EFFECT OF MOISTURE CONTENT LEVELS ON SOME ENGINEERING PROPERTIES OF LOCUST BEAN (*Parkia biglobosa*) SEEDS

BY

OLAJIDE AYODELE SADIKU

B.Sc. (Hons), M.Sc. Agricultural Engineering (Ibadan)

A dissertation in the
Department of Agricultural and Environmental Engineering
submitted to the Faculty of Technology in partial fulfilment of the
requirements for the degree of

MASTER OF PHILOSOPHY
OF THE
UNIVERSITY OF IBADAN

July, 2012

ABSTRACT

Locust bean (*Parkia biglobosa*) seed is a source of a nutritious and medicinal food condiment consumed in Nigeria. The drudgery associated with locust bean seed processing necessitates its mechanization. However, there is a dearth of information on the engineering properties of locust bean required for machine design. Since water absorption by seeds causes changes in their structure and size, this study was designed to investigate some engineering properties of locust bean at different moisture content levels.

Locust bean pods were collected from Araromi, Saki in Oyo State. The moisture content and physical properties were determined using American Society of Agricultural Engineers' (S 352.2), Mohsenin's (1986) and Stepanoff's (1969) methods. Universal testing machine was used to determine the mechanical properties. Force was applied transversely at 5 mm/min loading rate. Normal and shear stresses were determined for 200 – 500 g loads at 100 g interval. Thermal properties were determined using methods of mixture and steady-state heat of vaporization. Data were analysed using ANOVA.

Seed length, width and surface area increased from 10.2±1.0 to 11.3±0.9 mm, 8.5±0.8 to 9.1±0.6 mm, and 191.2±24.6 to 208.3±26.3 mm^2 respectively. Static and dynamic angles of repose increased from 48.4±0.9 to 56.0^o ±1.4 and 25.2±1.5 to 30^o ±1.2 respectively as seed moisture content increased from 5.9 to 28.2 % d.b. Seeds became sticky and clung together at high moisture content, hindering free flow and piling at rest, and increased angle of repose. Static coefficient of friction increased on plywood (0.48±0.02 to 0.60±0.01), glass (0.40±0.05 to 0.54±0.01), mild-steel (0.52±0.04 to 0.54±0.02), galvanized iron (0.51±0.04 to 0.52±0.03), rubber (0.41±0.04 to 0.60±0.05) and decreased on aluminium (0.54±0.02 to 0.52±0.04) and stainless steel (0.55±0.03 to 0.50±0.04). The increase was due to increased adhesion between the seeds and the test surfaces at high moisture levels while surface smoothness reduced adhesion, accounting for the decrease in static friction on aluminium and stainless steel. Seed thickness, sphericity and rupture force decreased from 5.49±0.43 to 5.26±0.62 mm, 0.75±0.04 to 0.71±0.03 and 214.4±82.3 to 129.9±51.9 N respectively while normal stress increased with increase in moisture content and loads; 8.4 to 8.7 gcm^{-2} for 200 g, 9.4 to 9.7 gcm^{-2} for 300 g, 10.4 to 10.7 gcm^{-2} for 400 g and 11.4 to 11.7 gcm^{-2} for 500 g. Shear stress was highest at 11.11 % moisture d.b. under 500 g load (1.5 gcm^{-2}) and lowest at 5.93 % moisture d.b. under 200 g load (0.6 gcm^{-2}). Increase in stresses was due to reduced porosity within the grain bulk at high moisture content. Thermal diffusivity, specific heat capacity and thermal conductivity increased from 2.93 x 10^{-8} to 3.79 x 10^{-8} m^{2}/s, 2.74 to 4.38 kJ/kg ^{o}C and 0.052 to 0.118 W/m ^{o}C respectively, these showed that seeds were able to transmit and retain heat within the grain bulk at high moisture content.

A baseline data of the engineering properties of locust bean seeds useful for design of necessary equipment have been established. The properties are useful in designing flat storage facilities and steamers.

Keywords: Locust bean seed, Thermal properties, Mechanical properties, Physical properties, Moisture content.

Word count: 494

AKNOWLEDGEMENT

My profound gratitude goes to my heavenly Father, the Lord Almighty, who is greater than the greatest, higher than the highest and a finisher. Thank you for starting and finishing this work with me, against all odds. Thank you for life.

My sincere gratitude goes to my supervisor, Dr. A. Isaac Bamgboye for his diligent supervision, guidance, forbearance, understanding, constructive criticism and help. I appreciate his challenge to make this work current and standard.

I cannot but appreciate my immediate boss, Professor E.A. Aiyelari for his encouragement and enormous support I received to make this work possible. I appreciate the exposure he gave me and the confidence he built in me in the academic field. Thank you for believing in me. My heartfelt appreciation also goes to all the Professors and other academic staff of the Department of Agronomy for their genuine concern, fatherly advices, help and professional contributions to the success of this work. I appreciate the immediate past Head of the Department of Agronomy, Professor H. Tijani-Eniola for giving me enough room to do this work. I acknowledge the unequalled merciful and courageous effort of the current Head of the Department of Agronomy; Professor V.O. Adetimirin in making a landmark difference in my career. Thank you for being my angel.

The concern, interest, support and advices received from my teachers in the Department of Agricultural and Environmental Engineering are highly appreciated especially the Head of Department; Dr. Y. Mijinyawa, Professors Olorunisola, Onilude and Lucas. Thank you for your concern and the knowledge imparted into me. I say a big thank you to all members of the Christian Fellowship of the Department of Agronomy for the encouragement, prayerful and moral support given to see me through this work. An enormous appreciation goes to my mother, Mrs. R.E.A. Sadiku for her prayerful support and encouragement. I'll forever appreciate the sacrifice you paid to give me good education and an unequal moral and spiritual upbringing. You are a rare kind of a mother. I warmly thank and appreciate my loving family for giving me the peace of mind and support I needed to finish this work. The sacrifice you all paid for the success of this work can never be forgotten. Indeed, life with all of you; Ufuomanefe, Olawale and Odunayo is beautiful and fulfilling.

DEDICATION

To my wife, Ufuomanefe; a loving, faithful partner and our sons, Olawale and Odunayo; God's gifts to us.

CERTIFICATION

I certify that this work was carried out by Mr. O.A. Sadiku in the Department of Agricultural and Environmental Engineering, Faculty of Technology, University of Ibadan, Ibadan.

Isaac A. Bamgboye (Ph.D.)
Department of Agricultural &
Environmental Engineering,
University of Ibadan,
Nigeria.

TABLE OF CONTENTS

CHAPTER 1: INTRODUCTION

CHAPTER 2: LITERATURE REVIEW

CHAPTER 3: MATERIALS AND METHOD

CHAPTER 4: RESULTS AND DISCUSSION

LIST OF TABLES

PLATES

LIST OF FIGURES

CHAPTER 1

INTRODUCTION

1.1 The Locust Bean

Locust bean is the matured fruit seed that comes from the *Parkia* tree. It is the most important part of the tree and a source of a fermented, natural and nutritious condiment that features frequently in the traditional diets of the people of both rural and urban dwellings in at least 17 West African countries including Nigeria. It is harvested, processed and fermented into a product known as *'Iru', 'Ogiri'* and *'Dawadawa'* in Yoruba, Igbo and Hausa languages respectively (Oni, 1997). Outside Nigeria, among the French-speaking countries of West Africa, the condiment is called *Soumbala*. In Zitenga, Burkina Faso, *soumbala* tops the list of edible food products locally sold in the market while in Mali, the seed ranks first among the eighteen edible forest products locally consumed (Diawara, 2000).

This accounts for ten percent of the total non-timber forest products locally used as food. In Nigeria, the Locust bean tree is found in the savannah zones with the bulk of it located in the Guinea Savannah i.e. semi arid to sub-humid area. The estimated average consumption for the condiment per head, per day for Nigeria, Togo and Ghana are 10g, 4g and 2g respectively (Oni, 1997). The locust bean after fermentation is eaten alone or cooked along with food e.g. rice, soup, stew as soup condiment. It contains a high content of protein (40 %), vitamin and sugar (Klanjcar, 2002). The locust bean seed is flat and spherical in shape and it is blackish – brown in colour. It is covered with hard, smooth testa (seed coat) which makes the raw seed very hard and inedible (Booth and Wickens, 1988). The hard, smooth testa protects the seed even when it passes through the gut of an animal. During processing, dehulling of the seed is made difficult or laborious because of the hardness of the testa (Diawara, 2000). When the seed is removed from the pod, the testa is covered by a yellow, sweet, soft and floury pericarp, referred to as the 'Pulp' which is very rich in Vitamin C. The yellowish colour of the pulp is turned to cream colour after drying the seed. The average weight of the seed is approximately 0.25 g (Campbell-Platt, 1980). The seed can be dispersed by man and other vertebrate animals like bats, parrots, baboons, other birds and chimpanzees (Gakou et. al., 1994).

1.2 Economic Importance of the Locust Bean

The socio-economic importance and multi-purpose use of the locust bean cuts across various facets of human life. It is significantly important in human diet as it serves as food and medicine for man. Alabi et. al. (2005) reported that locust bean is rich in lipid, protein, carbohydrate, soluble sugars and ascorbic acid. The cotyledon is very nutritious, has less fibre and ash contents. The oil content is suitable for consumption since it contains very low acid and iodine contents. The oil has very high saponification value and hence would be useful in the soap industry (Diawara et. al., 2000). Locust bean has high protein content (40%) and could adequately serve as a supplement for fish, meat and other animal protein sources. It also contains high vitamin, moderate fat content (35%), carbohydrate and macronutrients such as potassium, sodium, magnesium, calcium, nitrogen and phosphorus. These make the locust bean especially important in the Nigerian diet (Odunfa and Adesomoju, 1985).

Campbell-Platt (1980) also reported that locust bean contains 31 – 40 % oil, 11.7 - 15.4% carbohydrate and 39 - 40% protein. It has essential acids and vitamins and serves as a protein supplement in the diet of poor families. *Dawadawa* is used in soups, sauces and stews to enhance or impart meatiness (Diawara et. al., 2000).

