea seeds are boiled as a fresh vegetable, or may be canned or frozen. Dry mature seeds are also suitable for boiling and canning (PROTA, 2003).

Cowpea is the preferred food legume in large parts of Africa. The seed is cooked together with vegetables, spices and often palm oil. In West Africa, the seed is decorticated and ground into flour and mixed with chopped onions and spices and made into cake which are either deep fried or steamed. The flour can be used as a basic ingredient in the preparation of baby foods (PROTA, 2003).

In Ghana, cereals such as maize, millet and sorghum are traditionally used as the main ingredients of weaning foods (Plahar *et al*., 2003 cited in Nagai, 2008). In order to enhance the nutrients of these traditional weaning foods, new formulas have been developed. The suggested method for fortifying "koko" is to add dehulled cowpeas or soybeans to soaked maize to make a cowpea-fortified fermented maize dough (CFMD) or soybean-fortified fermented maize dough (SFMD) (Plahar *et al.*, 1997; Afoakwa *et al.*, 2004; Sefa-Dedeh, 2005 cited in Nagai, 2008). The method suggested for fortifying Tom Brown is to add roasted cowpeas or soybeans and roasted groundnuts to roasted maize before milling (Nagai, 2008).

Trading fresh produce and processed food and snacks provide rural and urban women with the opportunity for earning cash income. As a major source of protein, minerals, and vitamins in daily diets, it positively impacts on the health of women and children. The bulk of the diet of the rural and urban poor Africa consists of starchy food made from cassava, yam and plantain. Hence, the addition of even a small amount of cowpea ensures the nutritional balance of the diet and enhances the protein quality by the synergistic effect of high protein and high lysine from cowpea (Davis *et al*, 1991).

In Ghana, cowpea is an important nutritious component in some of the traditional meals such as *tumbanni* and cakes as well as a component of livestock feed.

2.3 Varieties of Cowpea in Ghana

Two new varieties are IT87D-611-3 with the name "Nhyira", meaning blessing in Akan and IT87D-2075 with the name "Tona", meaning profit in Dagarti. The two varieties were proposed based on the results of on-station and on-farm evaluation, chemical composition and sensory evaluation done by the Crop Research Institute (CRI) of the Council for Scientific and Industrial Research (CSIR). The development of the two new varieties was also to address the malnutrition problem among lactating mothers and children in the country.

“Nhyira” is early maturing (65-68 days), high yielding (2.3t/ha), moderately resistant to virus, resistant to Anthracnose and Cercospora leaf spot, high in iron, energy and phosphorus contents, protein, tolerant to leaf hoppers, bold, white seed with brown eye and drought tolerant.

The "Tona" variety has high energy, phosphorus and iron, resistant to Cercospora leaf spot and viruses, resistant to leaf hoppers, and has medium maturing for 71-80 days and is drought tolerant.

The new varieties could be used for *koose*, *gari* and beans, rice and beans, cake, *aprepransa*, sausage rolls, jam rolls, pie, chips, and can also be used in the school feeding programme based on their nutritional content.

"Ayiyi" is an aphid resistant line (IT83S-728-13), introduced from IITA in 1987. It is upright, but has a sprawling growth habit. Seeds are white with brownish helium, medium maturing (between 65 to 70 days). Its average grain yield is about 1,255 kg ha^{-1}, but has a potential of about 2.6 tons ha^{-1} (Addo-Quaye *et al*., 2011).

"Bengpla", an early maturing line (IT83S-818) was also introduced from IITA in 1987. It has an erect growth habit. The seeds are white with black-eyes, but smaller in size than California Black-eye cultivar. It matures between 60 to 65 days. It has a mean grain yield of about 1,023 kg ha^{-1} and a potential of 1.8 tons/ha (Addo-Quaye *et al.*, 2011).

The UCC-Early variety has determinate semi-erect growth habit and with ovate leaves. It has light brown pod color and reddish seed coat. It matures at about 62 days after planting (Addo-Quaye *et al.*, 2011).

The improved varieties IT89KD-288, IT89KD-391, IT97K-499-35, and IT93K-452-1 produce high-quality grains for use as food and fodder and are also resistant to striga, a parasitic weed that reduces yields in susceptible local cowpeas by as much as 80 per cent (Atser, 2009).

2.4 The 'Asontem' (IT82E-16) variety

The grain yield of Asontem ranged from 1.1 to 2.4 Mg/ha which was about 200% higher than farmers' varieties and about 44% higher than the best improved variety in the same maturity group. It also has 26% protein and 2% oil compared to 25% protein and 1.6% oil in other varieties (Asafo-Adjei *et al*., 2005).

Asontem is adapted to all five major agro-ecological zones and as such can flourish in these zones, but it is more popular in the coastal savannahs (major and minor seasons), semi deciduous forest zone (minor season), forest–savannah transition zone (minor season), and Guinea and Sudan savannahs (early or midseason). Due to its adaptability and early maturity, Asontem is currently the most widely cultivated improved cowpea variety in Ghana occupying 44% of area planted to improved cowpea in the Guinea savannah zone (Abatania *et al.*, 2000 cited in Asafo-Adjei *et al*., 2005).

Figure 2 Sample of the Asontem cowpea variety

2.5 Physical Properties

2.5.1 Introduction

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 physical 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).

The size, shape, density and aerodynamic properties of kernels and plant parts are important for the proper design of combines which thresh the kernels from the plants and separate kernels from the straw and chaff. Knowledge of frictional properties and the characteristics from flow of chutes and orifices are needed for the design of handling equipment. Physical properties are also useful when designing and sizing machine components such as those used for metering seeds into the soil (Stroshine and Hamann, 1995).

Due to the mostly non-uniform dimensions of agricultural products, the use of average measurements in their analysis and description becomes necessary. Length, width and thickness measurements are usually replicated several times due to their irregular nature.

According to Stroshine and Hamann (1995), the dimensions of agricultural materials also vary widely with growing season, growing location and variety. Therefore it is best to perform measurements on a large number of specimens from the particular variety grown under cultural practices typical of the region.

2.5.2 Size and Shape

Length, width and thickness determination is useful in the design of seed metering devices, sorting sieves, 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).

Principal axial dimensions of rough rice grains are useful in selecting sieve separators and in calculating power during the seed milling process. They can also be used to calculate surface area and volume of kernels which are important during modelling of grain drying, aeration, heating and cooling. Dimensional changes are important in designing drying and storage bins and seed pod threshers (Varnamkhasti *et al.*, 2007 cited in Karimi *et al.*, 2009).

Differences in size and shape can be used to improve the quality of grains by removing foreign materials and damaged particles. Seeds may be separated into size categories before being sold on the market. Dimensions are known to increase with increasing moisture content up to a certain point after which there is no more appreciable. Most experiments are carried out between 5% and 25% moisture content.

According to Baryeh (2000), for groundnuts, all the dimensions increased with grain moisture content up to 25% moisture content. Beyond which there was no appreciable dimensional change. The grains probably retain some tiny air voids as they absorb water and these are replaced with water beyond 25% moisture content thereby making the grains display no dimensional changes.

When cherry fruits are transported hydraulically, design of fluid velocities are related to both density and shape. Volumes and projected area of cherries must be known for accurate modelling of heat and mass transfer during cooling and drying. Porosity of cherries can be used for controlling temperature of stored cherry fruits (Naderiboldaji *et al*., 2008).

Shape is important in orienting fruits and vegetables prior to mechanized operations such as peeling, removal of cores and pits, or positioning for machine assisted packing. Proper performance of machine vision systems for sizing and quality evaluation will also depend on proper orientation. For example, the bottom part of pears is ellipsoidal but the upper portion is conical, hence the centre of gravity is nearer the bottom. When pears fall into the notch of a belt roller, they assume a position in which their centre of gravity is as low as possible and therefore their stem ends point upwards, good for separation purposes (Stroshine and Hamann, 1995).

According to Stroshine and Hamann, (1995), knowledge of seed size is also helpful in selecting the flexible tubing used to transport singulated seeds to the drop point. The number of seeds per unit volume could be used to size the hopper on the planter which holds the seeds prior to planting.

Table 4 Length, width and thickness dimensions of cocoa at different moisture contents

Moisture content(%)	Length (mm)	Width (mm)	Thickness (mm)	Dg (mm)	1000-grain mass (g)
8.60	22.41	12.64	7.40	12.73	1125
13.27	21.58	12.03	7.36	12.33	1180
18.80	22.50	12.86	7.70	12.90	1222
24.00	21.89	12.20	7.62	12.58	1247

Source: Bart-Plange and Baryeh (2002)

For instance, the application of physical properties such as shape which is an important parameter for stress distribution in materials under load is important in developing sizing and grading machines and for analytical prediction of its drying behaviour (Esref and Halil, 2007 cited in Chukwu and Sunmonu, 2010).

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. The packing coefficient of agricultural products is also dependent on the size. The market price of fresh fruits and vegetables are often influenced by their sizes. In packing operations, smaller sizes can be diverted for use in juicing or canning processes (Stroshine and Hamann, 1995).

2.5.3 1000 Grain Mass

This refers to the mass of 1000 grains and includes the dry matter and the moisture present within the grains. The moisture present however is dependent on the water holding ability of the grain and void spaces.

A model study of the effect of barley grain moisture content on the distribution of horizontal and vertical pressures in a silo by Kusiñska (2002), showed that in the course of storage of both wet and dry barley grain, the horizontal and vertical pressures are subject to change and also the increased moisture content and longer storage time cause pressure values to increase. Pressure values increase due to an increase in the dimensional measurements of individual grains caused by an increase in weight from moisture absorption. This provides useful information in the design of silos taking into consideration weight increase and volumetric expansion.

The mass of 1000 grains has been found to increase linearly with an increase in moisture content for spinach seeds (Kilickan *et al*., 2010) and red pepper seeds (Üçer *et al.*, 2010).

According to Bart-Plange and Baryeh (2002), the variation of 1000 grain mass with moisture content was found to increase linearly for category B cocoa beans from 1125.02g to 1247.19 g at moisture contents ranging between 7.56% and 19.00% (wb).

The 1000 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 shrivelled or immature kernels (Varnamkhasti *et al*., 2008).

Aerodynamic properties such as terminal velocity are useful for air conveying or pneumatic separation of materials in such a way that when the air velocity is greater than the terminal velocity, it lifts the particles. The air velocity at which the seed remains in suspension is considered as terminal velocity (Mohsenin, 1986). The terminal velocity is useful in the design of separators, sorters and graders which are necessary for removing insects, soil particles and debris; and also for grouping grains into quality and marketable fractions.

2.5.4 Bulk Density

This is the ratio of the mass of grains to the volume including the space of void. The bulk density can be determined using a container of known volume. The container is weighed, filled with the seeds, striking off the top without being compacted and reweighed. 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 some physical properties 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 Deshpande *et al*. (1993) for soybeans; Suthar and Das (1996) for karigda seeds; Jain and Bal (1997) for pearl millet and Akinci *et al*. (2004) for Juniperus drupacea fruits.

According to Baryeh (2000), the bulk density decreases as the moisture content increases up to 25%, beyond which it does not change appreciably. A decrease in bulk density as moisture content increases has been reported by Singh and Goswami (1996) for cumin seeds; Gupta and Das (1997) for sunflower seeds and Deshpande *et al.* (1993) for soybeans.

In precision agriculture, diverse approaches are used to determine the volume of the existing grain in a combine hopper. To determine the weight of product in the hopper, knowledge of bulk density is necessary. The bulk density of grains is also useful in the design of silos and storage bins (Varnamkhasti *et al*., 2008).

Densities of liquid foods are important in separation by centrifugation and sedimentation and in determining flow properties and power requirements. When grains and other particulate solids are transported pneumatically or hydraulically, the design fluid velocities are related to both density and shape (Stroshine and Hamann, 1995).

In such sorting systems, fruits are placed in solutions like salt brine or alcohol-water. The specific gravity of the solution is adjusted to a value, which will differentiate between those fruit which are desirable and those, which are not. Problems to be overcome include contamination of the solution by dirt which causes an accompanying change in solution density (Mohsenin, 1986).

2.5.5 True Density

The 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 (Tavakoli *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 cited in Karimi *et al.*, 2009) and for determining volume fractions for use in dielectric mixture equations (Nelson, 1992).

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 Gupta and Das (1997) for sunflower seeds.

2.5.6 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 and is calculated as the ratio of the volume of the air to the total volume of the chamber. The pycnometer is constructed of two air-tight chambers of nearly equal volumes V_1 and V_2 connected by a small diameter tubing. The valves isolate the chambers from each other and the outside atmosphere. The material to be measured is placed in the second tank. In a similar measurement sequence the sample is placed in chamber 2, and valves 2 and 3 are closed. Valve 1 is opened and the gauge pressure P_1 in chamber is increased to 700-1000Pa. Valve 1 is closed the pressure P1 is recorded and the valve 2 is opened.

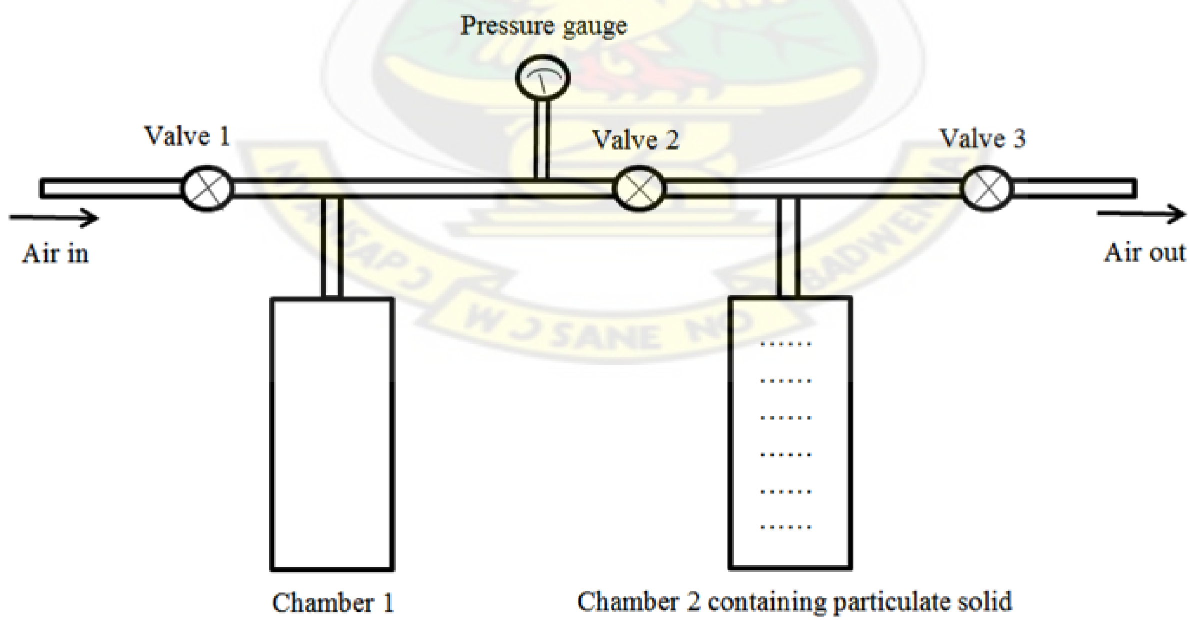

Figure 3 Diagram of air comparison pycnometer (Source: Stroshine and Hamann, 1995)

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 which is the percentage of air space in particulate solids, affects the resistance to airflow through bulk solids. Airflow resistance in turn affects the performance of systems designed for forced convection drying of bulk solids and aeration systems used to control the temperature of stored bulk solids (Stroshine and Hamann, 1995).

Porosity increases nonlinearly with increase in seed moisture content from 8% porosity at 5% seed moisture content to 28% porosity at 25% seed moisture content for pigeon pea (Baryeh and Mangope, 2002). Singh and Goswami (1996) and Gupta and Das (1997) found the porosity of cumin and sunflower seeds, respectively, to increase with increase in moisture content.

Joshi *et al.* (1993) and Suthar and Das (1996) however found porosity to decrease linearly with an increase in moisture content for pumpkin and karingda seeds, respectively. Baryeh (2000) also reports a non-linear increase in porosity from 38% at 5% grain moisture content to 43% at 20% moisture content and then decreases non-linearly to 40.5% at 35% moisture content for Bambara groundnuts.

According to Bart-Plange and Baryeh (2002), 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 inter-bean voids when the porosity is high for cocoa beans.

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

Grain bed with low porosity will have greater resistance to water vapor escape during the drying process, due to the reduction in pore spaces which may lead to higher power to drive the aeration fans (Ghasemi Varnamkhasti *et al*., 2007 cited in Karimi *et al.*, 2009). Hence in the design of postharvest drying equipment, knowledge of porosity of crops is essential when designing fans. A relationship between the porosity, amount of power required to drive a specific volume of air through a specific volume and mass of grains and the time taken to carry out this action in order to bring grains to some particular moisture content is necessary in designing storage aeration fans.

Porosity, on the other hand, allows gases, such as air and liquids to flow through a mass of particles in aeration, drying, heating, cooling and distillation operations (Karimi *et al*., 2009).

2.5.7 Sphericity and Geometric Mean 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).

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). Data from sphericity is useful in sieve size determination and in selecting sieve separators.

$$\text{Sphericity} = \left[\frac{volume\ of\ ellipsoid\ with\ equivalent\ diameters}{volume\ of\ circumscribed\ sphere}\right]^{1/3} = \frac{(LWT)}{L}^{1/3}$$

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 or equivalent diameter was calculated from the equation 1 (Mohsenin, 1970 cited in Ucer *et al.*, 2010)

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

The degree of sphericity is then calculated using equation 2 (Mohsenin, 1970 cited in Ucer *et al.*, 2010)

$$\Phi = \frac{(LWT)^{1/3}}{L} \text{ X } 100 \quad 2$$

$$\Phi = \frac{Dg}{L} X\ 100 \quad 3$$

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

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

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

2.5.8 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. When a burette is used, the volume of solid particles, the volume of fluid and the volume after addition of the solid particles are determined from the markings on the burette

Volume, V and grain surface area, S may be given by equations 6 and 7

$$V = \frac{\pi}{6} Dg^3 \qquad 6$$

$$S = \pi Dg^2 \qquad 7$$

Jain and Bal (1997) have also stated that the seed volume, V and surface area, A may be given by

$$V = \frac{\pi B^2 L^2}{6(2L-B)} \qquad 8$$

$$S = \frac{\pi B L^2}{2L-B} \qquad 9$$

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

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. The effects of size and surface area on drying rates of particulate materials can also be characterized by using the surface to volume ratio. When diffusion of water within the particle limits drying rate, larger particles dry more slowly than smaller particles of the same shape. Also, the ratio of surface area to volume affects drying time and energy requirements (Stroshine and Hamann, 1995).

Volume considerations have practical applications where shape affects the process such as separation and product loading, e.g. hopper, while weight considerations have practical applications in unit operations such as conveying as well as cleaning. Weight and volume are also useful in mathematical and computer modelling of handling and processing operations where the behaviour of the bulk system is predicted from the microscopic behaviour especially individual seed (Rong *et al*., 1995 cited in Akaaimo and Raji, 2006; Raji and Favier, 2004 cited in Akaaimo and Raji, 2006).

The seed volume decreases from 94.25 mm^3 at 5% seed moisture content to 28.20 mm^3 at 20% seed moisture content and increases to 37.50 mm^3 at 25% seed moisture content. This is explained by the reduction in the seed dimensions as the seed moisture content increases for pigeon pea (Baryeh and Mangope, 2002).

Surface area can also be determined from the equation $S = \pi D_g^2$, which utilizes the geometric mean diameter (Mohsenin, 1970 cited in Ucer *et al.*, 2010).

The surface area of an agricultural product is generally indicative of its pattern of behavior in a flowing fluid such as air, as well as the ease of separating extraneous materials from the product during cleaning by pneumatic means (Omobuwajo *et al.*, 1999).

Surface area of leaves and plant components are needed for the modelling and prediction of transpiration, respiration and photosynthesis rates. Surface area of fruits and vegetables can be useful in studies of respiration rate during storage and water absorption rate during soaking. The rate of heating or cooling is affected by the ratio of volume to surface area (Stroshine and Hamann, 1995).

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 (Tabatabaeefar, 2003 cited in Tavakoli *et al.*, 2009**).**

2.5.9 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. These angles are very useful for calculating the quantity of granular materials which can be placed in piles or flat storages (Stroshine and Hamann, 1995).

The 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. (Tavakoli *et al*., 2009).

The angle of repose is also important in designing the 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).

A linear increase in angle of repose as the seed moisture content increases has been reported by Suthar and Das (1996) for karingda seeds, Baryeh and Mangope (2002) for pigeon pea, Bart-Plange and Baryeh (2002) for cocoa beans and Kabas *et al*. (2007) for cowpeas.

Flow ability of agricultural grains is usually measured using the angle of repose. This is a measure of the internal friction between grains and can be useful in hopper design, since the hopper wall's inclination angle should be greater than the angle of repose to ensure the continuous flow of the materials by gravity (Gharibzahedi *et al*., 2010).

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. Hence low moisture content is advisable for belt conveying, while high moisture content is advisable when unloading for the beans (Bart-Plange and Baryeh, 2002).

2.5.10 Coefficient of Static Friction

Coefficient of static friction is determined by the use of a tilting table and a lifting screw mechanism. It is calculated as the tangent inverse ($\tan^{-1}$) 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, galvanized steel and aluminium; Kabas *et al.* (2007) for cowpeas using rubber, plywood and galvanized sheet; Aviara *et al.* (2005) for sheanut using metal sheet, formica and plywood.

The materials used for the experiment were considered because they are commonly used in the handling and processing of grains and construction of storage and drying bins. The reason for the increased friction coefficient at higher moisture content may be owing to the water present in the grain. The grains also 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. If a rubber surface is to be used for conveying cocoa beans, it will be advisable to roughen the surface to increase friction between the beans and the surface. On the other hand, discharging requires less friction to enhance the discharging process (Bart-Plange and Baryeh, 2002).

The knowledge of coefficient of friction of food grains on various structural surfaces is necessary in analysis and design of post-harvest equipment such as grain bins, silos, conveyors. A machine can only be started or stopped if forces of static friction or dynamic friction are overcome by a power source. Therefore, information on both static and dynamic coefficient of friction is vital in estimating the power requirement of machines (Nwakonobi and Onwualu, 2009).

The friction coefficient is important in the design of conveyors because friction is necessary to hold grains to the conveying surface without slipping or sliding backward (Tavakoli *et al*., 2009).

Table 5 Static coefficient of friction of some agricultural materials on some selected surfaces

Material	Type of Surface	Moisture Content	Static Coefficient of Friction
Barley	Concrete, wood float finish	12.3	0.52
Oats	Concrete, wood float finish	13.0	0.44
Soybeans	Concrete, wood float finish	12.2	0.52
Corn shelled	Concrete, wood float finish	13.9	0.54
Wheat	Concrete, wood float finish	11.2	0.51

Source: Stroshine and Hamann, 1995

2.6 Practical Application Examples

2.6.1 Case Study 1

Chukwu and Akande, (2009) worked on the performance evaluation of a Bambara groundnut sheller. Some physical properties of Bambara groundnut pod relevant to bulk handling and processing were investigated, a machine was constructed and tested for materials handling.

The Bambara groundnut sheller was designed to operate by means of roller mechanism, consisting of a feed hopper, shelling unit, winnowing unit and power system. Measurements of the bulk and grain densities as well as 1000 grain mass were necessary in the construction of the winnowing unit. As the mixture of seed and shell falls through the winnowing chamber, the air current from the blower lifts the lighter shell and carries it out through the shell outlet. The denser seed falls through the air stream into the collection chute.

Measurements of the physical properties showed that at the moisture content of 5% (wb), the major, intermediate and minor diameters of Bambara groundnut pod averaged 1.89 cm, 1.57 cm and 1.44cm respectively. Values of the axial dimensions governed the clearance between the rollers of the sheller that would engender effective shelling of the pod.

The true and bulk densities, porosity and one thousand-pod weight averaged 754.83 kg/m^3 and 432 kg/m^3, 42.77% and 1.24 kg, respectively and the angle of repose and static coefficient of friction of the pod on steel sheet averaged 30.40^0 and 0.56. These properties played important roles in the determination of the sheller features and performance characteristics. The true and bulk densities, porosity and coefficient of friction influenced the pressures exerted on hopper walls and flow through the orifice. The one thousand pod weight could be used for the theoretical determination of the pod's effective diameter and the angle of repose was used to determine the hopper inclination. The coefficient of static friction is most needful in determining the type of material to be used in the construction of the hopper which would give least resistance to the flow of grains.

In the design of a chopping and impelling unit, the engineers need information on the sliding coefficient of friction of grains on steel (Hintz and Schinke, 1952 cited in Abano and Amoah, 2011).

2.6.2 Case Study 2

Gbadam *et al*. (2009), worked on the determination of Some Design Parameters for Palm Nut Crackers. This study sought to determine some parameters for palm nut crackers in order to design new crackers that will reduce kernel breakage. The nut is cracked to liberate the kernel for kernel oil production. The conventional method of cracking is manual which involves the use of stones for cracking. The manual method has the disadvantage of being time consuming and in addition the person cracking was in constant danger of inadvertently hitting their fingers with the stones. Currently, locally manufactured nutcrackers are being used but kernel breakage is a major setback.

Preserving the kernel embedded in the palm nut when cracking the nutshell is important in the subsequent palm kernel and shell separation and, in enhancing the quality of the palm kernel oil.

Inappropriate spacing of the impactors (blow bars) may also result in a number of uncracked nuts in the finished product as well as the feeding rate of the nut into the cracking chamber (Ofei, 2007). Determination of the size dimensions at appropriate moisture levels provides relevant data which is useful in finding the right spacing of impactors. Kernel breakage also results partly because the kernel upon release from the nutshell rebound in the cracking chamber and is subjected to secondary impacts which induce breakage.

Kernel oil production is an important cottage industry that involves rural women. If the production is carefully engineered, the product could compete internationally thereby increasing the foreign exchange base of the country and offering employment for the youth especially women. This study was aimed at providing useful design parameters for palm nut crackers in order to minimize kernel breakage during cracking.

The results provide support for differential cracking of palm nuts based on nut sizes. Otherwise, some nuts will experience excessive impacts with attendant kernel breakage, while some will be discharged without cracking.

One interesting trend to be noted is the higher values of average sphericity index 73.0, % for the *Dura* variety compared to the values for the *Tenera* variety, which is 70.0 %. This indicates that *Dura* has a higher tendency to have its shape towards a sphere than the *Tenera*.

It is evident that the grain sizes of the *Dura* shell are smaller than the *Tenera* shell. This further explains that the pore structure of the *Dura* shell is densely packed; which results in minimum water absorption and longer drying period. Again, the compactness of the pore structure creates greater stress concentration which increases the propagation of cracks under compression. The magnitude of force required to break the shell open is thus great.

The pore structure of the *Tenera* shell is more loosed, which makes it permeable for water absorption. Due to the nature of the pore structure, the drying rate is decreased as moisture evaporates readily into the atmosphere. Again, due to the less stress concentration (large pore radii of curvature), crack propagation under compression is not rapid, hence, requires minimum breaking force.

These properties reveal that there is a clear difference in the physical properties of *Tenera* and *Dura* varieties of palm nut, which are the main commercial types. In particular, these properties are very useful in the design of processing machines such as cracker, sterilizer, digester and oil press. Taking advantage of the difference in the properties of the nuts will assist in the design of versatile machines to handle the processing of the two varieties.

2.6.3 Case Study 3

Jayan and Kumar, (2004) worked on planter design in relation to the physical properties of agricultural seeds. Seed flow through a planter is dependent on size, shape, sphericity, true density and angle of repose of seeds. In addition, the impact of seeds on the internal components of the planter is influenced by the coefficient of friction of seeds on various impinging surfaces.

Since the metered seeds were to be transferred to the seed placement unit (dibbler) quickly, the lower sphericity value of cotton was taken into consideration for designing the slope of the seed transfer cup; bringing out the necessity of the angle of repose. Again, seed weight affects seed flow from seed metering device to the dibbler, and in turn, influences the design of seed hopper; data on the 1000 grain mass and the bulk density was quite important in designing the weight holding capacity of the metering device.

The mean angle of repose of maize, redgram, and cotton were 22.10, 28.48, and 21.48 degrees respectively. Hence, the slope of the seed hopper was kept at 30 degrees to ensure free flow of seed, which is modestly higher than the average angle of repose of seeds. Furthermore, seeds that fell on the rubber sheet experienced minimum coefficient of restitution compared to that on the mild steel sheet. Therefore, a 3 mm thick rubber sheet was imbedded on the inner surface of the seed transfer cup to minimize seed bouncing.

2.7 Water Properties

Three concepts are important in the discussion of moisture in agricultural materials and food products: equilibrium moisture content, water activity and water potential.

Equilibrium moisture describes the final moisture reached during drying of lower moisture agricultural materials and food products and also affects the rate at which they dry. Water potential describes the effect of moisture loss or gain on both volume changes and force deformation behaviour of fruits and vegetables (Stroshine and Hamann, 1995).

Water potential is the potential energy of water per unit volume relative to pure water in reference conditions. Water potential quantifies the tendency of water to move from one area to another due to osmosis, gravity, mechanical pressure, or matrix effects such as surface tension (Taiz and Zeiger, 2002).

When the moisture content (W_w) of agricultural material and food products are described by the percentage of total weight (W_t), it is called wet basis moisture content. However if it is expressed as the percentage equivalent to the ratio of weight of water only (W_w) to the weight of dry matter (W_d) it is called the dry basis moisture content. They are described by the following formulas;

$$M_w = 100\,\frac{W_w}{W_t} = 100\,\frac{W_w}{W_w+W_d} \qquad (10)$$

$$M_d = 100\,\frac{W_w}{W_d} \qquad (11)$$

$$M_w = 100\,\frac{M_w}{100+M_d} \qquad (12)$$

$$M_d = 100\,\frac{M_d}{100-M_w} \qquad (13)$$

W_w = weight of water in the material

W_d = weight of dry matter in the material

W_t = total weight of sample = W_w+W_d

M_w = moisture content expressed in wet basis

M_d = moisture content expressed in dry basis

The amount of dry matter in a sample is assumed to be constant. The amount of dry matter is calculated from initial weight and initial moisture content (m.c.). The dried or rewetted sample will contain the same amount of dry matter (Stroshine and Hamann, 1995).

2.7.1 Properties of Water in Foods

According to Taiz and Zeiger (2002), despite having the same chemical formula (H_2O), the water molecules in a food product may be present in a variety of different molecular environments depending on their interaction with the surrounding molecules. The water molecules in these different environments normally have different physiochemical properties namely:

- *Bulk water* - Bulk water is free from any other constituents, so that each water molecule is surrounded only by other water molecules. It therefore has physicochemical properties that are the same as those of pure water, *e.g.*, melting point, boiling point, density, compressibility, heat of vaporization, electromagnetic absorption spectra.

- *Capillary or trapped water* - Capillary water is held in narrow channels between certain food components because of capillary forces. Trapped water is held within spaces within a food that are surrounded by a physical barrier that prevents the water molecules from easily escaping, *e.g.*, an emulsion droplet or a biological cell. The majority of this type of water is involved in normal water-water bonding and so it has physicochemical properties similar to that of bulk water.

- *Physically bound water* - A significant fraction of the water molecules in many foods are not completely surrounded by other water molecules, but are in molecular contact with other food constituents, *e.g.* proteins, carbohydrates or minerals. The bonds between water molecules and these constituents are often significantly different from normal water-water bonds and so this type of water has different physicochemical properties than bulk water

- *Chemically bound water.* Some of the water molecules present in a food may be chemically bonded to other molecules as water of crystallization or as hydrates, *e.g.* $NaSO_4.10H_20$. These bonds are much stronger than the normal water-water bond and therefore chemically bound water has very different physicochemical properties to bulk water. In addition, foods may contain water that is present in different physical states: gas, liquid or solid.

2.7.2 Moisture Measurement

A number of techniques have been developed for measuring the moisture content of agricultural materials and food products. Moisture content often varies slightly when different methods are used for the determination. The reason may be that some of the water may actually be chemically bound as a constituent of the product itself or heating may decompose some of the constituents and water may be one of the products of the decomposition. An accurate determination of moisture is dependent upon proper sampling procedures. Moisture content can be determined by either the direct or indirect methods. Direct methods are simpler and accurate but time-consuming. Indirect methods such as chemical and electrical methods are convenient and quick but less accurate (Stroshine and Hamann, 1995).

2.7.2.1 Direct Measurement

Water content is determined by removing moisture and then by measuring weight loss. 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 they require special equipment (e.g. an oven and analytical balance), and measurements can only be implemented in laboratories. They are also time-consuming (Stroshine and Hamann, 1995).

2.7.2.2 Indirect Measurement

An intermediate variable is measured and then converted into moisture content such as electrical conductivity (Stroshine and Hamann, 1995).

2.7.3 Moisture Meters

All commonly used methods are based on electrical property of grains. An electrical current unit, resistance or capacitance, is measured and then converted into moisture content.

- Resistance: the meter measures the electrical resistance of grains when a current is applied between two electrodes. Grains are placed in a constant and known volume.
- Capacitance: the meter measures an electrical current between two plates of a condenser which constitute the walls of a recipient. A precise weight of sample is required.

In both techniques, temperature corrections are required for accurate measurements. Most moisture meters are equipped with temperature correction software.

Limits of the method

Calibration charts must be established for each grain type. This means that a meter must be calibrated separately for robusta beans and arabica beans, but also for cherries and parchment to obtain accurate measurements. Accurate measurements are obtained within a range given by the manufacturer (Stroshine and Hamann, 1995).