Okpala (1990) in his report gave a table of the chemical and nutritive composition of the locust bean seed (Table 1.1). Oni (1997) reported that the locust bean is used to treat ailments like hypertension, veneral diseases, vision and mental alertness, measles, stomach pains, external wounds, fresh cuts, injuries, diabetes, toothache and mouth ulcer, diarrhoea, sore eyes, snake bites, scorpion sting, ear problem, bronchitis, pneumonia, guinea - worm and rickets among many others. These medicinal benefits are derived mostly from the regular consumption of the fermented locust bean product. In his work, he collated and listed in a tabular form (Table 1.2) some medicinal uses of the locust bean. Booth and Wickens (1988) also reported that the liquid extract from the locust bean when pounded and boiled is used as stomach pain reliever in Singapore and Malaysia.

Table 1.1. Chemical composition (per kg dry matter) of different forms of locust bean.

Constituent	Raw Seed	Raw Seed + Testa + Pulp	Cooked Seed + Testa	Cooked Seed without Testa	Seed Testa
	-	-	-	-	-
Gross energy [MJ]	-	-	20.30	23.60	-
Gross energy [M Cal]	-	-	4.85	5.65	-
Crude protein	303	277	299	425	102
Diethyl ether	196	121	198	246	16
Extract [g]	-	-	-	-	-
Crude fibre [g]	121	90	116	36	281
Ash [g]	68	76	66	72	59
N–free extract [g]	312	468	321	221	542
Calcium [mg]	3730	3996	3543	2043	-
Phosphorus [mg]	2463	2807	2392	3876	-
Magnesium [mg]	3628	4024	3611	3988	-
Manganese [mg]	70	81	65	30	-
Sodium [mg]	45	43	45	43	-
Zinc [mg]	62	54	61	32	-
Copper [mg]	80	81	79	72	-
Iron [mg]	380	450	380	396	-

Source: Okpala (1990)

Table 1.2. Medicinal uses of *Parkia biglobosa* seed.

Type of healing	Ailment	Preparation	Geographical origin of report	Reference
Physical	Hypertension	Addition of processed seed (fermented bean) in soup or sauce peparation	Nigeria	Olapade (1995), Rendu and Auger (1993)
Injuries/cuts	Snake bites , scorpion stings.	Fermented seed	Nigeria	Olapade (1995)
Psychological	Vision and mental alertness	Fermented seeds	Nigeria	Olapade (1995)

Source: Oni (1997)

Oni (1997) further stated, in his work that locust bean is also used for the production of beverages, vegetable oil and the manufacturing of margarine and soap. The friable yellow pulp surrounding the seed is sweet and it is eaten or licked raw, especially by children and can be fermented into alcoholic drinks. The pulp is rich in sugars and vitamin C. The seed can also be processed and used as a substitute for coffee (Dalziel, 1937). It is used as cocoa and sugar replacement to produce chocolate – flavoured products, because not only does the bean taste and smell like chocolate, but it is a pure natural ingredient and does not contain caffeine. The effluent from locust bean processing is usually used locally to kill termites when it is used to spray or wet the affected area (Hagos, 1962). Although, the locust bean contains tannin, which is a toxic substance in its cotyledon and testa, the fermentation process enhances the eradication or drastic reduction in tannin level in the seed. This makes it harmless for consumption. The testa is also used for animal feed (Kessler, 1994). Information received from Cadbury Nigeria PLC, manufacturer of the popular ‘Dadawa cube’ stated that the company uses locust bean as raw material for manufacturing the product.

It has been reported that *‘Iru’* (fermented locust bean) is exported to countries like the United States of America and Britain by many Nigerian food marketers. Therefore, if the production of *‘Iru’* is increased and well packaged, it can serve as a means of earning foreign exchange. Each stage of *‘Iru’* processing, from harvesting to fermentation, in Nigeria is still largely traditional and cumbersome. It is the vocation of the rural dwellers, who are mostly women. Manual labour is employed for all stages of production hence; the quality and quantity of production remain very low. Processing of locust bean for other various uses in Nigeria is also largely manual and traditional.

1.3 Moisture content and engineering properties of agricultural materials: the importance.

Engineering properties of agricultural materials are important in solving problems that are related to the engineering development of agricultural machines and equipment. They are also important in the analysis of the behaviour of agricultural materials during handling which is very important in agricultural production and food sustainability.

The knowledge of engineering properties of an agricultural material is highly imperative in the design of agricultural processes. Kutte, reported by Akaiimo and Raji (2006) stated that:

> in the design of agricultural machines, properties of the crop must be
> taken into account such as grain length, width, mass, hardness,
> angle of repose, grain – straw ratio and bulk density.

Pneumatic separation and conveyance during handling and processing of agricultural materials are often done using air as the medium for transporting and separating unwanted materials from the desirable product. Therefore aerodynamic properties of agricultural materials are needed. Frictional properties of agricultural materials are also of necessity in predicting the lateral pressure on the wall of storage structures and hoppers for gravity flow. The angle of friction is applied to problems of flow of bulk granular materials in the design of gravity and forced flow equipment. Dynamic and static effect of friction of grains on engineering material surfaces (e.g wood, galvanized metal, glass and rubber) are required for the prediction of motion of the material in the design of harvesting and handling equipment. The physical properties of materials such as size, shape, surface area and drag coefficient are needed in the determination of the terminal velocity of an object in a fluid. Hence, to allow a gentle fall of a particle the air velocity is adjusted to a level below its terminal velocity. Mechanical properties of agricultural materials also help in predicting the behavior of a material under loading such as its yielding point, maximum rupture force that can be applied and the extent of its deformation when load is applied.

These properties are also important in the development of seed dehullers, decorticators, milling equipment and other processing machines. The process of hydration (addition of water) is commonly used in the processing of cereal grain and the seeds of pulses. A number of important changes in the structure of the raw materials take place in the course of hydration and they are mainly associated with increased moisture content (Andrejko and Kaminska, 2005). Water absorption by the seeds which in consequence brings about increase in size (i.e. swelling) is an important phenomenon. Water is bound in the seed by various chemical and physical forces and its content changes with the changes occurring in the immediate environment. In the process of hydration especially in its initial stage, colloids contained in the seeds are filled with water and the rate of water absorption decreases with time which is dependent on the kind of colloids, their capacity, temperature and pH value.

1.4 Problem statement

Beaumont (2002) identified several constraints to the processing of locust bean into a condiment. These include among others, low production due to the use of rudimentary equipment, high wood fuel consumption and poor manufacturing practices. He further stated that it is time consuming, laborious and inefficient hence, production has not increased substantially. The declining popularity of *Iru* (fermented locust bean) especially among the growing urban population has led to rapid increase in importation of foreign soup flavours. In order to increase supply, it is necessary to modernize production techniques or optimize processing conditions (Audu et al., 2004). To increase production, mechanization of processing stages and conditions is imperative. Therefore the determination of the engineering properties of locust bean required for the design of equipment for its handling and processing is necessary. Efforts have been made to determine some engineering properties of *Parkia biglobosa* relative to pod shelling at a single moisture content level (Oje, 1993). Work has also been done to determine some physical properties of *Parkia filicoidea*, another variety of *Parkia* at a single moisture content level (Ogunjimi et. al., 2002).

Mohsenin (1986) stated that the compression behaviour of agricultural products is affected by the physical nature of such products, moisture content and maturity, rate of loading, temperature and other processing parameters. Therefore, there is a need to determine the relationship between the engineering properties of *Parkia biglobosa* and seed moisture content variation which will be useful in generating a baseline data required for the engineering design and development of equipment needed for handling and processing of locust bean.

1.5 Objectives

This work was therefore carried out to:

1. Determine the physical, mechanical and thermal properties of locust bean at five different moisture levels.
2. Determine the relationship between moisture content and the properties of locust bean stated above.
3. Generate equations for predicting the properties of locust bean at any moisture level.

CHAPTER TWO

LITERATURE REVIEW

2.1 Origin and distribution of the African Locust Bean (*Parkia spp*.)

The *Parkia* tree, named after the famous Scottish botanist and surgeon, Mungo Park by Brown (1826) has long been widely recognized as an important indigenous multipurpose fruit tree in many countries of the sub-saharan Africa. It is commonly called the 'African Locust Bean'. *Parkia* tree is a legume belonging to a family called '*mimosaceae*'. There are about forty species of *parkia* in the family *mimosaceae*, three of which are found naturally existing in Africa such as *Parkia bicolor, Parkia filicoidea and Parkia biglobosa.*

Parkia biglobosa is found naturally occurring in the following countries of West Africa: Republic of Benin, Burkina Fasso, Cameroun, Chad, Cote d'Voire, Central Africa Republic, Gambia, Ghana, Guinea Bissau, Mali, Niger, Nigeria, Senegal, Sierra Leone, Sudan, Togo, Uganda and Zaire (Booth and Wickens, 1988) as shown in figure 2.1.

Among the various species of parkia, the most important is *Parkia biglobosa* due to the following:

- Its economic importance
- Its traditional role in the economy of the rural populace
- Its multipurpose use, viz:
  - Significance in the provision of food and medicine
  - Stabilization of degraded environment, shade, livestock feed and fuel wood supply (Booth and Wickens, 1988).

In Nigeria, *parkia biglobosa* is found in the savannah zones with the bulk of it in the Guinea savannah, that is, semi–arid to sub–humid areas. This is as a result of its ecological and environmental requirements which are easily met in these areas.

Fig. 2.1 Map showing the distribution (shaded portions) of *Parkia biglobosa* in Africa. *Source:*www.worldatlas.com

The distribution of *parkia biglobosa* in Nigeria covers Abuja, Adamawa, Bauchi, Gombe, Kaduna, Kano, Katsina, Kebbi, Kogi, Kwara, Nasarawa, Niger, Oyo, Taraba, Yobe, Plateau and Zamfara States.