2.7.4 Moisture Content Determination Techniques

2.7.4.1 Electrical Method

An awareness of the effect of moisture on the electrical properties of resistance and capacitance led to the development of electrical moisture meters. In meters which use the principle of conductance, the sample is compressed by two plates made of conducting material and connected in series to a source of electric current. The current is measured with a galvanometer. A series of fixed resistors may be included in the circuit to increase the sensitivity of the galvanometer. The resistance of the sample is dependent on the pressure which the plates apply to the sample. The capacitance type acts as a dielectric material when placed between two plates or concentric metal cylinders which form a capacitor (Stroshine and Hamann, 1995).

2.7.4.2 Hygrometers

These devices measure the relative humidity in the air space between grains. Values given by these meters refer to water activity of grains and are useful for microbiological purposes. The accuracy of measurements depends on the uniformity of the distribution of moisture in the sample and equilibration must be achieved to have reliable measurements. For high moistures, equilibration time may take few hours (www.unix-oit.umass.edu/mcclemen)

2.7.4.3 Evaporation Method

This method relies on measuring the mass of water in a known mass of sample. The moisture content is determined by measuring the mass of a food before and after the water is removed by evaporation:

$$\%Moisture = \frac{M_{initial} - M_{dried}}{M_{initial}} X\,100 \qquad (14)$$

Here, M_{initial} and M_{dried} are the mass of the sample before and after drying, respectively. The basic principle of this technique is that water has a lower boiling point than the other major components within foods, *e.g.*, lipids, proteins, carbohydrates and minerals. Sometimes a related parameter, known as the *total solids*, is reported as a measure of the moisture content. The total solids content is a measure of the amount of material remaining after all the water has been evaporated:

$$\% \text{ Total Solids} = \frac{M_{dried}}{M_{initial}} X\ 100 \qquad (15)$$

Thus, %Total solids = (100 - %Moisture).

2.7.4.4 Hot-air Oven Method

The sample is weighed and heated in an insulated oven to constant weight. The difference in weight is the water that has evaporated. The sample is usually weighed in a flat-bottomed, shallow dish (made of material that will not react with food nor pick up moisture readily). The oven must be thermostatically controlled and usually set at 100°C or 105°C. The size, weight, etc., of the sample is very critical. To help fast and uniform drying, the sample should be disintegrated into fine particles. Very often, an internal fan is also fitted in the oven to circulate the hot air. This method is suitable for nuts, flour, powders, meat and meat products, and most fruits and vegetables (www.unix-oit.umass.edu/mcclemen)

Advantages

- Precise
- Relatively cheap

- Easy to use
- Officially sanctioned for many applications
- Many samples can be analysed simultaneously

Disadvantages

- Destructive
- Unsuitable for some types of food
- Time consuming

2.7.4.5 Distillation Method

Distillation methods are based on direct measurement of the amount of water removed from a food sample by evaporation: %Moisture = 100 (M_{water}/$M_{initial}$). Basically, distillation methods involve heating a weighed food sample ($M_{initial}$) in the presence of an organic solvent that is immiscible with water. The water in the sample evaporates and is collected in a graduated glass tube where its mass is determined (M_{water}) (www.unix-oit.umass.edu/mcclemen).

Dean and Stark Method

A known weight of food is placed in a flask with an organic solvent such as xylene or toluene. The organic solvent must be insoluble with water; have a higher boiling point than water; be less dense than water; and be safe to use. The flask containing the sample and the organic solvent is attached to a condenser by a side arm and the mixture is heated. The water in the sample evaporates and moves up into the condenser where it is cooled and converted back into liquid water, which then trickles into the graduated tube. When no more water is collected in the graduated tube, distillation is stopped and the volume of water is read from the tube (www.unix-oit.umass.edu/mcclemen).

Advantage

- Suitable for application to foods with low moisture contents
- Suitable for application to foods containing volatile oils, such as herbs or spices, since the oils remain dissolved in the organic solvent, and therefore do not interfere with the measurement of the water
- Equipment is relatively cheap, easy to setup and operate
- Distillation methods have been officially sanctioned for a number of food applications.

Disadvantages

- Destructive
- Relatively time-consuming
- Involves the use of flammable solvents
- Not applicable to some types of foods.

2.7.4.6 Chemical Reaction Methods

Reactions between water and certain chemical reagents can be used as a basis for determining the concentration of moisture in foods. In these methods a chemical reagent is added to the food that reacts specifically with water to produce a measurable change in the properties of the system, e.g.,mass, volume, pressure, pH, colour or conductivity. Measurable changes in the system are correlated to the moisture content using calibration curves. To make accurate measurements it is important that the chemical reagent reacts with all of the water molecules present, but not with any of the other components in the food matrix (www.unix-oit.umass.edu/mcclemen).

2.7.5 Rewetting

2.7.5.1 Methods of Rewetting

Several methodologies have been used in literature for preparing rewetted materials and among which the following are commonly utilized.

Grain particles are often rewetted by immersion in water during different periods of time depending on the initial moisture content that must be attained. Other researchers rewet particles by contacting the mass of grains to be rewetted with the exact amount of water required to reach the desired initial moisture content. Another methodology used considers rewetting of the particles by placing them within an environment of saturated air for the time necessary for them to reach the moisture content of interest (Ruiz *et al*., 2007).

Soaking is a slow process controlled by the diffusion of water in the grain (Engels *et al*., 1986). Thus soaking at room temperature may provoke microbial contamination, which affects quality attributes (such as colour, taste and flavour) of the product (Bello *et al*., 2004). Warm water soaking is a common method to shorten the soaking time, because higher temperature increases hydration rate (Kashaninejadl and Kashiri, 2007).

Moisture content each time after soaking is calculated based on the increase in the sample weight at corresponding times. For this purpose, at regular time intervals, kernels are rapidly removed from test tubes and superficially dried on a large filter paper, to eliminate the surface water. The kernels are then weighed to determine the moisture uptake. The samples are subsequently returned to water via wire mesh baskets, and the process is repeated until the kernels moisture content attains a saturation moisture content, (i.e., when three successive weight measurements differ from the average value in less than ±1%) (Resio *et al*., 2005).

2.7.5.2 Importance of Rewetting

In the canning industry, knowledge in hydration characteristics of grains prior to further processing is necessary to know the changes such as leaching losses, and grain expansion in the can during a thermal process. In order to control and predict the process, optimizing the hydration condition is vital since hydration governs the subsequent operations and the quality of the final product (Kashaninejadl and Kashiri, 2007).

The wetting process is commonly applied in cereal and other crop grains. It is used as a preliminary process (e.g. before hulling) during processing of leguminous plant seeds. Wetting plays an important role at preparing the seeds for milling. Properly performed it has a significant influence on extract index value for white flours and the quality of the obtained milled products. Moreover, it ensures the optimum working conditions for a grinding device resulting in a uniform condition of the seeds by improving such traits as endosperm tenderness as well as ductility and elasticity of cover (Chemperek and Rydzak, 2006).

Kondo and Okamura (1930) found that field rewetting increased the number of cracked rice kernels, and that the percentage of cracks increased with the duration of exposure to moisture. The level of rewetting which is based on the moisture content of kernels can then be used to determine the degree of cracking, hence a relation between rewetting and cracking. Depending on the moisture level, an estimate can be given for the number of cracked kernels which would lead to a reduction in cracked kernels or increase in head rice yield for industrial processing.

2.7.6 Drying

Drying is the oldest method of preserving food. The early American settlers dried foods such as corn, apple slices, currants, grapes, and meat. Dried foods keep well because the moisture content is so low that spoilage organisms cannot grow. Drying will never replace canning and freezing because these methods do a better job of retaining the taste, appearance, and nutritive value of fresh food; but drying is an excellent way to preserve foods that can add variety to meals and provide delicious, nutritious snacks. One of the biggest advantages of dried foods is that they take much less storage space than canned or frozen foods. Drying is a mass transfer process consisting of the removal of water or moisture from another solvent, by evaporation from a solid, semi-solid or liquid (Greensmith, 1998).

Drying is traditionally defined as that unit operation which converts a liquid, solid or semi-solid feed material into a solid product of significantly lower moisture content. In most cases, drying involves the application of thermal energy, which causes water to evaporate into the vapour phase Foods are dried commercially, starting either from their natural state (e.g. vegetables, fruits, milk, spices, grains) or after processing (e.g. instant coffee, whey, soup mixes, non-dairy creamers) to addition to preserving the product and extending its shelf life, to obtain desired physical form (e.g. powder, flakes, granules), to reduce volume or weight for transportation and to obtain desired colour, flavour or texture (Methakhup, 2003).

2.7.6.1 Methods of Drying

- Application of hot air (convective or direct drying). Air heating increases the driving force for heat transfer and accelerates drying. It also reduces air relative humidity, further increasing the driving force for drying. In the falling rate period, as moisture content falls, the solids heat up and the higher temperatures speed up diffusion of water from the interior of the solid to the surface (Greensmith, 1998).

- Indirect or contact drying (heating through a hot wall), as drum drying, vacuum drying. Again, higher wall temperatures will speed up drying but this is limited by product degradation or case-hardening (Mujumdar, 1998).

- Freeze drying or lyophilisation is a drying method where the solvent is frozen prior to drying and is then sublimed, i.e., passed to the gas phase directly from the solid phase, below the melting point of the solvent. It keeps biological properties of proteins, and retains vitamins and bioactive compounds (Chemical Engineers' Handbook).

- Sun drying is the old-fashioned way to dry food because it uses the heat from the sun and the natural movement of the air. This process is slow and requires a good deal of care. The food must be protected from insects and covered at night. Sun drying is not as sanitary as other methods of drying (Chemical Engineers' Handbook, 2007).

2.7.6.2 Importance of Drying on Quality of Food Products

The added heat and exposure times of the product at elevated temperatures affect three quality degradations of the food products. These three qualities are in terms of chemical quality such as browning reaction, lipid oxidation, and colour loss; physical quality such as rehydration, solubility, and texture; and nutritional quality such as vitamin loss, protein loss and microbial survival (Methakhup, 2003).

Foods are dried to inhibit microbial development and quality decay. However, the extent of drying depends on product end-use. Cereals and oilseeds are dried after harvest to the moisture content that allows microbial stability during storage. Vegetables are blanched before drying to avoid rapid darkening and also to avoid development of browning in storage. Concerning dried fruits, the reduction of moisture acts in combination with its acid and sugar contents to provide protection against microbial growth (Greensmith, 1998).

CHAPTER THREE

3.0 MATERIALS AND METHODS

3.1 Introduction

For the experiment, 4kg of Asontem cowpea variety was obtained from the Crops Research Institute of the Council for Scientific and Industrial Research (CSIR) at Fumesua, Kumasi. The grains were already clean from chaff and other foreign materials. The necessary quality checks had been performed before the grains were given out. The initial moisture content of the grains was found to be 8.07% (wb). They were acquired as part of grains from the 2010 major harvesting season. They were cleaned again to remove any foreign material present before the commencement of the experiment. All the physical properties were determined at four moisture contents each for rewetting and drying in the range of 8.07–22.45% (wb) with four replications at each moisture content.

3.2 Materials

- Ceramic weighing pans
- Micrometre screw gauge
- Measuring cylinder
- Beaker
- Distilled water
- Electronic balance
- Toluene (C_7H_8)
- Circular wooden plate (20cm diameter)

- Protractor
- Coefficient of friction apparatus (tilting table mechanism)

3.3 The physical Properties

- Length, width and thickness measurements
- Geometric Mean Diameter
- Sphericity
- Volume
- Surface Area
- 1000 Grain Mass
- Bulk Density
- True Density
- Porosity
- Filling Angle of Repose
- Static Coefficient of Friction

3.4 Methods

3.4.1 Moisture Content Determination

The vacuum oven method was used to determine the moisture content of the cowpeas. Four ground samples each weighing 5g was placed in the oven at $130^{oC} \pm 2^{oC}$ for 2 hours. After this, the moisture content on wet basis was determined by dividing the mass of moisture evaporated from the sample by the initial weight of the samples. The average was then recorded.

The size and principal axes of the seeds (minor, intermediate and major) were determined using a BILTEMA micrometre screw gauge of precision 0.01 mm, model Art.16-1140. The mass of seeds was determined by using a 'Mettler Toledo ADP 2100' electronic balance of maximum allowable mass 400g (Mettler Toledo GmbH, Greifensee, Switzerland) to an accuracy of 0.0lg. The moisture content was determined using a 'Memmert' drying oven model 854 Schwabach, made in Germany.

3.4.2 Drying

To decrease the moisture content of grains to a lower one after rewetting, sun drying was carried out for about 6 hours. Grains were spread out evenly on polythene bags and regularly stirred to ensure uniform drying. Samples were taken at regular time intervals and moisture content determination carried out. The grains were allowed to cool down to room temperature for about 2 hours before beginning each experiment.

3.4.3 Rewetting

Several methodologies have been used in literature for preparing rewetted materials. Grain particles are often rewetted by immersion in water during different periods of time depending on the initial moisture content and required moisture content. This was used by Ezeike (1986) cited in Aviara *et al*., (2005), and involved the soaking of different bulk samples of Bambara groundnuts in clean water for a period of one to four hours, followed by spreading out in a thin layer to dry in natural air for about eight hours. After this, the samples were sealed in polyethylene bags and stored in that condition for a further 24 hours to achieve a stable and uniform moisture content of the samples.

However, for this study, samples were conditioned to moisture contents in the range of 8.07% - 22.45% by adding calculated amount of distilled water, sealing in low density polythene bags and stored in a refrigerator at a temperature of 5 degrees for 72 hours. This was done to create a favourable environment for the absorption of water by the grains and also to prevent the action of microbes on the moist seeds. Before starting a test, the required quantities of the samples were taken out of the refrigerator and allowed to warm up to the room temperature for about 2 hours (Singh and Goswami, 1996).

$$Q = \frac{W_i(M_f - M_i)}{100 - M_f} \qquad (16)$$

Where Q is the mass of water to be added

W_i is the initial mass of sample

M_i is the initial moisture content

M_f is the final or desired moisture content

3.5 Dimensional Properties

The dimensions of agricultural materials vary widely with growing season, growing location and variety. Therefore it is best to perform experiments on a large number of specimens from the particular variety grown under cultural practices typical of the region. The mean and standard deviation should be determined and can be compared to other means and standard deviations of other samples (Stroshine and Hamann, 1995)

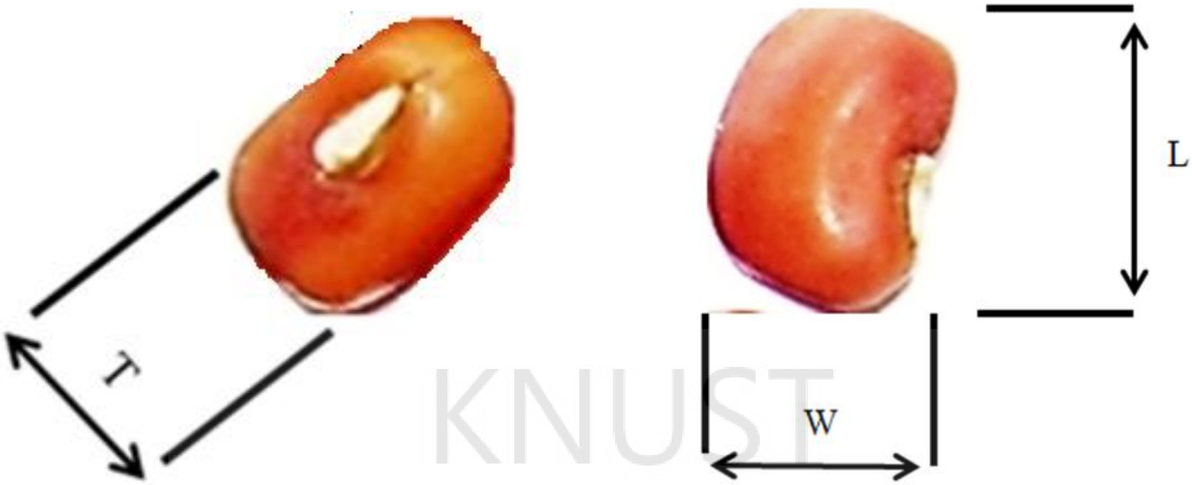

Figure 4 Shape and dimension of cowpea grain

400 grains were picked at random from the bulk grains and their principal dimensions being length (L), width (W) and thickness (T) measured with a micrometre screw gauge at 0.01mm accuracy.

3.6 Geometric Mean Diameter, Sphericity and Surface Area

The length, width and thickness dimensions were recorded by carefully placing each single grain within the micrometre screw gauge. The compressive force of the micrometre was controlled when it made contact with a seed in order to minimize compression.

Based on measurements of the length, width and thickness, data for the geometric mean diameter, sphericity, surface area and volume were determined using the mathematical equations 17, 18, 19 and 20 respectively.

$$D_g = (LxWxT)^{1/3} \quad (17)$$

$$\Phi = \frac{(LxWxT)^{1/3}}{L} \quad (18)$$

$$S = \pi\left(D_g{}^2\right) \quad (19)$$

$$V = \frac{\pi}{6}\left(D_g{}^3\right) \quad (20)$$

3.7 1000 Grain Mass

Four replications of 100 grains were picked at random from each of the four samples and weighed on an electronic balance to 0.01g accuracy. The weight was then multiplied by 10 to give the 1000 grain mass and the average mass was recorded. Similar methods have been used by Wang *et al*. (2007) for Fibered Flaxseed; Tunde-Akintunde and Akintunde (2007) for beniseed; Igbozulike and Aremu (2009) for garcinia kola seeds; Ozdemir and Akinci (2009) for hazelnut; Tavakoli *et al.* (2009) for barley grains and Gharibzahedi *et al*. (2010) for pine nut.

3.8 Bulk Density, True Density and Porosity

The bulk density was determined using the standard test weight procedure. A standard container (beaker) of known weight and volume of 400ml was filled with grains from a height of 15 cm at a constant rate. The grains were then levelled by striking off the top of the container. No additional manual compaction was done. The total weight of grains and cylinder was recorded. Bulk density was determined as the ratio of the mass of grains only to the volume occupied by the grains (volume of container).

For true density, 100 grains were picked at random from each sample and the mass determined. Toluene was poured into a measuring cylinder and the volume recorded. The grains were then used to displace toluene in the measuring cylinder. The true density was found as an average of the ratio of the mass of grains to the volume of toluene displaced by grains. Toluene (C_7H_8) was used in place of water because it is absorbed by seeds to a lesser extent. Also, its surface tension is low, so that it fills even shallow dips in a seed and its dissolution power is low (Aydın, 2002 cited in Kabas *et al*., 2007; Demir *et al*., 2002 cited in Kabas *et al*., 2007).

Similar methods have been used by Tavakoli *et al.* (2009) for barley grains; Ozturk *et al.* (2010) for new common beans and Khodabakhshian *et al*. (2010) for sunflower seeds and kernels.

The porosity of the grains was calculated from the values of the bulk and particle densities using the mathematical expression

$$\varepsilon = \frac{\ell_p - \ell_b}{\ell_p} x100 \qquad (21)$$

Where ℓ_p is the true density and ℓ_b is the bulk density.

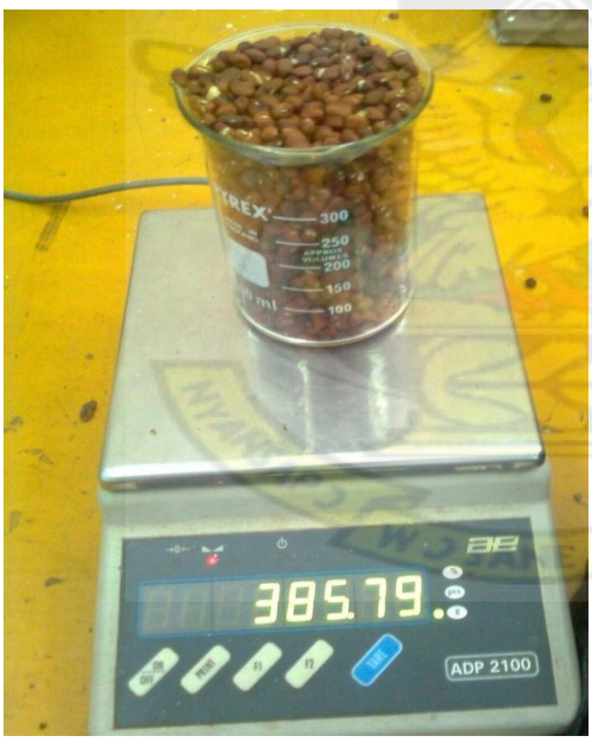

Figure 5 Bulk Density Determination set up

3.9 Filling Angle of Repose

The angle of repose, the angle between the horizontal and natural slope of the grain when it is piled has also been determined by other researchers using a topless and bottomless cylinder of 150 mm diameter and 250 mm height. A removable circular plate is placed under the cylinder, the sample is poured into the cylinder and then the cylinder is slowly raised allowing the sample to form a cone on the circular plate. The height of cone is measured and the angle of repose calculated by dividing the height of the cone by the radius of the circular plate (Akaaimo and Raji, 2006 for proposis Africana seeds and Ozturk *et al*., 2010, for Common Bean cv. 'Kantar-05').

In determining the filling angle of repose (Θ_f) for asontem, grains were poured from a height of 15cm unto a circular wooden plate of radius 10cm. The height of the heap was measured and the angle of repose was determined from the equations 22 and 23

$$\text{Tan}\ \gamma = \frac{h}{r} = \frac{h}{10} \quad (22)$$

$$\gamma = \tan^{-1}\frac{h}{r} \quad (23)$$

Where h, is height of the heap and r, is the radius of the plate.

Similar methods have been used by Bart-Plange and Baryeh (2002) for category B cocoa beans and Bart-Plange *et al*. (2005) for obatanpa maize variety.

3.10 Static Coefficient of Friction

The static coefficient of friction (μ) of the grains was determined against three structural surfaces namely; mild steel, plywood and rubber. The tilting table apparatus was used which includes the following; a frictionless pulley fitted on a frame, a PVC container, loading pan and the testing surfaces. The friction surface is part of a special construction hinged at one end and lifted at the other end by means of a bolt and nut arrangement.

A cylindrical PVC container, hollow at both ends of dimension 100mm diameter and 50mm height was filled with grains and lifted slightly about 2mm, so as not to touch the friction surface. The surface was gradually raised with the screw device until the cylinder along with the sample just begun to slide down. The angle of inclination which is the angle between the friction surface and the horizontal was read from the protractor. The coefficient of friction was calculated from the equation

$$\mu = \tan\theta \quad (24)$$

Where μ = coefficient of static friction

θ = angle of tilt of table

a. aerial view

b. side view

Figure 6 Static Coefficient of Friction set up

3.11 Experimental Design and Data Analysis

All tests were conducted at four levels of moisture content with four replications at each level. The experimental design used was the completely randomised design (CRD). The relationship between physical properties of cowpeas and levels of moisture content was determined. Analysis of variance (ANOVA) was carried out on the data using Microsoft Excel version 2010 at a significance level of 5%. The Least Significant Difference (LSD) was determined where a significance difference existed between treatments means. The Regression Coefficient (R^2), the mean square error (MSE) and the variation of predicted values (SS) were used to evaluate the fitness of models to the experimental data.

CHAPTER FOUR

4.0 RESULTS AND DISCUSSION

4.1 Linear Dimensions

The average values of the linear dimensions presented in Table 6 show that during rewetting, as moisture content increased from 8.07% wb to 22.54% wb, length increased non-linearly from 7.00mm to 7.29mm, width from 6.27mm to 6.33mm and thickness from 4.54mm to 4.69mm. Length, width and thickness dimensions showed significant differences at 5%. The average length at 8.07% wb was found to be significantly different ($P<0.05$). Again significant differences were recorded for the length between 8.07% wb and 22.54% wb; and 11.45% wb and 22.54% wb for the average width. Thickness values recorded significant differences among all the treatment means with high significance between 8.07% wb and 22.54% wb; and 11.45% wb and 22.54% wb.

Table 6 Average linear dimensions for rewetting and drying under varying moisture contents

Rewetting(%wb)	L(mm)	W(mm)	T(mm)	Drying(%wb)	L(mm)	W(mm)	T(mm)
22.54	7.29	6.33	4.69	19.00	8.16	6.36	4.77
17.20	7.23	6.28	4.61	15.13	7.43	6.34	4.77
11.45	7.20	6.25	4.58	11.50	7.37	6.33	4.66
8.07	7.00	6.27	4.54	9.58	7.11	6.28	4.61

Under drying conditions, the length decreased non-linearly from 8.16mm to 7.11mm, width from 6.36mm to 6.28mm and thickness from 4.77mm to 4.61mm. High significant differences were recorded among all the treatment means except 11.50 and 15.13% wb for length ($P<0.05$). Significant difference was recorded between 9.58 and 19.00% wb for the average width. Thickness data analysis showed significant differences between all treatment means except 15.13 and 19.00% wb ($P<0.05$).

Table 7 Equations describing rewetting and drying trends

Rewetting Equations	R^2	Drying Equations	R^2
$L=-0.0017M^2 + 0.0709M + 6.5659$	0.8968	$L=0.0102M^2 - 0.19M + 8.0688$	0.9436
$W=0.0007M^2 - 0.0161M + 6.3532$	0.9758	$W=-0.001M^2 + 0.0353M + 6.0387$	0.8983
$T=0.0003M^2 + 0.0002M + 4.5242$	0.9750	$T=-0.0026M^2 + 0.0928M + 3.9512$	0.9739

Where M represents the moisture content (%wb)

The increase in the linear dimensions can be attributed to the addition of moisture causing a volumetric expansion of the grains. During rewetting, length had the highest increase in dimension of 4% from 4.54mm to 4.69mm, followed by thickness of 3% and then width of almost 1%. However, a sharp decrease in length (from 8.16mm to 7.11mm), representing a 14.7% decrease was recorded under drying conditions. For drying, length recorded the highest decrease in dimension followed by thickness (3.4%) and then width (1.2%).

Similar results have been reported by Deshpande *et al.*(1993) for soybean, Altuntas and Yildiz (2007) for faba bean, Ahmadi *et al*. (2009) for fennel seeds and Gharib-Zahedi *et al*. (2010) for black cumin seeds.

Despande *et al.* (1993), however, found the expansion of soybean seeds to be largest along their thickness in comparison with their other two principal axes. This could be due to the different cell arrangements in the grains.

4.2 Geometric Diameter, Sphericity, Surface Area and Volume

4.2.1 Geometric Mean Diameter

The geometric mean diameter, sphericity, surface area and volume were calculated from the values of the length, width and thickness.

Values for rewetting increased with increasing moisture content while that for drying decreased with decreasing moisture content. However the decrease in geometric mean diameter during drying (from 6.27mm to 5.90mm) of 0.37mm was more than the increase in geometric mean diameter for rewetting (from5.83mm to 5.99mm) of 0.15mm.

The equations describing drying and rewetting trends are as follows:

Drying $D_g = 0.0012M^2 - 0.0024M + 5.7802$ $R^2 = 0.9727$ (25)

Rewetting $D_g = -0.0003M^2 + 0.0183M + 5.7086$ $R^2 = 0.9563$ (26)

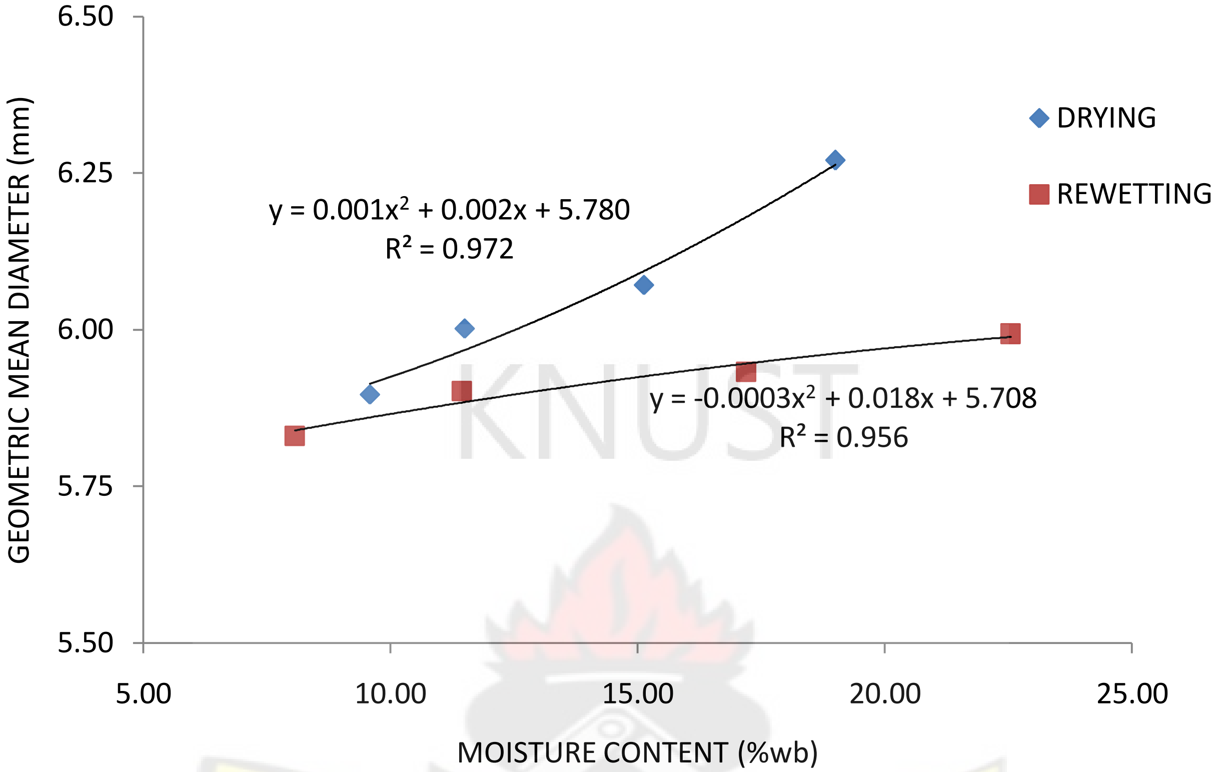

Figure 7 Variation of geometric mean diameter with moisture content for drying and rewetting

Geometric diameter values for rewetting showed significant difference among all treatment means except 11.45 and 17.20% wb ($P<0.05$).

Bart-Plange *et al*. (2006) found the geometric mean diameter of maize to increase non-linearly with increasing moisture content. Tavakoli *et al*. (2009) and Ozturk *et al*. (2009) found the geometric mean diameter to increase linearly with increasing moisture content for barley grains and common beans respectively.

4.2.2 Sphericity

During rewetting, sphericity reduced from 0.8371 at 8.07% wb to 0.8217 at 11.45% wb and increased to 0.8258 at 22.45% wb. The variation is almost linear between 11.45% and 22.54% seed moisture content. This suggests that as the seed moisture content increased from 8.07% to 22.54%, its shape deviated from a sphere and started approaching the shape of a sphere again between 17.20% and 22.54% wb. This is due to the changes of the three major dimensions as the grains absorb moisture. Also an increase in sphericity may indicate that the rate of increase of width and thickness is higher compared to the length, giving the grain the assumed spherical shape. 8.07% wb showed significant difference ($P<0.05$).The graph for rewetting cannot be described as increasing or decreasing, indicating that moisture content may not have had much effect on the sphericity; there is little difference in sphericity relative to the moisture content increase.

Table 9 Average Sphericity (Φ) for drying and rewetting under varying moisture contents

Moisture Content (%wb)	Φ Drying	Moisture Content (%wb)	Φ Rewetting
19.00	0.772949	22.45	0.825812
15.13	0.821628	17.20	0.822679
11.50	0.819021	11.45	0.821729
9.58	0.833272	8.07	0.837102

However, during drying, there was a sharp decrease from 0.8333 at 9.58% wb to 0.8216 at 15.13% wb and then a further decrease to 0.7729 at 19.00%wb. Significant differences were recorded among all treatment means except 11.50% wb and 15.13% wb.

The graph for drying can be described as decreasing non-linearly and from this it can be said that the Asontem variety approaches the shape of a sphere as moisture content increases.

The equations describing drying and rewetting trends are as follows:

Drying $\Phi = -0.0008M^2 + 0.0184M + 0.7289$ $R^2 = 0.9134$ (27)

Rewetting $\Phi = 0.0002M^2 - 0.0069M + 0.8778$ $R^2 = 0.8206$ (28)

According to Baryeh and Mangope (2002), sphericity reduced from 0.91 to 0.82 and increased to 0.84 for the seed moisture range considered for pigeon pea. This suggests that as the seed moisture content increased from 5% to 20% its shape deviated more and more from the shape of a sphere and started approaching a sphere again between 20% and 25% seed moisture content.

Also, the sphericity of the grains increased linearly from 47.55% to 49.35% as the moisture content increased from 7.34% to 21.58% (d.b.) for barley grains. This suggests that as moisture content of the grains increases, its shape approaches a sphere (Tavakoli *et al*., 2009).

The sphericity of groundnuts was found to be decreasing non-linearly with increasing moisture content (Baryeh, 2001). Deshpande *et al.* (1993) however found the sphericity of soybeans to be increasing linearly with increasing moisture content.

Other researchers have found sphericity to increase with increasing moisture content. These include Ahmadi *et al.* (2009) for fennel seeds and Altuntas *et al.* (2005) for fenugreek seeds.