2.2 Description

2.2.1 The *Parkia* tree

Parkia biglobosa [Jacq] Benth, popularly called the African locust bean tree is an important tree in many countries of the Sub – Saharan Africa. As a result of age long association with traditional agriculture and diverse usage, it has attained protective status in most agricultural systems (Hagos, 1962; Hopkins, 1983). The *Parkia biglobosa* tree (Plate. 2.1) is a deciduous tree which can grow up to a height of 30 m though it is usually found to be between 7 and 20 m in height (Sabiite and Cobbina, 1992). The bark is streaked dark grey or brown and thick, which makes it fire tolerant to some extent. The branches tend to develop low down the trunk while the crown is large and widely spread like an umbrella shape, forming shade for cattle and serving as windbreak. It also reduces the impact of rain drops on the soil.

The bark is soft wood, while the heart is hard and whitish in colour. It is fairly heavy, weighing 580 to 640 kg/m (FAO, 1988). When newly felled, it has an unpleasant smell, which resembles that of onions. The wood is of little commercial value because of its low resistance to termites and fungus which causes its discoloration. It can tolerate draught up to 5 months (Plate. 2.2). Oni et. al. (1998) in their work, stated that *Parkia biglobosa* was not cultivated in the past, but grew naturally in dotted form in the savannah. It is however cultivated nowadays due to its multipurpose uses by transplanting wild ones, transplanting from the nursery and direct planting. It is better raised in the nursery than direct planting. It should be cultivated on a well drained soil. When planted in the nursery, two seed per hole at 5 m by 5 m spacing is employed followed by thinning within 8 – 10 th year after planting, making a total of 100 trees/ha (Hopkins, 1983).

Plate 2.1 The *Parkia biglobosa* tree during the rainy season. Source: Van der Maesen (2002).

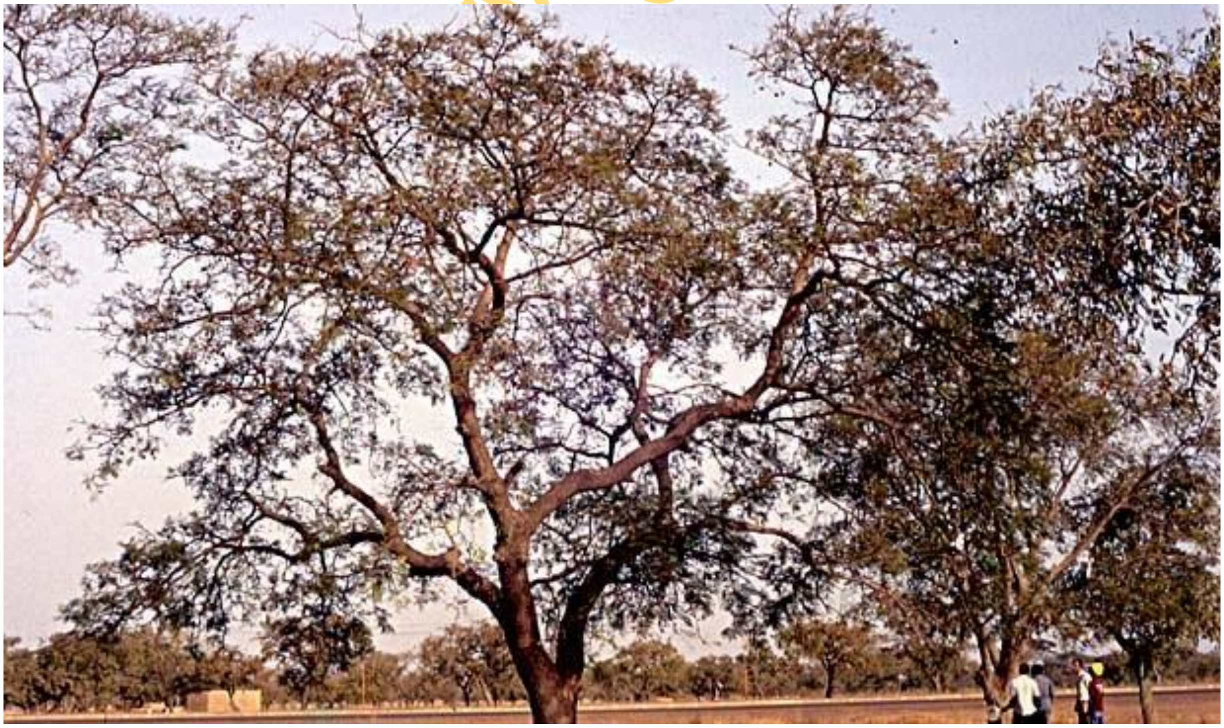

Plate 2.2 A Locust bean (*Parkia biglobosa*) tree during the dry season. Source: Van der Maesen (2002).

2.2.2 Inflorescence and flower

The distinctive large bright red globes or inflorescence of *Parkia biglobosa* are seen blooming from December through February. The inflorescence or capitulum is composed of up to 2500 individual flowers arranged in a spherical bud. The capitulum measures 45 – 70 mm long and 35 – 60 mm in diameter. The capitulum is divided into two distinct parts; a large apical ball and a constricted basal portion of the capitulum. The fertile flowers are approximately 15 mm long, with anthers measuring 1.0 – 1.5 mm long and the staminoidal flowers measure approximately 6 – 7 mm (Hopkins, 1983). The flowers are red or orange with a pendulous head and 35-60 mm in diameter and produce indehiscent pods and edible seeds. (Sabiite and Cobbina, 1992).

2.2.3 The Leaf.

The leaves are dark green in colour, and are alternated and bipinnately arranged. The ranchis is 20 – 40 mm long, holding 30 - 60 pairs of sub-opposite leaflets. These leaflets are 7 – 30 mm long and 2 – 3 mm wide. At the base of the petiole, there is a single orbicular gland which secretes nectar used to attract ants in the seedling stage of growth. An important attribute of the *parkia* tree is that most of its leaves remain green throughout the dry season. *Parkia biglobosa* trees readily coppice after cutting. Mature trees, if cut down to 50 cm above the ground can produce new shoots after one week. The trees coppicing ability can continually produce biomass with a cutting interval of sixteen to twenty – four weeks without reduction in leaf nutritional value. Leaf retention is very high, especially in young ones. Hagos (1962) reported that, in mature trees, there is a sudden leaf fall in November to December preceding flowering but by January, new lush and vigorous leaves are already formed on the branches. January to April is the time when supplementing livestock feed with *parkia* fodder is crucial in Nigeria as this is the peak of the dry season. Table 2.1 also displays the mineral content of *parkia* leaves from trees of different ages.

Table 2.1 Mineral contents in the leaves of *Parkia biglobosa*

	A	B	C
Total N (%)	2.26	2.39	1.82
	(14.1)*	(15.0)	(1.4)
Total P (%)	0.15	0.11	0.12
Ca (%)	0.93	0.71	0.72
Mg (%)	0.23	0.43	0.25
K (%)	1.46	1.30	1.20
Na (ppm)	193	-	-
Mn (ppm)	106	-	-
Fe (ppm)	100	-	-
Cu (ppm)	2	-	-
Zn (ppm)	13	-	-

*Figures in brackets represent crude protein; A = leaves from 2 months re-growth of one year old tree; B = leaves from 4 months of re-growth of three year old tree; C leaves from a mature tree of over 5 years old. Source: Oni (1997).

2.2.4 The *Parkia* pod

The *parkia* pod is oblong-linear, often woody and thick. Pods are in clusters of 4 - 25, brownish black indehiscent, hanging on the tree for a long time. Each pod contains 23 – 30 seeds. Booth and Wickens (1988) reported that *Parkia biglobosa* tree, first fruits after eight to ten years, (typically with 20 to 25 pods from a single capitulum). The pod when young is green, fleshy and pliable and it is sometimes eaten by humans after roasting it. Odunfa (1985) also reported that the pods occur in linear, large bunches and vary between 120 – 130 mm in length. Each pod may contain up to 23 seeds (Hopkins, 1983). The pods become brown when matured. At 15 – 20 years, each tree would produce 25 – 100 kg of pods. Harvesting of pods is done by plucking them from the tree (using a locally made implement called 'go to hell') in the months of March and May. Dropped pods are also gathered for use. The pods are sometimes referred to as the fruits. Their colour ranges from pink brown to dark brown when mature. They are about 45 cm long and 2 cm wide; may contain up to 30 seeds embedded in a yellow pericarp known as the 'pulp' (FAO, 2001).

Locust bean pod could be up to 15 cm long. Pods are harvested during September and October each year, around the Mediterranean. The seeds carried in the pods are embedded in a yellow, sweet pulp, which is edible and contains vitamin C and carbohydrate (Anonymous, 2001). In his work, Okpala (1990) stated that the pods of *parkia biglobosa* contain some nutrients and food substances as seen in table 2.2.

2.2.5 The Seed

The most important use of *parkia biglobosa* is found in its seed. Each seed weighs about 0.25 g and consist of 30 % testa and 70 % cotyledon. The seed constitute 22 % of the fruit while the pod is 42 % and the pulp is 36 % (Campbell-platt, 1980). The thick seed coat protect the seed from the natural conditions of the savannah; extreme heat, low moisture, drought and digestive juices of ruminant and primates. The hard testa prevents seed germination, hence dormancy. Germination of the seed occurs after the seed coat becomes permeable. Natural germination can occur from prolonged contact with water, chewing or ruminating by animals, mechanically scarifying the testa, contact with digestive juices. Fire can also break the seed coat.