4.2.3 Surface Area

The surface area was found to be increasing non-linearly with increasing moisture content for both rewetting and drying. The surface area increased from 107.03mm^2 at 8.07% wb to 113.09mm^2 at 22.54% wb for rewetting. The increase in surface area during rewetting may be attributed to the increase in the three linear dimensions. Significant differences were recorded among all treatment means except 17.20 and 22.54% wb ($P<0.05$). A high significant difference was recorded between 8.07 and 22.54% wb; and 8.07 and 17.20% wb.

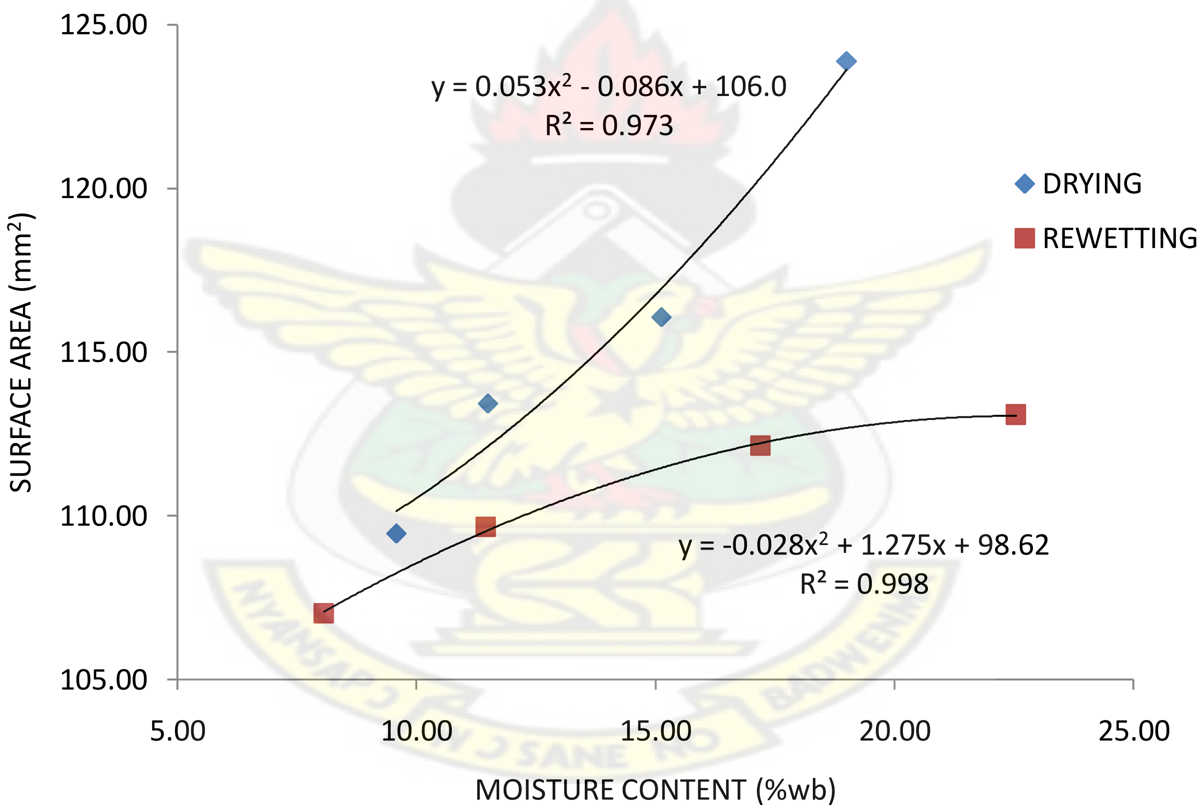

Figure 8 Variation of surface area with moisture content for drying and rewetting

However, drying showed a higher reduction in surface area compared to rewetting. Significant differences were found to exist among all the treatment means for drying with exceptionally high significance between 9.58 and 19.00% wb.

The equations describing drying and rewetting trends are as follows:

Drying $S_A = 0.0532M^2 - 0.0868M + 106.09 \quad R^2 = 0.9733$ (29)

Rewetting $S_A = -0.0282M^2 + 1.2755M + 98.627 \quad R^2 = 0.9987$ (30)

Deshpande *et al*. (1993), however, found the surface area of soybeans to increase linearly with grain moisture content up to 24% and Baryeh (2001) reported a non-linear increase with increasing moisture content.

4.2.4 Volume

The volume was found to increase non-linearly with increasing moisture content for both rewetting and drying as shown in figure 9.

Under rewetting conditions, the volume increased from 104.45mm^3 at 8.07% wb to 113.45mm^3 at 22.54% wb, representing an 8.62% increase in the initial volume. Under drying conditions, the volume decreased from 130.23mm^3 at 19.00% wb to 109.07mm^3 at 9.58% wb, representing a decrease of 16.30%. Values for drying were higher than those for rewetting.

Significant differences existed among all treatment means except 11.45 and 17.20% wb for rewetting but drying conditions showed significant differences among all treatment means.

Ozturk (2009) also recorded an increase in volume with increasing moisture content for common beans cv. 'Elkoca-05' likewise Gharib-Zahedi *et al.* (2010) for black cumin (*Nigella sativa L.*) seeds.

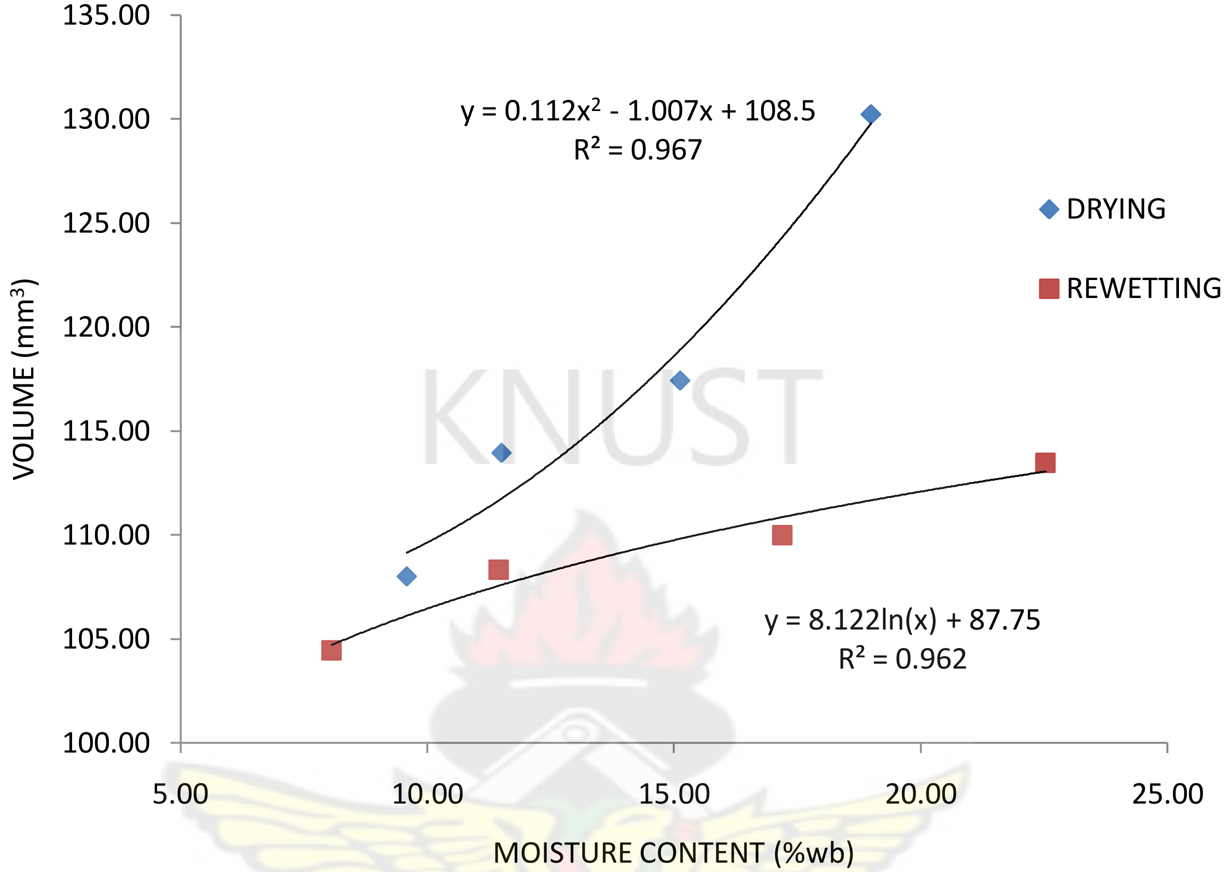

Figure 9 Variation of volume with moisture content for drying and rewetting

The equations describing drying and rewetting trends are as follows:

Drying $V = 0.112M^2 - 1.0078M + 108.54$ $R^2 = 0.9679$ (31)

Rewetting $V = 8.1229\text{In}(M) + 87.7590$ $R^2 = 0.9624$ (32)

4.3 1000 Grain Mass

Figure 10 shows that for both rewetting and drying, 1000 grain mass increased non-linearly with increasing moisture content. Rewetting from 8.07% wb to 22.54% wb caused an increase in mass from 120.15g to 130.58g whiles drying recorded a reduction in mass from 132.85g to 120.93g. An increase in mass of 8.67% was recorded during rewetting whiles a reduction in mass of 9.86% was recorded during drying.

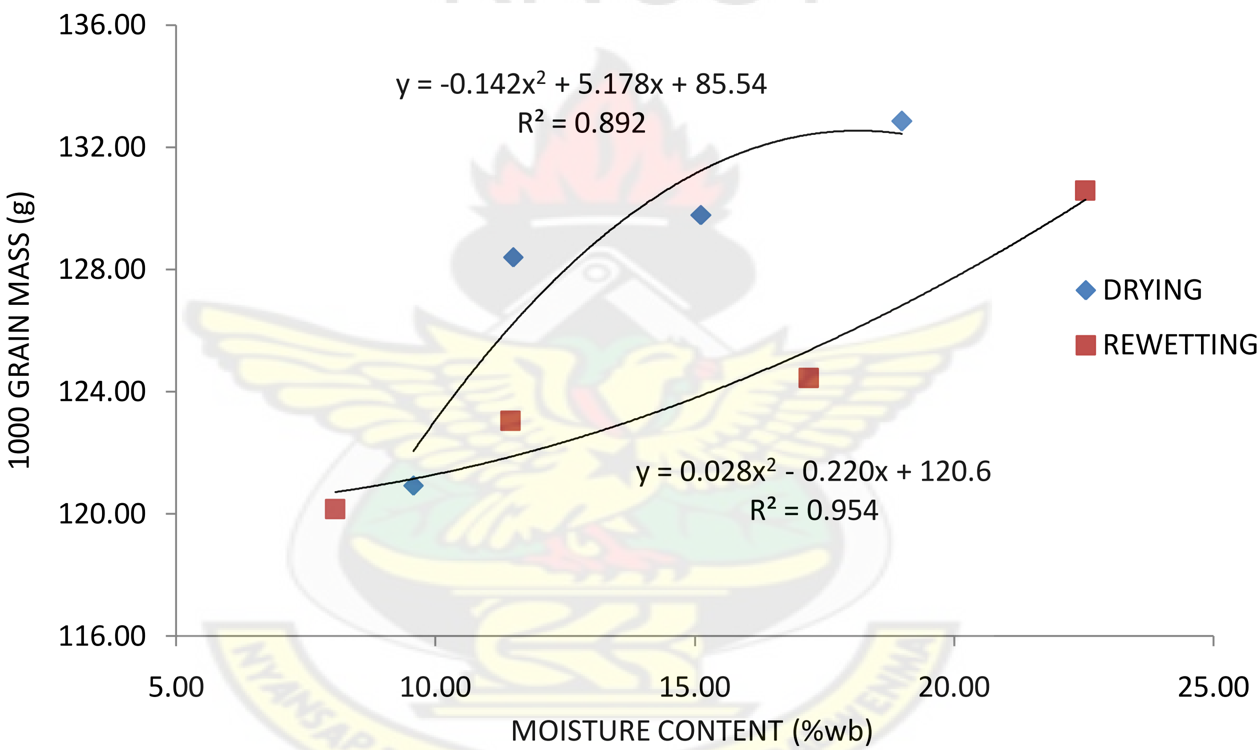

Figure 10 Variation of 1000 grain mass with moisture content for drying and rewetting

The variation in 1000 grain mass for drying and rewetting can be expressed as follows:

Drying $1000_m = -0.1426M^2 + 5.1784M + 85.54$ $R^2 = 0.8921$ (33)

Rewetting $1000_m = 0.0288M^2 - 0.2203M + 120.62$ $R^2 = 0.9548$ (34)

A linear increase in 1000 grain mass has been recorded by Singh and Goswami (1996) for soybean; Baryeh and Mangope (2002) for QP-38 variety pigeon pea; Wang *et al.* (2007) for flaxseed; Altuntas and Yildiz (2007) for faba bean; Tavakoli *et al*. (2009) for barley grains and Gharib-Zahedi *et al.* (2010) for black cumin.

Values for drying were found to be significantly different at 5%. Significant differences were recorded among moisture content 9.75% wb and 11.50%wb; and 9.75% wb and 19.00%wb.

Significant differences were found to exist among all the moisture content levels for rewetting except 1.45% wb and 17.20% wb.

4.4 Bulk Density

During rewetting, the values decreased non-linearly with increasing moisture content. It decreased from 752.95kg/m^3 at 8.07% wb to 682.93kg/m^3 at 22.54% wb. Drying gave an inconclusive description of the nature of the values; at 15.13% wb and 11.50% wb the bulk density increased to 712.92kg/m^3 and 740.50 kg/m^3 respectively but then decreased to 638.07 kg/m^3 at 9.58% wb. The decrease in bulk density may be attributed to a higher volumetric increase resulting in more pore spaces between grains compared to an increase in mass; hence there are fewer grains occupying the same volume.

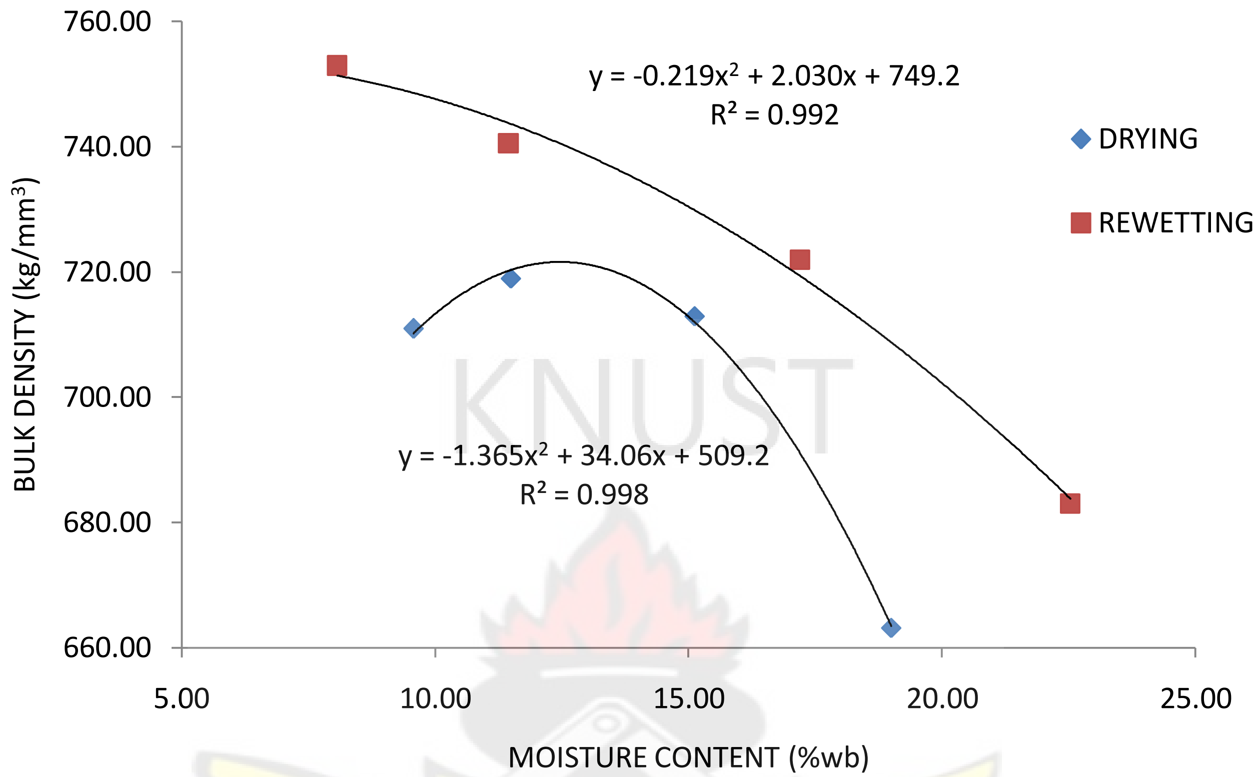

Figure 11 Variation of bulk density with moisture content for drying and rewetting

The variation with moisture content for drying and rewetting can be expressed respectively as follows:

Drying $\ell_b = -1.3656M^2 + 34.06M + 509.24$ $R^2 = 0.9983$ (35)

Rewetting $\ell_b = -0.219M^2 + 2.0307M + 749.24$ $R^2 = 0.9927$ (36)

The decreasing trend of bulk density has been reported by Deshpande *et al*. (1993) for soybean within the moisture range of 8% db to 25% db; Ozturk *et al.* (2009) for new common bean cv. 'Elkoca-05' within the moisture range of 7.50% db and19.85% db; and Tunde-Akintunde and Akintunde (2007) for beniseed within the moisture range of 3.5% db and 25.0 % 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.