Table 2.2 Mean levels of five macro-nutrients (mg/100 g dry weight of pod) and three food substances (g/100 g dry weight) in mature pods of *parkia biglobosa.*

	Constituents								
	N	P	K	Mg	Ca	Starch	Total soluble carbohydrate	Starch (Total soluble carbohydrate)	Protein
Husk	500	658	595	4.70	1206	7.07	1.78	3.97	3.12
Pulp	5.20	716	598	1.84	1643	22.60	9.69	2.33	3.18
Seed	5010	775	1016	6.32	1175	43	4.63	9.29	31.64

Source: Okpala (1990)

Table 2.3 Mineral nutrient content of *parkia biglobosa* seeds in mg/g

	Nutrient (mg/g)									
	N	P	K	Ca	Mg	Mn	Fe	Cu	Zn	Na
Cotyledon	6.17	0.82	0.91	0.66	0.60	0.05	0.14	0.02	0.08	0.08
Testa	1.82	0.24	0.28	0.99	0.13	0.18	0.04	0.04	0.02	0.70

Source: Alabi (1993)

Table 2.4 Some dietary contents of *Parkia biglobosa* seeds

	Lipids mg/g	Total sugar mg/g	Protein mg/g	Fibre %	Cellulose %	Ash %	Oxalo Acetic acid	Hydro-cyanic acid	Ascorbic acid
Cotyledon	168	128	3.60	7.30	0.04	5.0	0.84	0.92	14.5
Testa	28	16	1.00	10.8	16.2	10.0	5.70	3.92	0.6

Source: Alabi (1993)

To propagate seedlings, the testa can be pre-treated to encourage germination by soaking seeds in hot water, treating seeds up to 15 minutes with H_2SO_4, HCl or HNO_3, or mechanical scarification. All these produce good germination rates of up to 80 % (Hall et al., 1997). Alabi (1993) in his work showed tables of nutrient and dietary contents of *parkia biglobosa* seeds (tables 2.3 and 2.4) to buttress his report on the nutritive value of the seeds.

2.3 Work done

2.3.1 Engineering properties of locust bean

The moisture content of African locust bean (*Parkia filicoidea*) fruit at harvest was determined by Oni (1990) and torsional shear tests were conducted on pod samples at 9.34 and 11.83 % moisture content. Pod samples at these moisture levels were also selected for machine shelling (decortication) to determine the influence of crop and machine parameters on shelling efficiencies. Results showed that field drying of African locust bean fruit progressed rapidly soon after full maturity. The torsional tests showed an exponential relationship of shear stress with applied torsional strain for each moisture level. Lower stress values were obtained for the 9.34% moisture content. Effects of machine speed and the speed-moisture content interaction were statistically significant ($p< 0.05$) for the overall shelling efficiency. Nevertheless it is still necessary to explore other stages of locust bean processing in order to make the whole production process less tedious and non-cumbersome.

Oje (1993) studied some of the engineering properties of locust bean (*Parkia biglobosa*) pods and seeds, relevant to dehulling. He indicated that the pods have major diameter ranging from 76 to 277 mm as against 8 to 12 mm for the seeds. The seed thickness ranged from 5.75 to 7 mm. An average sphericity of 67 and roundness of 65 are the characteristics that allow for some rolling of the seeds as well as sliding on its flat surface. The seed is unable to float in water but the pod can. This work was carried out at a single moisture level. But considering the fact that locust bean processing involves cooking and soaking the seeds in water, especially dehulling, it will be necessary to vary the moisture content levels at which the engineering properties are determined.

To explore the possibility of developing handling and processing equipment for locust bean (*Parkia filicoidea*) seed, some engineering properties namely: size, 1000 seed weight, true density, bulk density, porosity, static coefficient of friction on wood, angle of repose, specific heat and cracking force, were determined by Ogunjimi et al. (2002). At a moisture content of 10.25 % (db), seed length varied from 0.80 to 1.20 cm, width from 0.60 to 0.85 cm and thickness from 0.45 to 0.60 cm. One thousand seed weight averaged 0.283 kg with a standard deviation of 0.00264. True density lay between 1098.0 and 1215.7 kg/m^3, while bulk density was between 538.02 and 565.30 kg/m^3 and porosity was between 51.0 and 53.5 %. Static coefficient of friction on wood averaged 0.43 with a standard deviation of 0.021, angle of repose 20.32 with a standard deviation of 1.84 and specific heat 1415.3 J/kgK with a standard deviation of 103.81. Minimum cracking force was obtained by loading the seed along its thickness. This force averaged 174.38 N with a standard deviation of 10.21. These results indicate that a mechanical dehulling process to obtain whole kernel from locust bean seed should be possible.

The effect of moisture content on some physical properties of locust bean (*Parkia filicoidea L.*) seed (LBS) was also evaluated by Sobukola and Onwuka (2010) as a function of moisture content varying from 7.37 to 28.09 % (db). The length, width, thickness and geometric mean diameter increased linearly from 10 to 11.72 mm; 7.80 to 9.22 mm; 4.00 to 4.85 mm; and 6.78 to 8.06 mm, respectively. The sphericity index, seed volume, seed surface area and thousand - seed mass also increased linearly from 67.82 to 68.79, 96.09 to 157.39 mm^3, 121.75 to 177.24 mm^2 and 245.24 to 300.67 g, respectively. Bulk density, true density and porosity decreased linearly from 996 to 799 kg/m^3; 1,500 to 1,071 kg/m^3; and 33.60 to 25.39 %, respectively. Static coefficient of friction was found to increase on plywood, galvanized iron, aluminium and stainless-steel surfaces. It increased linearly from 0.47 to 1.00; 0.41 to 0.89; 0.39 to 0.78; and 0.34 to 0.69, respectively. Angle of repose increased linearly on plywood, galvanized iron, aluminium and stainless-steel surfaces from 21.43 to 37.46°; 17.43 to 35.61°; 16.44 to 32.82°; and 15.23 to 27.06°, respectively. The highest static coefficient of friction and angle of repose was found on plywood surface. Though this work was done using *Parkia filicoidea*, it is still necessary to do same for *Parkia biglobosa*, another variety of the parkia spp. and compare the trend in the results which may also establish the influence or effect of seed variety on the engineering properties of LBS. Moreover, moisture dependent physical properties of LBS are not enough to generate a baseline data for development of its handling and processing equipment. It is therefore highly essential to investigate the mechanical and thermal properties as a function of moisture content.

Some physical properties of Parkia speciosa seeds were examined by Abdullah et al. (2011). The average moisture content (wet basis) of the seeds was found to be 74.15 (±3.45) % while the mean moisture content (wet basis) of the pods was 73.02 (±0.43) %. The mean of length, width and thickness of the seeds was 23.20 (±1.13), 17.27 (±0.99) and 9.87 (±0.82) mm respectively. The average value for geometric mean diameter, sphericity, aspect ratio, mass, surface area, volume, true density, bulk density and porosity was 15.80 (±0.85) mm, 68.15 (±2.52) %, 74.51 (±4.26) %, 1.868 (±0.316) g, 786.86 (±84.47) mm^2, 2084.37 (±336.00) mm^3, 1089.46 (±73.40) kgm^{-3}, 419.88 (±15.27) kgm^{-3} and 61.29 (±3.18) % respectively. The coefficient of static friction on four types of structural surface was found to be varying from 1.056 (±0.063) for plywood to 1.378 (±0.110) for glass surface. This variety of locust bean is foreign to West Africa. The common varieties in West Africa are; *Parkia biglobosa*, *Parkia bicolor* and *Parkia filicoidea*. Comparing these results with those reported by Ogunjimi et al. (2002), it can be inferred that the engineering properties of different varieties of *parkia* may differ thus, the seed varieties may likely exhibit different behavioural trends.

2.3.2 Related work done

1. *Physical properties*:

Ozarslan (2002) in his study on physical properties of cotton seed as a function of moisture content discovered that the average length, width and thickness of seeds ranged from 9 to 9·2, 4·7 to 4·9 and 4·3 to 4·5 mm respectively, as the moisture content increased from 8·3 to 13·8 % dry basis (d.b.). In the same moisture range, studies on rewetted cotton seed showed that the sphericity increased from 0·63 to 0·64, the seed volume from 95·4 to 109·6 mm^3, thousand seed mass from 104·1 to 109·6 g, projected area from 35·9 to 40·1 mm^2 and the terminal velocity from 8·5 to 8·7 m s^{-1}. The static coefficient of friction of cotton seed also increased linearly on four structural materials, namely; stainless steel (0·27 – 0·35), galvanized iron (0·38 – 0·41), plywood (0·39 – 0·42) and rubber (0·42 –

0·44). The bulk density decreased from 642 to 610 kg m^{-3}, true density from 1091 to 1000 kg m^{-3}, porosity from 41·2 to 39·0 % and the shelling resistance from 65·0 to 50·2 N.

The physical properties of millet were evaluated by Baryeh (2002) as a function of grain moisture content varying from 5 to 22.5 % (d.b.). In this moisture range, grain length, width, thickness and geometric diameter increased from 3.5 to 4.2 mm, 2.7 to 3.2 mm, 2.2 to 2.8 mm and 2.8 to 3.3 mm, respectively. The grain surface area, volume and sphericity increased from 23.9 to 35.1 mm^2, 8.2 to 14.7 mm^3 and 0.80 to 0.80 respectively while the 1000 seed mass, true density, angle of repose and terminal velocity increased from 14 to 44 g, 1550 to 1712 kg/m^3, 34.5º to 48.5º, 2.75 to 4.63 m/s respectively. The sphericity increased slowly with moisture content up to 18 % and increased rapidly after that. The coefficient of static friction increased from 0.42 to 0.79, 0.39 to 0.75 and 0.36 to 0.69 for plywood, mild steel and galvanized iron respectively. Bulk density increased with grain moisture content up to 10 % and decreased with moisture content thereafter, while porosity decreased with moisture content up to 7.5 % and increased with moisture content thereafter.

Tabatabaeefar, (2003) evaluated the moisture-dependent physical properties of wheat for moisture content in the range of 0 to 22 % d.b. The average length, width, thickness and thousand-kernels weight were 7.1, 3.3, 3.0 mm and 29.6 g at a moisture content of 7.4 % d.b. The average length for dry land farming wheat varieties was longer than that for irrigated. The average geometric mean diameter and percentage sphericity was 4.3 mm and 60. Studies on rewetted wheat showed that the bulk and true densities decreased from 740 to 538.8 kg m $^{-3}$ and 1240 to 847.2 kg m $^{-3}$, whereas the corresponding bulk porosity increased. The static coefficient of friction varied from 0.28 to 0.45 over different material surfaces, while the dynamic angle of repose varied from 34.7 to 45° within the moisture range studied.