Values for rewetting and drying were found to be significantly different at 5%. Significant differences were found to exist among all the four levels of moisture content for rewetting.

4.5 True Density

From figure 12, it can be realized that an increase in moisture content led to a non-linear decrease in true density. True density for both drying and rewetting decreased non-linearly with increasing moisture content from 1219.90 kg/m^3 to 1161.39 kg/m^3 for rewetting and from 1185.92 kg/m^3 to 1063.80 kg/m^3 for drying.

The variation with moisture content for drying and rewetting can be expressed respectively as follows:

Drying $\ell_g = -1.4677M^2 + 28.285M + 1054.5$ $R^2 = 0.9861$ (37)

Rewetting $\ell_g = -0.222M^2 + 2.6995M + 1213.1$ $R^2 = 0.9991$ (38)

Only values for drying were found to be significantly different at 5%. Significant differences were found to exist between the pairs 19.00 and 9.75% wb; and 19.00 and 15.10% wb. Rewetting values were not significant.

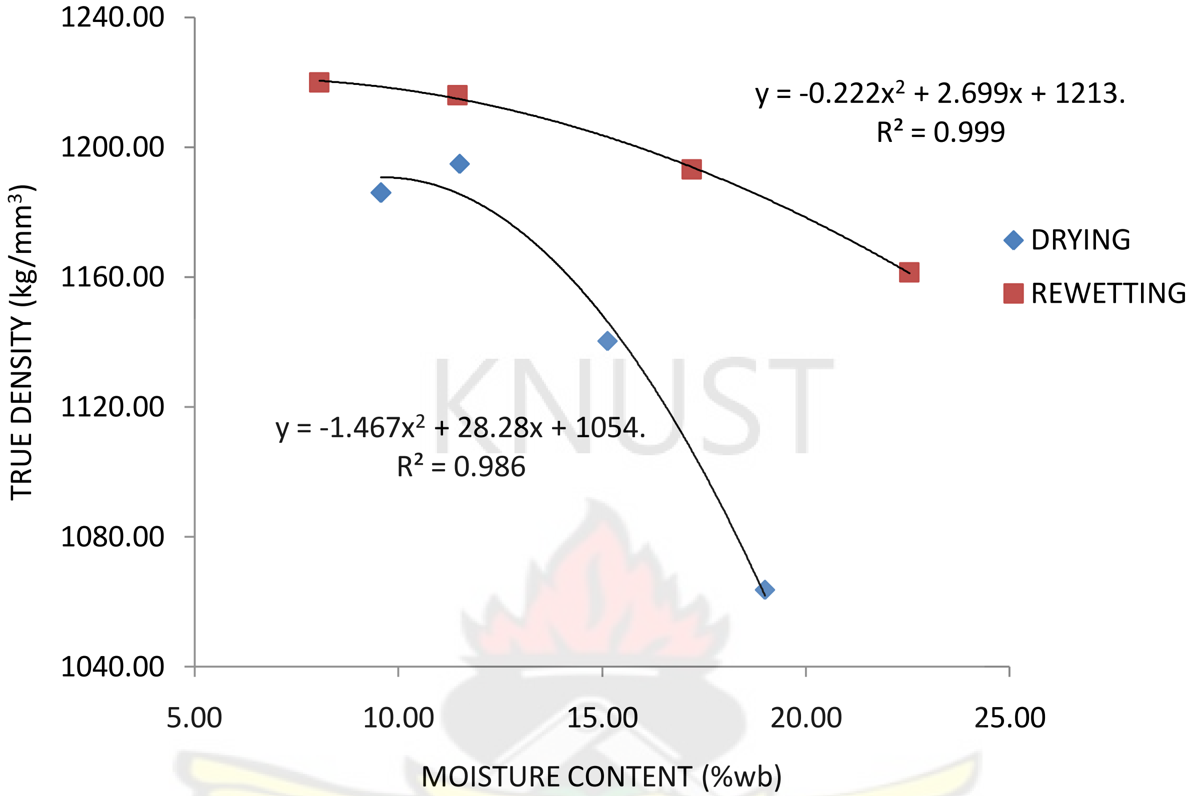

Figure 12 Variation of true density with moisture content for drying and rewetting

The true density decreased with increasing seed moisture content as reported by Deshpande and Ojha (1993) for soybeans; Joshi *et al*. (1993) for pumpkin seeds; and Suthar and Das (1996) for karingda seeds. These seeds thus have lower weight increase in comparison to volume increase as their moisture content increase.

However, other researchers such as Wang *et al.* (2007) for flaxseed; Singh and Goswami (1996) for cumin seeds; Gupta and Das (1998) for sunflower seeds and Gharib-Zahedi *et al.* (2010) for black cumin found the true density to increase with increasing moisture content.

4.6 Porosity

Table 15 shows an increase in porosity with increasing moisture content for rewetting from 38.13% to 41.16%. On the other hand, for drying, porosity decreased non-linearly from 39.98% at 9.58% to 37.55% at 19.00% wb.

The increase in porosity during rewetting can be attributed to the expansion and swelling of seeds that might have resulted in more voids space between the seeds and increased the bulk volume. This is also exhibited in the reduction of bulk density with increase in moisture content. Again, the increase may be due to decrease in the cohesion of the bulk grains as a result of an increase in moisture content.

Table 15 Average Porosity for drying and rewetting under varying moisture contents

Moisture Content (%wb)	(ε) Drying	Moisture Content (%wb)	(ε) Rewetting
19.00	37.5483	22.45	41.1580
15.13	37.9677	17.20	39.8677
11.50	39.7960	11.45	39.0664
9.58	39.9757	8.07	38.1326

The variation with moisture content for drying and rewetting can be expressed respectively as follows:

Drying $\varepsilon = 0.0163x^2 - 0.7551x + 45.917$ $R^2 = 0.9392$ (39)

Rewetting $\varepsilon = 0.1994M + 36.602$ $R^2 = 0.9859$ (40)

Values for rewetting and drying were not significant ($P<0.05$)

Tavakoli *et al*. (2009) found the porosity of soybean grains to increase linearly from 43.29 to 44.48 % (P<0.05) in the specified moisture levels. Both bulk and true densities of soybean grains decreased with increase in moisture content, whereas the porosity increased during rewetting. Similar results have been reported by Wang *et al.* (2007) for flaxseed; Gharib-Zahedi *et al.* (2010) for black cumin and Ahmadi *et al.* (2009) for fennel seeds

However, a linear decrease in porosity has been reported by other researchers including Deshpande *et al*. (1993) for soybean; Joshi *et al*. (1993) for pumpkin seeds; Tunde-Akintundeand Akintunde (2007) for beniseed and Tavakoli *et al.* (2009) for barley grains.

4.7 Filling Angle of Repose

The filling angle of repose for both rewetting and drying increased non-linearly with increasing moisture content. The values for rewetting increased from a low of 27.81^0 at 8.07% wb to 32.31^0 at 22.54% wb and that for drying increased from 27.91^0 at 9.58% wb to 29.35^0 at 19.00% wb.

The increase in filling angle may be due to an increase in surface roughness as well as size of individual grains which affect their ability to form a heap.

The variation with moisture content for drying and rewetting can be expressed respectively as follows:

Drying $\theta_f = -0.0188M^2 + 0.701M + 22.853$ $R^2 = 0.9753$ (41)

Rewetting $\theta_f = 0.0063M^2 + 0.0945M + 26.867$ $R^2 = 0.9599$ (42)

Results obtained for rewetting showed significant difference at 5%. Significant differences were recorded among all the moisture levels. Results for drying were not significant.

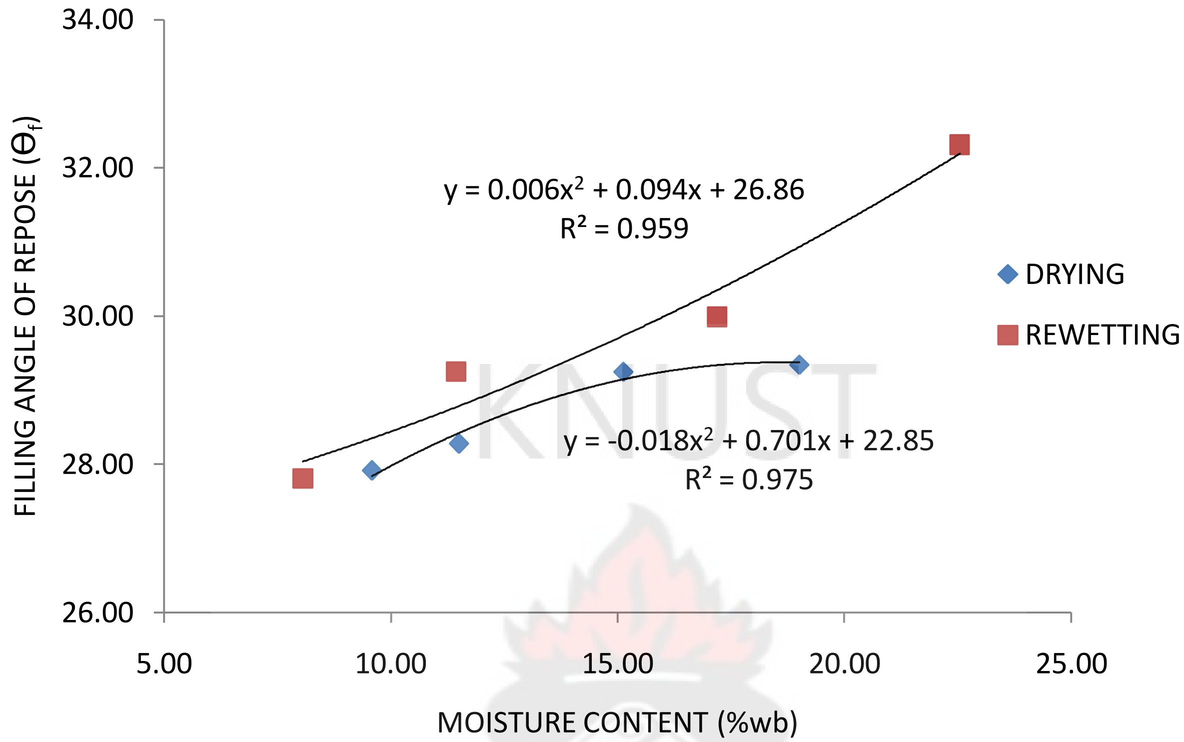

Figure 13 Variation of filling angle of repose with moisture content for drying and rewetting

According to Tavakoli *et al.* (2009), values for the filling angle of repose increased from 31.16° to 36.90° with an increase in the 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.

According to Gharibzahedi *et al*. (2010), it was observed that the angle of repose increased with an increase in moisture content. It increased from 35.4° to 39° in the moisture range from 6.3% to 20.1% (d.b.) ($P < 0.05$).

At higher moisture content nuts might tend to stick together due to the plasticity effect (stickiness) over the surface of the nuts resulting in better stability and lower flow ability thereby increasing the angle of repose (Irtwange and Igbeka, 2002).

Similar results have been reported by Singh and Goswami (1996) for cumin seed; Baryeh (2002) for millet; Altuntas *et al.* (2005) for fenugreek; Baryeh (2001) for bambara groundnut and Joshi *et al.* (1993) for pumpkin seeds.

4.8 Coefficient of Static Friction

4.8.1 Plywood

The coefficient of friction for plywood increased non-linearly with increasing moisture content during rewetting from 0.29 at 8.07% wb to 0.41 at 22.54% wb. Drying showed an increase from 0.29 at 9.58% wb to 0.41 at 15.13% wb and then decreased slightly to 0.36 at 19.00% wb.

The variation with moisture content for drying and rewetting can be expressed respectively as follows:

Drying $\mu_p = -0.0029M^2 + 0.0933M - 0.349$ $R^2 = 0.8326$ (43)

Rewetting $\mu_p = 0.0011M^2 - 0.0242M + 0.4188$ $R^2 = 0.9943$ (44)

Results obtained for rewetting and drying showed significant difference at 5%. Significant differences were recorded among all the moisture levels except 8.07% wb and 11.45% wb for rewetting. Significant differences were recorded among all the moisture levels except 9.58% wb and 11.50% wb for drying.

4.8.2 Mild steel

The variation of coefficient of static friction with moisture content during rewetting on mild steel was found to increase non-linearly with increasing moisture content from 0.30 at 8.07% wb to 0.45 at 22.54% wb. Drying also showed a non-linear increase with increasing moisture content; however, there was a sharp increase from 0.28 at 9.58% wb to 0.38 at 15.13% wb.

The variation with moisture content for drying and rewetting can be expressed respectively as follows:

Drying $\mu_m = -0.0018M^2 + 0.0599M - 0.1434$ $R^2 = 0.7659$ (45)

Rewetting $\mu_m = 0.0012M^2 - 0.0263M + 0.4394$ $R^2 = 0.9956$ (46)

Rewetting values showed a high level of significant difference at 5% among all the levels of moisture content.

4.8.3 Rubber

For rubber, the coefficient of static friction increased from 0.25 at 8.07% wb to 0.32 at 22.54% wb. Drying on the other hand, recorded an almost linear increase in static coefficient of friction with increasing moisture content from 0.21 at 9.58% wb to 0.33 at 15.13% wb and then decreased sharply to 0.31 at 19.00% wb.

The variation with moisture content for drying and rewetting can be expressed respectively as follows:

Drying $\mu_r = -0.0024x^2 + 0.0806x - 0.3388$ $R^2 = 0.9547$ (47)

Rewetting $\mu_r = 0.0004M^2 - 0.007M + 0.2864$ $R^2 = 0.9977$ (48)

Rewetting and drying values were both statistically significant. All the moisture levels recorded significant differences

Table 16 Static coefficient of friction for drying and rewetting under varying moisture contents

Rewetting	Plywood	Mild steel	Rubber	Drying	Plywood	Mild steel	Rubber
22.54	0.411762^{a}	0.453199^{a}	0.324920^{a}	19.00	0.363970^{a}	0.356674_{a}	0.312998_{a}
17.20	0.321178^{b}	0.345987^{b}	0.278452^{b}	15.13	0.414214_{b}	0.383864_{b}	0.334595^{b}
11.45	0.275070^{c}	0.289202^{c}	0.258618^{c}	11.50	0.308213_{c}	0.282029_{c}	0.251739^{c}
8.07	0.295265^{d}	0.308213^{d}	0.253968^{d}	9.58	0.292420_{d}	0.286745_{d}	0.218035^{d}

Means in columns with same letters are not significantly different at $p \leq 0.05$

4.8.4 Overview of Coefficient of Static Friction

The coefficient of static friction for mild steel recorded the highest value followed by plywood and lastly rubber. The increasing coefficient may be due to smoother surface of rubber compared to plywood and mild steel. The increase in static coefficient of friction with increasing moisture content may be due to the increase in weight of grains from moisture absorption which reduces its ability to slide. The grains also possibly become rougher on the surface as the moisture content increases making the coefficient of friction increase.

The static coefficient of friction increased with increase in moisture content on all surfaces. The design of the dimension of hoppers, bunker silos and other bulk solid storage and handling structures should ensure non-arching phenomena. The higher the coefficient of friction is, the lower the mobility coefficient is, hence requiring larger hopper opening, larger hopper side wall slope and steeper angle of inclination in inclined grain transporting equipment like chutes (Irtwange and Igbeka, 2002).

According to Fathollahzadeh *et al.* (2009) the reason for the increased coefficient of static friction of barberry at higher moisture content may be due to the higher moisture present in the barberry offering a higher cohesive force on the surface of contact.

Bart-Plange *et al.* (2005); Bart-Plange *et al*. (2006); Tavakoli *et al*. (2009) and Gharib-Zahedi *et al*. (2010) also found increasing linear relationships for cowpeas, maize, barley and black cumin grains respectively on plywood, rubber, glass and galvanized iron sheet.

CHAPTER FIVE

5.0 CONCLUSION AND RECOMMENDATIONS

5.1 CONCLUSION

The investigation of selected physical properties of Asontem cowpea variety revealed the following:

1. All linear dimensions, geometric mean diameter, surface area, volume and 1000 grain mass increased non-linearly with increasing moisture content.
2. During drying, the geometric mean, surface area and volume decreased non-linearly with decreasing moisture content from 5.90mm to 6.27mm, 110.77mm^2 to 123.89mm^{2}and 109.07mm3 to 130.23mm^3 respectively.
3. The geometric mean, surface area and volume increased non-linearly with increasing moisture content during rewetting from 5.84mm to 5.99mm, 107.93mm^2 to 113.09mm^2 and 106.79mm^3 to 113.45mm^3 respectively.
4. The bulk density decreased non-linearly with increase in moisture content from 710.93kg/m^3 to 663.12 kg/m^3 under drying conditions and from 752.95 kg/m^3 to 682.93 kg/m^3 under rewetting conditions.
5. The true density decreased non-linearly with decreasing moisture content from 1185.92 kg/m^3 to 1063.80 kg/m^3 under drying conditions and increased with increasing moisture content from 1219.90 kg/m^3 to 1161.39 kg/m^3 under rewetting conditions.
6. The porosity increased linearly during rewetting from 38.13% to 41.16%. However, it decreased non-linearly from 39.98% to 37.55% during drying.

7. The 1000 grain mass increased non-linearly from 120.93g to 132.85g during drying and from 120.15g to 130.58g during rewetting.
8. The filling angle of repose varied from 27.92^0 to 29.35^0 in the moisture range of 9.58% wb and 19.00% wb under drying conditions; and from 27.81 to 32.31 in the moisture range of 8.07% wb and 22.54% wb during rewetting.
9. The static coefficient of friction for rewetting increased non-linearly with increasing moisture content from 8.07% wb to 22.54% wb on all the three surfaces namely plywood (0.29 to 0.36), mild steel (0.28 to 0.35) and rubber (0.22 to 0.31). There was also a non-linear increase with increasing moisture content from 9.58% wb to 19.00% wb on all the three surfaces, plywood (0.29 to 0.41), mild steel (0.31 to 0.45) and rubber (0.25 to 0.32) during rewetting. For both conditions, mild steel offered the maximum friction followed by plywood and then rubber.

5.2 RECOMMENDATIONS

1. With more than twelve cowpea varieties in Ghana, the research should be conducted on the other varieties in order to provide data on their physical properties.
2. For the coefficient of friction, further investigations should be conducted on other surfaces such as aluminium, glass and different rubber thicknesses.
3. The research should be repeated; drying the grains initially and then rewetting.

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APPENDICES

Appendix 1: Averages of Physical properties under varying moisture content

Table 8 Average Geometric Mean Diameter under varying moisture contents

Moisture Content (%wb)	D_g Drying	Moisture Content (%wb)	D_g Rewetting
19.00	6.270376	22.54	5.993382
15.13	6.071284	17.20	5.932606
11.50	6.002231	11.45	5.901782
9.58	5.896758	8.07	5.830643

Table 10 Average Surface Area (S_a) under varying moisture contents

Moisture Content (%wb)	S_a Drying (mm^2)	Moisture Content (%wb)	S_a Rewetting (mm^2)
19.00	123.885670	22.54	113.089363
15.13	116.070792	17.20	112.135521
11.50	113.425215	11.45	109.657806
9.58	109.460708	8.07	107.025033

Table 11 Average Volume for rewetting and drying under varying moisture contents

Moisture Content (%wb)	Drying (mm^3)	Moisture Content (%wb)	Rewetting (mm^3)
19.00	130.233246	22.54	113.449189
15.13	117.440477	17.20	109.990900
11.50	113.957165	11.45	108.327034
9.58	108.016777	8.07	104.446354

Table 12 Average 1000 Grain Mass for drying and rewetting under varying moisture contents

Moisture Content (%wb)	1000_m Drying	Moisture Content (%wb)	1000_m Rewetting
19.00	132.8500	22.54	130.5750
15.13	129.7750	17.20	124.4421
11.50	128.4000	11.45	123.0500
9.58	120.9250	8.07	120.1500

Table13 Average Bulk Density for drying and rewetting under varying moisture contents

Moisture Content (%wb)	ℓ_b Drying (kg/m^3)	Moisture Content (%wb)	ℓ_b Rewetting (kg/m^3)
19.00	663.120	22.54	682.929
15.13	712.921	17.20	721.905
11.50	718.929	11.45	740.500
9.58	710.929	8.07	752.950

Table 14 Average True Density for drying and rewetting under varying moisture contents

Moisture Content (%wb)	ℓ_g Drying (kg/m^3)	Moisture Content (%wb)	ℓ_g Rewetting (kg/m^3)
19.00	1063.801	22.54	1161.393
15.13	1140.304	17.20	1193.042
11.50	1194.881	11.45	1215.885
9.58	1185.921	8.07	1219.897

Table 16 Average Filling Angle of Repose for drying and rewetting under varying moisture contents

Moisture Content (%wb)	Θ_f Drying (^{0})	Moisture Content (%wb)	Θ_f Rewetting (^{0})
19.00	29.3472	22.54	32.3102
15.13	29.2460	17.20	29.9877
11.50	28.2783	11.45	29.2479
9.58	27.9160	8.07	27.8104

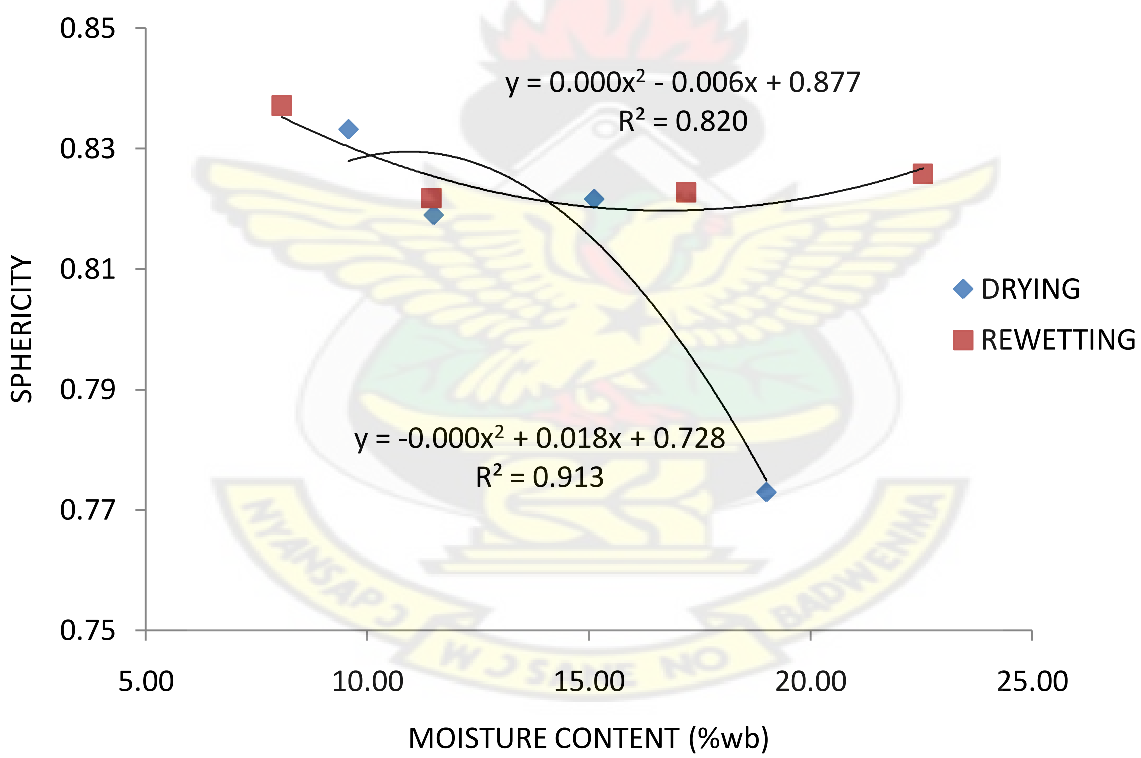

Figure 14 Variation of sphericity with moisture content for drying and rewetting

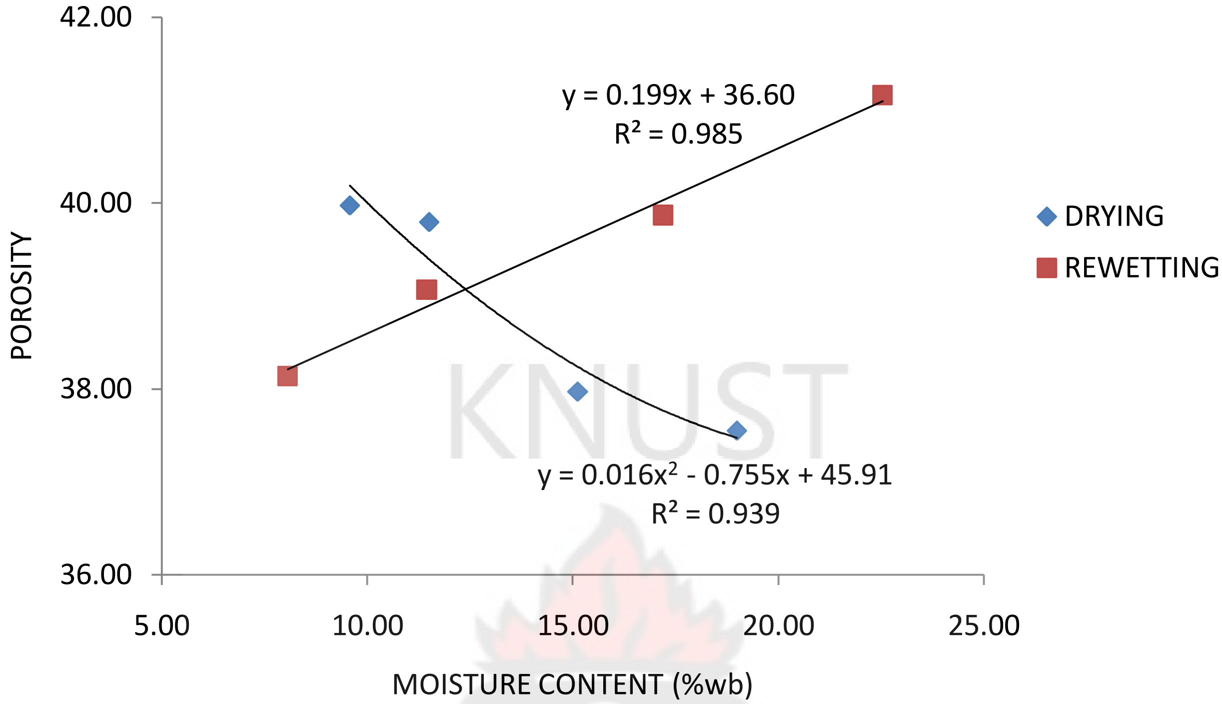

Figure 15 Variation of porosity with moisture content for drying and rewetting

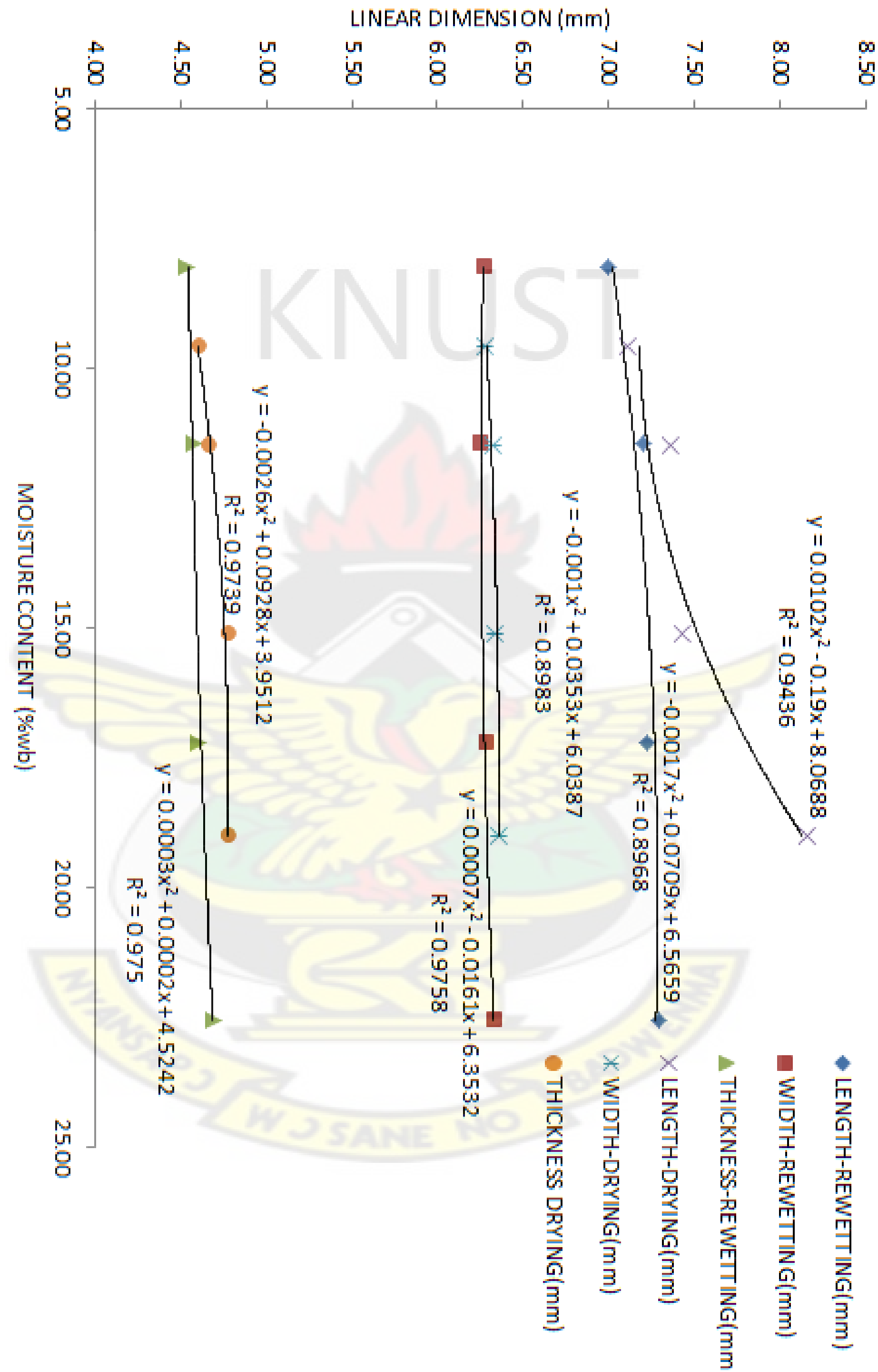

Figure 7 Variation of length, width and thickness with moisture content during drying and rewetting

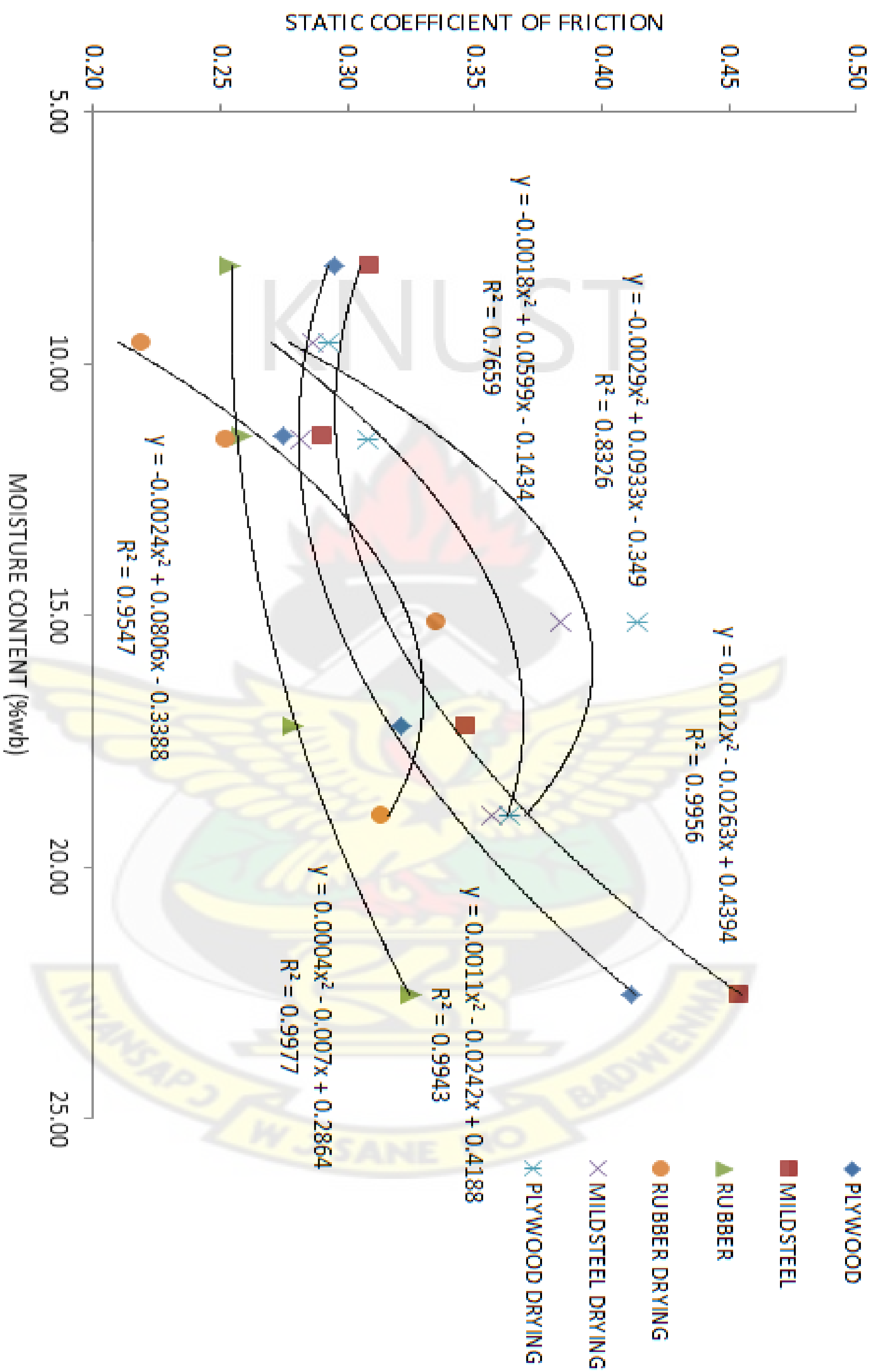

Figure 17 Variation of coefficient of static friction with moisture content for drying and rewetting