Amin et al. (2004) studied the effects of moisture content on some physical properties of lentil seeds. Four levels of moisture content ranging from 10.3 to 21.0 % (wet basis) were considered in the study. Diameter, thickness, porosity, mass of 1000 seeds and angle of repose increased linearly from 3.8 to 4.1 mm, 2.18 to 2.48 mm, 34.48 to 37.0 %, 20 to 25.5 g and 24.8 to 27.8° respectively with increase in moisture content from 10.3 % to 21.0 %. Bulk density and kernel density decreased linearly from 832 to

768 kg/m^3 and 1270 to 1212 kg/m^3 respectively with increase in moisture content from 10.3 % to 21.0 %. Static and kinetic coefficients of friction of lentil seeds were determined on a smooth concrete, galvanized iron, plywood and glass sheets at various moisture contents. It varied from material to material and depended on the roughness and wetness of the seeds. The highest static and kinetic coefficients of friction were found on the concrete surface and the lowest on the glass sheet among the materials tested.

Atluntas *et al*. (2005) evaluated some physical properties of Fenugreek seeds as a function of moisture content. The average length, width, thickness, geometric mean diameter and unit mass of the seed ranged from 4.0 to 4.2 mm, 2.4 to 2.6 mm, 1.5 to 1.7 mm, 2.4 to 2.7 mm and 0.0157 to 0.0164 g respectively as the moisture content increased from 8.9 % to 20.1 % d.b. In the moisture content range, studies on rewetted fenugreek seed showed that the sphericity increased from 60.8 to 64.1 %, the seed volume from 12.59 to 13.83 mm^3, 1000 seed mass from 15.5 to 16.4 g and surface area from 18.1 to 22.2 mm^2. As the moisture content increased from 8.9 % to 20.1 % d.b., the bulk density, kernel density were found to decrease from 701.16 to 645.81 Kgm^{-3} and 1240.36 to 1165.25 Kgm^{-3}, whereas angle of repose and porosity were found to increase from 14.34 to 16.88º and 43.47 % to 44.58 % respectively. The static and dynamic coefficients of friction on various surfaces namely plywood, mild steel and galvanized metal also increased linearly with increase in moisture content. The plywood surface offered the maximum friction followed by mild steel and galvanized metal.

Seyed and Elnaz (2006) investigated some physical properties of the watermelon seeds. Watermelon seeds of three major local Iranian varieties, *Sarakhsi*, *Kolaleh* and *Red*, at the moisture content of 4.6, 4.8 & 5.0 % (w.b.) respectively, were selected to study the physical properties. The results showed that the length, width, thickness, arithmetic mean diameter and geometric mean diameter of watermelon seeds varied from 13.5 to 19 mm, 8.4 to 10.7 mm, 2.9 to 3.1 mm, 8.3 to 10.9 mm and 6.9 to 8.5 mm, respectively. The sphericity by Jean & Ball's method, sphericity by the Mohsenin's method, surface area by McCabe et al's method and surface area by Jean & Ball's method, changed from 2.004 to 2.125, 0.446 to 0.513, 149.68 to 225.03 mm^2, 128.09 to 198.01 mm^2, respectively. The values of the seed volume, true density, bulk density and porosity were between 179.53 - 311.62 mm^3, 861.75 - 866.66 kg/m^3, 416.33 - 527.265 kg/m^3 and 39.14 - 51.68 %

respectively. The study on the coefficient of friction of watermelon seeds on some materials such as plywood, galvanized metal sheet, glass, fiberglass and rubber showed that the static coefficient of friction varied from 0.26 on glass to 0.68 on rubber. Furthermore, the filling and funnelling angles of repose for three watermelon seeds ranged from 27.09 to 32.38, 21.66 to 28.15, respectively. It is concluded that the physical properties of watermelon seeds vary from variety to variety and it is also a function of the seed moisture content, environmental and growth conditions.

Isik (2007), determined some engineering properties of Soybean Grains as a function of moisture content in the range of 10.6 – 27.1 % dry basis (d.b). The average length, width and thickness were 7.8, 7.1 and 4.2 mm, at a moisture content of 10.6 % d.b., respectively. In the above moisture range, the arithmetic and geometric mean diameters increased from 6.4 to 8.0 mm and from 6.1 to 7.9 mm, respectively, while the sphericity increased from 0.78 to 0.83. In the same moisture range, studies on rewetted soybean grains showed that the thousand grain mass increased from 200 to 255 g, the projected area from 37.69 to 53.39 mm^2, the true density from 1090 to 1200 kg m$^{-3,}$ the porosity from 40.4 to 54.2 % and the terminal velocity from 8.01 to 9.1 m s^{-1}. The bulk density decreased from 650 to 550 kg m^{-3} with an increase in the moisture content range of 10.6 – 27.1 % d.b. The static coefficient of friction of soybean grains increased linearly against surfaces of six structural materials, namely rubber (0.34 – 0.39), aluminium (0.29 – 0.34) , galvanized iron (0.29 – 0.34), glass (0.23 – 0.27) and MDF (medium density fiberboard) (0.21 – 0.26) as the moisture content increased from 10.6 – 27.1 %.

Effect of Moisture Content and Variety on Selected Physical Properties of Beniseed was examined by Tunde - Akintunde et al. (2007). Two varieties of beniseed were investigated within the moisture content range of 3.5 to 25.0 % dry basis (d.b.). The ranges of the three linear dimensions of the seed of the two varieties were 2.80 to 3.28 mm for length, 1.69 to 2.32 mm for width and 0.80 to 0.94 mm for thickness. An increase in moisture content resulted in a decrease in bulk density of the seeds from 659 to 617 kg/m^3 and 618 to 557 kg/m^3, decrease in porosity from 46 to 22.3 % and 36 to 25.1 % and an increase in angle of repose from 17.42 to 19.94^0 and 16.97 to 19^0 for varieties A and B respectively. In the above moisture range, the static coefficient of friction varied from 0.39 to 0.71 and 0.36 to 0.59 on different structural surfaces, while the terminal velocity increased from 4.2 to 4.9 m/s and 4.3 to 5.0 m/s for varieties A and B respectively. The analysis of variance (ANOVA) showed that the moisture content had a significant effect ($p<0.01$) on only the coefficient of friction of both varieties of beniseed. Relationship between the physical properties and moisture content were expressed by linear equations.

Wang et al. (2007) investigated the Effect of moisture content on the physical properties of fibered flaxseed within moisture content range of 6.2 to 16.3 %. The length, width, thickness and geometric mean diameter increased from 4.2 to 4.4 mm, 2.0 to 2.1 mm, 0.9 to 1.0 mm, and 2.0 to 2.1 mm, respectively in the moisture content range. One thousand seed weight increased linearly from 4.2 to 4.6 g. The bulk density decreased from 726.8 to 611.9 kg/m^3, while the true density increased from 1165.3 to 1289.3 kg/m^3 in the moisture content range. The porosity values of flaxseed increased linearly from 37.7 to 52.5 %. The highest static coefficient of friction was found on the plywood surface, while the lowest on the stainless steel surface. The static coefficient of friction increased from 0.47 to 0.97, 0.44 to 0.86, 0.49 to 0.92, and 0.49 to 0.84 for plywood, stainless steel, aluminum sheet and galvanized iron, respectively. The angle of repose increased linearly from 25.7 to 33.8° in the moisture content range.

Moisture dependent physical properties of dry sweet corn kernels were evaluated by Karababa and Coskuner, (2007) as a function of kernel moisture content, varying from 9.1 to 17.1 % (d.b.). In the moisture range, kernel length, width, thickness, and geometric mean diameter increased linearly from 9.9 to11.1 mm, 7.4 to 9.3 mm, 3.3 to 4.4 mm, and 6.2 to 7.6 mm respectively, with increase in moisture content from 9.1 - 17.1 %. The sphericity index, kernel volume, kernel surface area, and thousand seed weight increased linearly from 62.6 to 68.8, 93.8 to 194.3 mm^3, 120.1 to 182.9 mm^2, and 220 to 268 g respectively. Apparent density and bulk density decreased linearly from 1.315 to 1.232 g/cm^3 and 0.765 to 0.698 g/cm^3 respectively, while bulk porosity increased from 41.8 to 43.3 %. The highest static coefficient of friction was found on the plywood surface. The static coefficient of friction increased from 0.68 to 0.89, 0.60 to 0.74, and 0.53 to 0.64 for plywood, galvanized iron, and aluminum surfaces, respectively. The angle of repose increased linearly from 30.2 to 35.2° with the increase of moisture content.

The physical properties of three common Iranian varieties of melon seeds have been evaluated as a function of moisture content by Koocheki et al. (2007). The seed moisture content was varied from 4.8 to 47.6 %, from 5.0 to 46.8 % and from 4.6 to 45.2 % (w.b) for *Ghermez, Kolaleh* and *Sarakhsi* respectively. Increasing moisture content was found to increase axial dimensions, surface area, emptying angle of repose, bulk and true density, sphericity, geometric and arithmetic mean diameters, and static friction coefficient on five structural surfaces, while decreasing porosity and filling angle of repose were observed. Among the varieties, *Ghermez* had the highest values of geometrical properties, in all moisture content studied. An increase of surface area with moisture content was observed. The maximum values of bulk density and true density among the varieties were obtained for *Kolaleh* seeds. *Ghermez* melon seed had the highest porosity which decreased with increase in moisture content. The filling angle of repose decreased as the moisture content increased for all three varieties. The maximum and minimum values for emptying angle of repose were obtained for *Sarakhsi* and *Kolaleh*. At all moisture contents, plywood showed the highest friction coefficient, followed by galvanized iron sheet, then fibre glass and finally glass. The increase in friction coefficient with moisture content was the largest for *Ghermez* melon seed on fibre glass surface, followed by *Sarakhsi* and *Kolaleh* on fibre glass and galvanized iron sheet surfaces respectively. *Ghermez* variety had the highest friction on all frictional surfaces at all moisture levels.

Some physical properties of three common Iranian varieties of cucurbit seeds (*Riz, Chiny*, and *Gushty*) were studied by Milani et al. (2007), such as geometric properties (linear dimensions, sphericity, geometric and arithmetic mean diameters and surface area), gravimetric properties (true density, bulk density and porosity) and frictional properties (filling and emptying angles of repose and coefficient of static friction on five structural surfaces) were determined as a function of moisture content in the range of 5.18 to 42.76 % (w.b.). The results showed that the mean values of all geometric properties increased with increasing moisture content. Among the varieties, *Chiny* had the highest values of gravimetric properties, in all moisture contents studied. The maximum and minimum values of bulk density were obtained for *Riz* (550.3 kgm^{-3}) and *Chiny* (308.3 kgm^{-3}). The filling and emptying angles of repose ranged between 24.29 - 43.94^{0} and 13.01 - 44.98^{0} respectively. At all moisture contents, the coefficient of static friction was the greatest against rubber (0.52 - 1.05), followed by plywood (0.42 - 1), glass sheet (0.31

- 0.99), galvanized iron sheet (0.39 - 0.94), and the least for fiberglass sheet (0.38 - 0.98). Among cucurbit varieties, *Riz* and *Gushty* showed the least and the greatest static coefficients of friction in all moisture contents studied, respectively.

Aydin (2007) determined some physical properties of peanut fruit and kernel as functions of moisture content. At the moisture content of 4.9 % d.b. the average length, thickness, width, geometric mean diameter, sphericity, unit mass and volume of peanut fruits were 44.5 mm, 15.7 mm, 16.7 mm, 23.0 mm, 51.6 %, 2.2 g and 5.2 cm^3, respectively. Corresponding values for kernel at the moisture content of 6.0 % d.b. were 21.0 mm, 8.8 mm, 10.4 mm, 12.6 mm, 57.1 %, 1.1 g and 1.1 cm^3, respectively. Studies on re-wetted peanuts showed that the bulk density decreased from 243 to 184 kg/m^3, the true density, projected area, and terminal velocity increased from 424 to 545 kg/m^3, 4.9 to 6.9 cm^2 and 7.3 to 7.9 m/s, respectively as the moisture content increased from 4.9 to 32.0 % d.b.; for the kernel, the corresponding values changed from 581 to 539 kg/m^3, 989 to 1088 kg/m^3, 1.5 to 2.1 cm^2 and 7.5 to 8.1 m/s, respectively as the moisture content increased. The rupture strength of peanut and kernel decreased as moisture content increased. The dynamic coefficient of friction varied from 0.30 to 0.73 for peanut, and from 0.22 to 0.63 for kernel over different structural surface as the moisture content increased from 4.9 % to 32.0 % d.b.

Altuntas and Demirtola (2007) investigated the effect of moisture content on physical properties of some grain legume seeds such as kidney bean (*Phaselous vulgaris*), dry pea (*Pisum sativum*), and black-eyed pea (*Vigna sinensis*) seeds. Three different moisture contents for each grain legume were evaluated. The average length, width, thickness, geometric mean diameter, and unit mass of seeds ranged from 16.66, 8.86, 7.17, 10.17 mm, and 0.715 g for kidney bean; 7.46, 6.02, 4.49, 5.85 mm, and 0.158 g for pea; 9.19, 6.96, 6.26, 7.32 mm, and 0.255 g for black-eyed pea at a moisture content of 8.2, 8.2 and 5.7 % (wet basis), respectively. The sphericity, thousand - seed mass (1000 - seed mass), and projected area increased, whereas the bulk and kernel densities linearly decreased with an increase in moisture content for each grain legume seed. The porosity, the volume of seed, and angle of repose increased for three grain legumes seeds, whereas the angle of repose decreased for black - eyed pea seeds in the moisture contents studied. The static and dynamic coefficients of friction on various surfaces, namely, galvanized metal, chipboard, mild steel, plywood, and rubber also linearly increased with an increase in moisture content of each grain legume seed.

Moisture-dependent physical properties of Jatropha seed (*Jatropha curcas* L.) were determined by Garnayak et al. (2008). The study was conducted to investigate some moisture-dependent physical properties of jatropha seed namely, seed dimension, 1000 seed mass, surface area, sphericity, bulk density, true density, angle of repose and static coefficient of friction against different materials. The physical properties of jatropha seed were evaluated as a function of moisture content in the range of 4.75 – 19.57 % dry weight (d.w.). The average length, width, thickness and 1000 seed mass were 18.65 mm, 11.34 mm, 8.91 mm and 741.1 g, respectively at moisture content of 4.75 % d.b. The geometric mean diameter and sphericity increased from 12.32 to 12.89 mm and 0.66 to 0.67 as moisture content increased from 4.75 to 19.57 % d.w. respectively. In the same moisture range, bulk density of the rewetted jatropha seed decreased from 492 to 419 kg m^{-3}, true density increased from 679 to 767 kg m^{-3}, and the corresponding porosity increased from 27.54 to 45.37 %. As the moisture content increased from 4.75 to 19.57 % d.w., the angle of repose and surface area were found to increase from 28.15 to 39.95° and 476.78 to 521.99 mm^2, respectively. The static coefficient of friction of jatropha seed increased linearly against the surfaces of three structural materials, namely plywood (44.12 %), mild steel sheet (64.15 %) and aluminum (68.63 %) as the moisture content increased from 4.75 to 19.57 % d.w.

Moisture-dependent physical properties of wheat (*Triticum aestivum* L.) were studied by Kheiralipour et al. (2008). The physical properties of wheat grains (*Shiraz* variety) were determined as a function of moisture content in the range of 8 - 18 % wet basis (w.b.) using standard techniques. The average length, width and thickness were 6.78 mm, 3.45 mm and 2.84 mm, at a moisture content of 8 % w.b., respectively. In the moisture range from 8 % to 18 % w.b., studies on rewetted wheat grains showed that the thousand kernel weight (TKW) increased from 20.1 to 24 g, the surface area from 43.43 to 44.66 mm^2, the porosity from 0.42 to 0.44 %. Whereas the sphericity decreased from 0.6 to 0.58, the bulk density from 708.4 to 664 kgm^{-3} and the true density from 1222.4 to 1177.2 kg m^{-3} with an increase in the moisture content range of 8 –18 % w.b. The static coefficient of friction of wheat grains increased linearly against surfaces of three structural materials, namely, glass (0.33 – 0.4), plywood (0.46 – 0.55), and galvanized iron (0.34 – 0.54) and the static and dynamic angle of repose increased from 30.83 to 36.33^0 and from 37.33 to 47.33º, respectively as the moisture content increased from 8 to 18 % w.b.

Moisture - dependent physical properties of *Jatropha* fruit were also investigated by Pradhan et al. (2008) at various moisture levels. The average length, width, thickness and 1000 mass were 29.31 mm, 22.18 mm, 21.36 mm and 1522.10 g, respectively, at moisture content of 8.0 % d.b. The geometric mean diameter increased from 24.03 to 24.70 mm and the sphericity varied between 0.82 and 0.83 as moisture content increased from 8.0 % to 23.33 % d.b., respectively. In the same moisture range, the bulk and true densities decreased from 278 to 253 and 546 to 435 kg m^{-3}, respectively, whereas the corresponding porosity also decreased from 49.08 to 41.84 %. As the moisture content increased from 7.97 to 23.33 % d.b., crushing strength was decreased from 275 to 79 N, whereas the angle of repose and surface areas were found to increase from 36.41 to 41.72° and 1815.73 to 1917.59 mm^2, respectively. The static coefficient of friction of *jatropha* fruit increased linearly against the surfaces of three structural materials, namely plywood (47.81 %), mild steel (62.88 %) and aluminium (34.82 %) as the moisture content increased from 7.97 to 23.33 % d.b.

Zewdu and Solomon (2008) also worked on Moisture-dependent physical properties of Grass Pea *(Lathyrus sativus* L.) Seeds. The physical properties were studied at 8.5, 15.13, 21.43, and 30.66 % moisture content (wet basis). The length, width, thickness, geometric mean diameter, angle of repose and thousand grain mass increased linearly from 5.02 to 5.34 mm, 4.88 to 5.01 mm, 4.22 to 4.50 mm, 4.70 to 4.94 mm, 26.33 to 31.73 ° and 82.0 to 114.56 g, respectively with increase in moisture content from 8.5 to 30.66 %. Sphericity and porosity increased from 93.53 to 94.17 % and 34.24 to 37.1 %, with increase in moisture content from 8.5 to 15.13 % followed by a decrease from 94.17 to 92.46 % and 37.1 to 35.39 %, respectively when the moisture content increased from 15.13 to 30.66 %. The bulk and true densities decreased linearly from 882.58 to 744.00 kg m^{-3} and 1343.51 to 1205 kg m^{-3}, respectively. The coefficient of static friction increased from 0.301 to 0.443, 0.353 to 0.521 and 0.222 to 0.515 for mild steel, plywood and glass surfaces, respectively with increase in moisture content from 8.5 to 30.66 %. The coefficient of static friction was found to be highest for plywood (0.521 at 30.66 %) among the surfaces considered.

The effect of moisture content on physical properties of wheat was investigated by Karimi et al. (2009). Several physical properties of three popular wheat varieties (*Shiraz*, *Karoun* and *Shiroudy*) were determined and compared for moisture content in 8, 12 and 18 % w.b in 2007 in University of Tehran. The average length, width and thickness were 6.75, 3.26 and 2.77 mm at a moisture content of 8 % w.b., respectively. Studies on rewetted wheat seeds showed that the thousand-kernel weight increased from 18.38 to 22.43 g. The geometric and equivalent mean diameter, surface area, sphericity and aspect ratio at a moisture content of 8 % w.b were 3.93, 3.94 mm, 48.68 mm^2, 0.58, 0.48, respectively. The porosity increased from 0.43 to 0.45. Whereas the bulk density decreased from 0.72 to 0.66 kg m^{-3} and the true density from 1.25 to 1.19 kg m^{-3}, with an increase in the moisture content range of 8 – 18 % w.b. The static and dynamic angle of repose varied from 37.28 to 47.33 and 29.89 to 36.5^o. The mean of static friction coefficient of three wheat varieties increased linearly against surfaces of three structural materials, namely, compressed plastic (0.43 - 0.53), galvanized iron (0.33 - 0.53) and plywood (0.35 - 0.41) as the moisture content increased from 8 to 18% w.b.