Appendix 2: ANOVA calculations - Stepwise

Effect of rewetting on 1000 grain mass

Replication / Moisture Content(% wb)	1	2	3	4	Total	Mean
8.07	122.40	121.40	117.40	119.40	480.60	120.15
11.45	123.50	124.30	121.60	122.80	492.20	123.05
17.20	124.30	125.05	124.40	124.70	498.45	124.62
22.54	132.20	130.00	129.60	130.50	522.30	130.575
Total	502.40	500.75	493.00	497.40	1993.55	

Treatment Variation = [Crude Sum of Squares (SS)] – [Correction Factor (C.F.)]

$$= \sum_{\%MC} \left[\frac{T^2}{r}\right] - \left[\frac{[\sum_{x=1} X_i]^2}{n}\right]$$

T = No. of Treatment = 4

r = No. of Replications = 4

n = total number of replications = 4 x 4 = 16

Correction Factor (C. F.) = $\frac{G^2}{n} = \frac{[\sum_{x=1} X_i]^2}{n}$

$$= \frac{[480.60+492.20+498.45+522.30]^2}{16}$$

$$= \frac{[3974241.6030]^2}{16}$$

= 248390.1002

Crude Sum of Squares (SS) = $\sum_{\%MC}\left[\frac{T^2}{r}\right]$

$$= \left(\frac{480.60^2}{4} + \frac{492.20^2}{4} + \frac{498.45^2}{4} + \frac{522.30^2}{4}\right)$$

$$= \left(\frac{994486.8925}{4}\right)$$

= 248621.7231

Treatment Variation = 248621.7231 - 248390.1002

= 231.6229

Total Variation = [Total Sum of Squares] – [Correction Factor (C.F.)]

$$= \sum_{i=1}^{i=n} {X_i}^2 - \left[\frac{\sum_{i=1}^{i=n} {X_i}^2}{n}\right]$$

$$= (122.40^2 + 121.40^2 + 117.40^2 + \cdots + 130.00^2 + 129.60^2 + 130.50^2) -$$

(248390.1002)

= 248644.6725 - 248390.1002

= 254.5723

Error Variation = [Total Variation] – [Treatment Variation]

= 254.5723 - 231.6229

= 22.9494

Treatment Mean Square (Variance) = $\frac{Treatment\ Sum\ of\ Squares\ (Variation)}{Treatment\ Degree\ of\ freedom\ (dof)}$

$= \frac{S^2}{n-1}$

$= \frac{231.6229}{4-1}$

= 77.2076

Error Mean Square = $\frac{Error\ Sum\ of\ Squares}{Error\ Degree\ of\ freedom\ (dof)}$

$= \frac{22.9494}{12-1} = 2.08$

$F_{calc} = \frac{Treatment\ Mean\ Square}{Error\ Mean\ Square}$

$= \frac{77.2076}{2.08}$

= 37.1190

Reading the value of F from statistical charts;

Error Degree of freedom vrs. Treatment Degree of freedom gives 3.49

ANOVA Table

Source	Degree of Freedom	Variation	Variance	$F_{calculated}$	$F_{tabulated}$
Treatment	3	231.6230	77.37112	40.3711	3.4903
Error	12	22.9494	1.9125		
Total	15	254.5723			

Since F_{calc} (40.3711)> F_{tab} (3.4903), it implies that there exists a significant difference between the treatment means.

Finding the least significant difference (LSD)

» $$LSD = \left(\sqrt{\frac{2xError\ mean\ square}{r}}\right) x\ t_{error\ degree\ of\ freedom\ at\ 5\%}$$

Error degree of freedom = 12

Reading *t* from statistical tables: Error Degree of freedom vrs. 0.025 $\left(ie.\frac{5\%}{2}\right)$

$t_{error\ degree\ of\ freedom}$ = 2.179

$$LSD = \left(\sqrt{\frac{2x2.0863}{4}}\right) x\ 2.179$$

= 2.2255

Appendix 3: Output from Microsoft Excel 2010 for drying conditions (ANOVA)

Anova: Single Factor for mild steel

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
9.58	4	1.1451	0.2862	0.000237
11.50	4	1.4240	0.3560	0.048221
15.13	4	1.5356	0.3839	6.67E-05
19.00	4	1.4270	0.3567	0.000734

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.020875	3	0.006958	0.565048	0.648386	3.490295
Within Groups	0.147775	12	0.012315			
Total	0.16865	15				

Anova: Single Factor for plywood

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
9.58	4	1.1469	0.2867	5.95E-05
11.50	4	1.2324	0.3081	2.3E-05
15.13	4	1.6574	0.4143	0.000483
19.00	4	1.4564	0.3641	0.000453

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.039682	3	0.013227	51.96506	3.79E-07	3.490295
Within Groups	0.003055	12	0.000255			
Total	0.042737	15				

Anova: Single Factor for rubber

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
9.58	4	0.8686	0.2171	2.76E-05
11.50	4	1.0065	0.2516	2.16E-05
15.13	4	1.3384	0.3346	6.27E-05
19.00	4	1.2516	0.3129	8.45E-05

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.035261	3	0.011754	239.3457	5.74E-11	3.490295
Within Groups	0.000589	12	4.91E-05			
Total	0.035851	15				

Appendix 4:Output from Microsoft Excel 2010 for rewetting conditions (ANOVA)

Anova: Single Factor for mild steel

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
8.07	4	1.2324	0.3081	2.3E-05
11.45	4	1.1564	0.2891	0.00014
17.20	4	1.3782	0.3445	1.3E-05
22.54	4	1.8124	0.4531	0.0001

ANOVA

Source of Variation	*SS*	*df*	*MS(variance)*	*F*	*P-value*	*F crit*
Between Groups	0.06447	3	0.021489469	306.908	1.3E-11	3.49029
Within Groups	0.00084	12	7.00192E-05			
Total	0.06531	15				

Anova: Single Factor for plywood

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
8.07	4	1.1812	0.2953	0.000209
11.45	4	1.1001	0.2750	0.000374
17.20	4	1.2785	0.3196	1.82E-05
22.54	4	1.6467	0.4117	9.62E-05

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.043682	3	0.014561	83.60807	2.60423E-08	3.4902948
Within Groups	0.00209	12	0.000174			
Total	0.045771	15				

Anova: Single Factor for rubber

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
8.07	4	1.0156	0.2539	2.95E-05
11.45	4	1.025	0.2562	2.21E-05
17.20	4	1.0924	0.2731	7.4E-05
22.54	4	1.2997	0.3249	0.000188

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.013105	3	0.004368	55.81599	2.5462E-07	3.490294819
Within Groups	0.000939	12	7.83E-05			
Total	0.014044	15				

APPENDIX 5: Summary of the Averages and standard deviations of Physical Properties of Asontem cowpea variety under varying moisture content during drying

Physical Property	MC (%wb)			
	9.58	11.50	15.10	19.00
L (mm)	7.11^{a}	7.37^{b}	7.48^{b}	8.16^{c}
W (mm)	6.28^{a}	6.33^{b}	6.34^{b}	6.36^{c}
T (mm)	4.61^{a}	4.66^{b}	4.77^{c}	4.77^{c}
D_g (mm)	5.91^{a}	6.00^{b}	6.07^{c}	6.27^{d}
Shericity Φ (%)	0.8204^{a}	0.8190^{b}	0.8216^{b}	0.7729^{c}
Volume V (mm^3)	109.07^{a}	113.96^{b}	117.4405^{c}	130.2332^{d}
Surface Area S (mm^2)	110.77^{a}	113.43^{b}	116.0708^{c}	123.8857^{d}
1000_m (g)	120.93^{a}	128.40^{b}	129.78^{c}	132.85^{d}
Bulk Density ℓ_b (kg/m^3)	7110.9300^{a}	718.9300^{b}	712.9214^{c}	663.1200^{d}
True Density ℓ_p(kg/m^3)	1185.9210^{a}	1194.8810^{b}	1140.3043^{c}	1063.801^{d}
(ns) Porosity ε	39.9757	39.7960	37.9677	37.5483
(ns) Filling Angle Θ_f	27.9160	28.2568	29.2460	29.3472

Means in columns with same letters are not significantly different at $p \leq 0.05$

(ns) no significant difference recorded between the treatment means

Moisture Content	Physical Property	Mean ± St. Dev.	Standard Error
9.58	Length	7.11 ± 0.64	0.0316
	Width	6.28 ± 0.31	0.0141
	Thickness	4.61 ± 0.32	0.0153
	Geometric Diameter	5.91 ± 0.26	0.0129
	Sphericity	0.82 ± 0.06	0.0027
	Surface Area	110.77 ± 10.21	0.5042
	Volume	109.07 ± 16.13	0.7620
11.50	Length	7.37 ± 0.68	0.0341
	Width	6.33 ± 0.33	0.0163
	Thickness	4.66 ± 0.31	0.0157
	Geometric Diameter	6.00 ± 0.28	0.0139
	Sphericity	0.82 ± 0.06	0.0028
	Surface Area	113.43 ± 10.57	0.5285
	Volume	113.96 ± 15.99	0.7997
15.10	Length	7.43 ± 0.65	0.0326
	Width	6.34 ± 0.35	0.0173
	Thickness	4.77 ± 0.32	0.0158
	Geometric Diameter	6.07 ± 0.29	0.0144
	Sphericity	0.82 ± 0.05	0.0027
	Surface Area	116.07 ± 10.97	0.5485
	Volume	117.44 ± 16.70	0.8348
19.00	Length	8.16 ± 0.76	0.0379
	Width	6.36 ± 0.39	0.0193
	Thickness	4.77 ± 0.36	0.0179
	Geometric Diameter	6.27 ± 0.34	0.0171
	Sphericity	0.77 ± 0.05	0.0027
	Surface Area	123.89 ± 13.48	0.6739
	Volume	130.23 ± 21.24	1.0619

Physical Property	Equation	R^2
Length	$y = 0.0102x^2 - 0.19x + 8.0688$	0.9436
Width	$y = -0.001x^2 + 0.0353x + 6.0387$	0.8983
Thickness	$y = -0.0026x^2 + 0.0928x + 3.9512$	0.9739
Geometric Diameter	$y = 0.0015x^2 - 0.0078x + 5.858$	0.9768
Sphericity	$y = -0.0012x^2 + 0.0294x + 0.6447$	0.9572
Surface Area	$y = 0.0885x^2 - 1.2049x + 114.67$	0.9848
Volume	$y = 0.1405x^2 - 1.9106x + 115.47$	0.9746
Bulk Density	$y = -0.0014x^2 + 0.0341x + 0.5092$	0.9983
True Density	$y = -0.0015x^2 + 0.0283x + 1.0545$	0.9861
Porosity	$y = 0.0163x^2 - 0.7551x + 45.917$	0.9392
1000 Grain Mass	$y = -0.1426x^2 + 5.1784x + 85.54$	0.8921
Filling Angle	$y = -0.0188x^2 + 0.701x + 22.853$	0.9753
Mild steel	$y = -0.0018x^2 + 0.0599x - 0.1434$	0.7659
Plywood	$y = -0.0029x^2 + 0.0933x - 0.349$	0.8326
Rubber	$y = -0.0024x^2 + 0.0806x - 0.3388$	0.9547

APPENDIX 6: Summary of the Averages and standard deviations of Physical Properties of Asontem cowpea variety under varying moisture content during rewetting

MC (%wb)	MC (%wb)			
Physical Property	8.07	11.45	17.2	22.54
L (mm)	7.00[a]	7.20[b]	7.23[b]	7.29[b]
W (mm)	6.27[a]	6.25[b]	6.28[b]	6.33[c]
T (mm)	4.54[a]	4.58[b]	4.61[c]	4.69[d]
D_g (mm)	5.83[a]	5.90[b]	5.94[c]	5.99[d]
Shericity Φ (%)	0.8371[a]	0.8217[b]	0.8262[b]	0.8258[c]
Volume V (mm^3)	104.45[a]	109.66[b]	110.16[c]	113.45[d]
Surface Area S_A (mm^2)	107.03[a]	108.34[b]	112.16[c]	113.09[d]
1000_m (g)	120.15[a]	123.05[b]	124.61[b]	130.56[c]
Bulk Density ℓ_b (kg/m^3)	752.9500[a]	740.5000[b]	721.9050[c]	682.9290[d]
(ns) True Density ℓ_p(kg/m^3)	1219.897	1215.8850	1193.0420	1161.3930
(ns) Porosity ε	38.1326	39.0664	39.8677	31.1580
Filling Angle Θ_f	27.8104[a]	29.2479[b]	29.8967[c]	32.3102[d]

Means in columns with same letters are not significantly different at $p \leq 0.05$

(ns) no significant difference recorded between the treatment means

Moisture Content	Physical Property	Mean ± St. Dev.	Standard Error
8.07	Length	7.00 ± 0.65	0.0325
	Width	6.27 ± 0.30	0.0149
	Thickness	4.54 ± 0.32	0.0160
	Geometric Diameter	5.83 ± 0.27	0.0133
	Sphericity	0.84 ± 0.06	0.0028
	Surface Area	107.03 ± 10.00	0.5001
	Volume	104.45 ± 15.06	0.7529
11.45	Length	7.20 ± 0.52	0.0261
	Width	6.25 ± 0.33	0.0165
	Thickness	4.58 ± 0.37	0.0186
	Geometric Diameter	5.90 ± 0.27	0.0136
	Sphericity	0.82 ± 0.05	0.0023
	Surface Area	109.66 ± 10.25	0.5126
	Volume	108.34 ± 15.41	0.7707
17.20	Length	7.23 ± 0.56	0.0279
	Width	6.28 ± 0.31	0.0161
	Thickness	4.61 ± 0.33	0.0169
	Geometric Diameter	5.93 ± 0.26	0.0137
	Sphericity	0.83 ± 0.05	0.0024
	Surface Area	112.14 ± 10.32	0.5089
	Volume	110.06 ± 15.56	0.7828
22.54	Length	7.29 ± 0.60	0.0300
	Width	6.33 ± 0.34	0.0170
	Thickness	4.69 ± 0.36	0.0181
	Geometric Diameter	5.99 ± 0.28	0.0139
	Sphericity	0.83 ± 0.05	0.0025
	Surface Area	113.09 ± 10.52	0.5255
	Volume	113.45 ± 15.90	0.7949

Physical Property	**Equation**	**R^2**
Length	$y = -0.0017x^2 + 0.0709x + 6.5659$	0.8968
Width	$y = 0.0007x^2 - 0.0161x + 6.3532$	0.9758
Thickness	$y = 0.0003x^2 + 0.0002x + 4.5242$	0.9750
Geometric Diameter	$y = 5.5368x^{0.0253}$	0.9754
Sphericity	$y = 0.0002x^2 - 0.0054x + 0.8675$	0.5931
Surface Area	$y = -0.0282x^2 + 1.2761x + 98.623$	0.9987
Volume	$y = 8.1479\ln(x) + 87.71$	0.9653
Bulk Density	$y = -0.0002x^2 + 0.002x + 0.7492$	0.9927
True Density	$y = -0.0002x^2 + 0.0027x + 1.2131$	0.9991
Porosity	$y = 0.0006x^2 + 0.1802x + 36.73$	0.9860
1000 Grain Mass	$y = 0.0288x^2 - 0.2203x + 120.62$	0.9548
Filling Angle	$y = 0.0063x^2 + 0.0945x + 26.867$	0.9599
Mild Steel	$y = 0.0012x^2 - 0.0263x + 0.4394$	0.9956
Plywood	$y = 0.0011x^2 - 0.0242x + 0.4188$	0.9943
Rubber	$y = 0.0004x^2 - 0.007x + 0.2864$	0.9977