Effect of moisture content on some physical properties of paddy grains was determined by Zareiforoush et al. (2009). In the study, various physical properties of two different paddy cultivars were determined at five moisture content levels of 8, 11, 14, 18 and 21 % (d.b.). In the case of *Alikazemi* cultivar, the average length, width, thickness, equivalent diameter, surface area, volume, sphericity, thousand grain mass and angle of repose increased from 9.83 to 10.05 mm, 2.65 to 2.76 mm, 1.92 to 2.01 mm, 3.72 to 3.85 mm, 39.37 to 42.12 mm^2, 26.91 to 29.94 mm^3, 37.51 to 38.04 %, 27.63 to 31.20 g and 35.67 to 41.23^o, respectively, as the moisture content increased from 8 to 21 % (d.b.). The corresponding values increased from 10.20 to 10.25 mm, 2.31 to 2.40 mm, 1.85 to 1.92 mm, 3.53 to 3.63 mm, 36.87 to 38.61 mm^2, 23.12 to 25.11 mm^3, 34.53 to 35.27 %, 24.43 to 27.80 g and 38.27 to 44.37^o, respectively, for *Hashemi* cultivar. For *Alikazemi* cultivar, the static coefficient of friction of grains increased linearly against three various surfaces, namely, glass (0.3168 - 0.4369), galvanized iron sheet (0.4179 - 0.4965), and plywood (0.4394 - 0.5264) as the moisture content increased from 8 to 21 % (d.b.). The corresponding value for *Hashemi* cultivar increased from 0.3577 to 0.4650, 0.4629 to 0.5082 and 0.4857 to 0.5452, respectively, against three mentioned surfaces.

Seyed and Fathi (2009) worked on some physical properties of grape (*Vitis vinifera* L.) seeds as a function of seed moisture content varying from 16.55 -5.21% (dry basis). The average values of seed length, width, thickness, geometric mean diameter, surface area, filling angle of repose and terminal velocity decreased linearly with a decrease in the moisture content from 8.28 - 7.74 mm, 4.5 - 4.26 mm, 3.32-3.12 mm, 4.97 - 4.68 mm, 77.86 - 68.98 mm^2, 27.53 - 23.78° and 6.8 - 6.3 ms^{-1} respectively. The unit mass decreased nonlinearly from 0.056 - 0.049 g whereas the variation of sphericity was not statistically significant with a decrease in moisture content. The bulk density increased in a polynomial trend from 577.3 - 586.6 kg m^{-3}, while the true density and porosity had a polynomial decrease from 886.2 - 873.7 kgm^{-3}, and 34.85 - 32.86 %, respectively, when the moisture content decreased from 16.55 - 5.21 %. The static coefficient of friction decreased linearly from 0.38 - 0.18, 0.37 - 0.22, 0.5 - 0.41, 0.38 - 0.2 and 0.48 - 0.4 for glass, fibreglass, plywood, galvanized iron sheet and rubber, respectively. The static coefficient of friction plywood surface was highest at all moisture contents investigated.

Moisture dependent geometrical properties of sunflower seed, *Azargol* variety was investigated by Khodabakhshian et al. (2009) at various moisture content levels (3 – 14 % d.b.) in three categories of big, average and small sizes. The ranges of length, width and thickness were 13.31 – 15.97, 5.01 – 7.50 and 3.11 – 4.38 mm, respectively. Also, the ranges of arithmetic, geometric and equivalent diameter were 5.93 – 8.07, 7.15 – 9.29 and 6.04 – 8.26 mm, respectively. The sphericity and surface area varied from 0.44 to 0.53 and 110.47 to 204.6 mm^2, respectively.

Tavakoli et al. (2009) carried out a research on the Moisture-dependent engineering properties of Soybean grains. The study was carried out to evaluate the effect of moisture content on some physical properties and mechanical behavior under compression load of soybean grains (*Glycine max*L.). Four levels of moisture content ranging from 6.92 to 21.19 % d.b. were used. The average length, width, thickness, arithmetic and geometric mean diameter, surface area, thousand grains mass and angle of repose increased as the moisture content increased from 6.92 to 21.19 %. As the moisture content increased from 6.92 to 21.19 % d.b., the bulk density and true density were found to decrease from 650.95 to 625.36 kg/m^3 and from 1147.86 to 1126.43 kg/m^3 respectively, while the porosity was found to increase from 43.29 to 44.48 %. The static coefficient of friction of soybean increased linearly against various surfaces as the moisture content increased from 6.92 to 21.19 % d.b. The rupture energy of the grains increased in magnitude with an increase in moisture content, while rupture force decreased.

Tavakoli et al. (2009) did some work on the Physical properties of Barley grains as a function of moisture content. The study was carried out to evaluate the effect of moisture content on some physical properties of barley grains. Four levels of moisture content ranging from 7.34 % to 21.58 % (d.b.) were used. The average length, width, thickness, arithmetic mean diameter, geometric mean diameter, thousand grain mass, sphericity, surface area and repose angle increased from 8.91 to 9.64 mm, 3.30 to 3.74 mm, 2.58 to 2.98 mm, 4.93 to 5.45 mm, 4.23 to 4.75 mm, 44.48 to 51.30 g, 47.55 % to 49.35 %, 56.66 to 71.09 mm^2 and 31 to 36 respectively, as moisture content increased from 7.34 to 21.58 % (d.b.). The bulk density, true density and porosity were found to decrease with increasing moisture content. The static friction coefficient of the grains increased linearly against various surfaces (plywood, glass and galvanized iron sheet) as the moisture content increased. At all moisture content, the maximum friction was offered by plywood, followed by galvanized iron sheet and glass surface.

Moisture dependent physical properties of Dragon's Head seeds *(Lallemantia iberic*a) were determined by Shafiee et al. (2009) as a function of moisture content. As the moisture content increased from 7.18 to 48.46 % (d.b.), the average length, width, thickness and the geometric mean diameter varied from 4.48 to 4.97 mm, 1.69 to 1.85 mm, 1.16 to 1.35 mm and 1.97 to 2.31 mm, respectively. In the same moisture range, studies on Dragon's head showed that, sphericity, surface area, thousand seed mass and true density increased from 41.73 to 46.50 %, 12.16 to 16.79 mm^2 and 9.75 to 11.17 g and 837.2 to 1047 kg/m^3 , respectively. As the moisture content increased from 7.18 to 48.46 % (d.b.), bulk density decreased from 584.23 to 438.26 kg/m^3 whereas the angle of repose and porosity increased from 27.16 to 43.33° and 30.17 to 58.12 %, respectively. The static coefficient of friction of Dragon's head seeds increased linearly against surfaces of three structural materials, namely, glass (0.25 – 0.63), plywood (0.42 - 0.70), and galvanized iron (0.32 – 0.64) as the moisture content increased from 7.18 % to 48.46 % (d.b).

Igbozulike and Aremu (2009) also investigated the Moisture dependent physical properties of *Garcinia kola* seeds. The properties are size, shape, densities, porosity, one thousand seed weight, static coefficient of friction on different structural surfaces and angle of repose. Linear regression equations were used to express relationship between the properties and moisture. Experimental results revealed that moisture content affected all the properties. The moisture ranged from 39.79 % to 52.45 %. The length, width and thickness of the seeds increased linearly from 28.425 to 32.644 mm, 15.849 to 17.542 mm and 14.524 to 16.043 mm, respectively. In the same moisture range, true density decreased from 1249 to 1161 kg/m^3, bulk density increased from 690 to 728 kg/m^3, while porosity decreased from 44.76 to 37.24 %. The angle of repose was found to vary from 30.42 to 40.86^0. In the same moisture range, the static coefficient of friction against different structural materials varied from 0.20 to 0.46.

Physico - chemical grain properties of new common bean *CV. 'Elkoca - 05'* were determined by Ozturk et al. (2009) according to three selected moisture content; 7.50, 15.28, and 19.85 % d.b. In addition, some chemical and color parameter of the grain were studied. The average length, width, and thickness of grain were 14.38, 6.83, and 5.86 mm at 7.50 % d.b moisture content. The values of bulk density of the grains were determined as 811.57, 755.17 and 726.10 kg m^{-3} at 7.50, 15.28 and 19.85 % moisture content. The coefficients of dynamic friction increased from 0.173 to 0.353, 0.174 to 0.261, and 0.214 to 0.316 for steel, plywood, and wood with increasing moisture content. The force of rupture decreased from 138.09 to 100.65 N with increasing moisture content.

Moisture dependent physical properties of four common Iranian varieties of Canola seeds were determined by Razavi et al. (2009) viz; *Hyola*, *Okapi*, *Orient* and *SLM*) were evaluated as a function of their moisture contents. The average seed length and thousand seed mass varied linearly from 1.925 to 2.262 mm and from 3.06 to 4.84 g, respectively. The average diameter, geometric mean diameter, and sphericity varied non-linearly from 1.475 to 1.911 mm, 1.625 to 2.02 mm and from 0.82 to 0.93, respectively in a moisture content range of 5.27 to 23.69 % wet basis (w.b.). Among the varieties, *Hyola* had the highest values for length, diameter, geometric mean diameter, sphericity and thousand seed mass at all moisture levels. Maximum and minimum values of bulk density were obtained for *SLM* (738.8 kgm^{-3}) and *Hyola* (666.06 kgm^{-3}). The filling and emptying angles of repose ranges were determined as 25.37 - 28.54º and 25.48 - 28.68º respectively. At all moisture content levels, the static coefficient of friction was the greatest against rubber (0.372 - 0.460), followed by plywood (0.358 – 0.449), galvanized iron sheet (0.301 – 0.419) while fibreglass sheet (0.260 - 0.414) while the least for glass sheet (0.253 – 0.392). Among the four canola varieties, *Orient* and *SLM* showed respectively the least and the greatest static coefficients of friction at all moisture levels studied.

Firouzi et al. (2009) evaluated some physical properties of Groundnut (*Arachis Hypogaea*) as a function of moisture content. The average length, width, thickness, geometric mean diameter, unit mass, volume and sphericity were 20.83, 11.08, 8.94, 12.71 mm, 1.11 g, 1.16 cm^3 and 61.12 %, respectively, at the moisture level of 8 % d.b. The angle of repose increased from 30.3 to 37.2º with increasing moisture content from 8 to 32 %, d.b. The static friction coefficient of groundnut kernel increased against the surface of two structural materials, wood (0.35 to 0.69) and galvanized sheet (0.25 to 0.49), with increasing groundnut moisture level (8 to 32 % d.b). Amount of true density in groundnut kernel increased from 937.7 to 1112.5 kgm^{-3}, while the bulk density decreased from 538.5 to 434.8 kgm^{-3} with increase in moisture content.

Seed moisture - dependent physical properties of *Turgenia latifoli*a (T.L) were studied by Nalbandi et al. (2010). Some physical properties of wheat kernels (*cv. Sardari*) and T.L. seeds, namely axial dimensions, equivalent diameter, sphericity, bulk density, true density, angle of repose and static coefficient of friction as a function of moisture content, 7 to 20.8 % w.b. were investigated. There was significant difference between all physical properties of wheat and T.L seeds and the effect of moisture content on these properties was significant except for true density and length. True density varied polynomially from 1270 to 1300 kg/m^3 and from 970 to 1080 kg/m^3 for wheat and T.L. seeds, respectively, as their moisture content increased. Wheat and T.L. had the lowest static coefficient of friction on the plywood and steel surface, respectively. The highest static coefficient of friction was obtained on the aluminum surface for both of them. However, there was high significant difference between the true density of wheat and T.L seeds and the static coefficient of friction on the aluminium surface. Therefore, these properties can be used to design separation equipments for cleaning wheat seeds of weed seeds.

Davies (2010), worked on engineering properties of three varieties of melon seeds as potentials for development of melon processing machines. The engineering properties of melon seeds for three different varieties: *C. edulis, C. vulgaris and C. lanatus* were investigated at the moisture content of 6.25, 6.33 and 5.21% dry basis respectively. The axial dimension, mean diameter, sphericity, surface area, porosity, true and bulk density, angle of repose, coefficient of friction of the three varieties of melon seeds were determined using standard methods. The result obtained from the study revealed that length, width, thickness, arithmetic and geometric diameter, sphericity, surface area and 1000 unit mass ranged from 12.81 - 14.50 mm, 7.02 - 8.42 mm, 2.22 - 2.49 mm, 7.36 - 8.31 mm, 5.84 - 6.54 mm, 0.47 - 0.53, 134.64 - 192.23 mm^2 and 94.0 - 110.0 g respectively. The static coefficient of friction was determined for four frictional surfaces, namely, glass, plywood, galvanized steel and concrete. The highest coefficient of friction was observed in concrete surface for all the three varieties of melon investigated. The ratio of length to width, length to thickness and length to mass were equally investigated.

Moisture-dependent physical properties of Sunflower seed *(SHF819*0) were determined by Mohammad and Reza (2010) as a function of moisture content in the range of 4 - 22 % wet basis (w.b.) using standard techniques. The average length, width, thickness, geometric mean diameter, equivalent diameter, arithmetic diameter, sphericity, surface area and angle of repose ranged from 12.14 to 12.57 mm, 5.79 to 6.38 mm, 3.86 to 4.09 mm, 6.47 to 6.85 mm, 6.56 to 6.97 mm, 7.27 to 7.61 mm, 53.33 to 55.42 %, 112.16 to 125.01 mm^2 and 41 to 57° as the moisture content increased from 4 to 22 % w.b. respectively. The thousand grain weight (TGW) increased from 80.3 to 96.8 g whereas the bulk density decreased from 410 to 380 kgm^{-3} and the true density from 740 to 980 kgm^{-3} with an increase in the moisture content range of 4 – 22 % w.b. The data of sunflower seeds showed that the porosity ranged from 44.59 to 61.22 %. The static coefficient of friction of sunflower seeds increased linearly against different surfaces of structural materials, namely, plastic (0.29 – 0.55), plywood (0.36 – 0.53), and galvanized iron (0.36

– 0.55) and the static angle of repose increased from 41 to 57º, respectively when the moisture content increased from 4 to 22 % w.b.

A study was carried out by Figueiredo et al. (2010) to investigate the effect of the moisture content of the seeds on engineering properties of sunflower hybrids with different structural characteristics. The properties were evaluated at seven levels of moisture from 2.0 to 20.1 % (dry basis) for three selected sunflower hybrids. For both black-hull oilseed hybrid and confectionary hybrid, the variation in moisture content showed a statistically significant effect on dehulling ability, percentage of fines (broken grains with a diameter smaller than 2 mm) and all the physical properties studied (size, true density, bulk density, porosity, volume and weight, volumetric expansion coefficient, equivalent diameter and sphericity), except seed length in the confectionary hybrid and seed length and thickness in the black-hull oilseed hybrid. For the striped-hull oilseed hybrid, moisture content showed a significant effect only on dehulling ability, percentage of fines, seed width and thickness, bulk density and porosity. Of the oilseed hybrids, the striped hull genotype (higher hull content and both lower oil content and seed size) presented a higher dehulling ability. Nevertheless, the black hull hybrid resulted more sensitive to seed moisture changes. Although the confectionary hybrid showed a higher seed size, hull thickness and hull content, and lower oil content than the oilseed hybrids, the dehulling ability resulted fairly similar in the striped hull sunflower hybrids. The results suggest that sunflower seeds with different structural characteristics need to be conditioned with different moisture content before being subjected to the dehulling process.

Khodabakhshian et al. (2010), in their study evaluated gravimetric properties of three common varieties of Iranian sunflower seeds and their kernels (namely; *Shahroodi, Fandoghi* and *Azargol*) as a function of size category and variety with moisture content ranging from 3 to 14 % (d.b). In this moisture range, thousand grain mass, true volume, true density and porosity increased linearly for both seed and kernel in all varieties and categories. The bulk density of seeds and kernel linearly decreased as moisture content increased from 3 to 14 % (d.b). The true density of *Fandoghi, Azargol* and *Shahroodi* seeds for all sizes were found to vary from 700.80 to 791.22, 666.66 to 749.30, 718.59 to 800.70 kgm^{-3} while this value for the corresponding kernels varied from 104.60 – 1210.10, 1029.9 – 1199.9 and 1109.6 – 1249.9 kgm^{-3}, respectively with increase in moisture content from 3 to 14 %.

2. ***Mechanical properties***

Mechanical properties of wheat seed coats were evaluated by Mabille *et al*. (2001). They stated that the crumbliness of starchy endosperm and the resistance of bran are key characteristics that enhance milling behavior of wheat and are dependent on the genetic origin and moisture content of the grain. A method was developed to measure the mechanical properties of bran samples based on the measurement of tensile stress and strain. Tests conducted with this highly reproducible and sensitive method documented cultivar and moisture-content effects (6.3, 13.8, and 18 %, w.b.) on rheological behavior of wheat seed coats. A moisture-dependent reduction in stress to fracture (– 15 to – 30 %) and in Young's modulus (– 45 to – 55 %) was quantified. An increase in deformation to fracture of seed coats was also correlated with bran size differences after milling. The energy required to fracture a sample (from 0.4 to 1.3 J/mm^3) was considered the most valid of all presented parameters for assessing the milling behavior of wheat seed coats and the size of bran fractions.

Mass - volume - area related and mechanical properties of soybean as a function of moisture and variety were determined by Tunde-Akintunde et al. (2005) within a moisture content range of 6.3 to 11.6 % dry basis. The seed length, width and thickness for the three varieties increased with increase in moisture content while the sphericity and roundness of the three varieties increased within the range of 43.0 to 72.3 % and 45.5 to 75.9 % respectively. True density, bulk density and porosity decreased with increase in moisture content from 1203 to 964 kgm^{-3}, 809 to 740 kgm^{-3} and 0.35 to 0.22 respectively. The coefficient of friction also decreased with increase in moisture and the highest and lowest value were 23.7 and 17.3 on plywood while these on glass were 19.8 and 11.6, respectively. The angle of repose and terminal velocity increased from 10.2 to 15.3° and 10.1 to 12.6 m/s respectively for the varieties. The compressive force however decreased and the highest and lowest value were 12.85 and 3.5 N respectively for the three varieties.

Fraczek et al. (2005) worked on the effect of seed coat thickness on seed hardness. The study was carried out to determine the effect of seed coat thickness on the hardness of selected seeds at different levels of moisture content. The research was conducted on twelve seed types with and without coats at five levels of moisture content (0.11, 0.15, 0.19, 0.23, and 0.33 kg/kg dry mass (dm)). The study showed that the hardness of studied seeds decreased rapidly at levels of moisture content ranging from 0.11 to 0.19 kg/kg (dm). Moisture content was significantly correlated with the hardness of the seeds studied. Differences in hardness between seeds with and without coats decreased gradually with increased moisture content. The seeds were grouped into seven groups and an empirical equation was developed to describe the hardness of all these groups, using different regression coefficients.

Moisture dependent physical and compression properties of safflower seed were investigated by Baümler et al. (2006). The objective of the study was to investigate the effect of moisture content on some physical properties and fracture resistance of the safflower seeds typically cultivated in Argentina. The safflower seeds have an oil content of 43 ± 3.6 % dry basis (d.b.), 37 % (d.b.) hull contents and the initial moisture content of the safflower seeds was 6.9 % (d.b.). The results obtained showed that the modifications of moisture content of safflower seed caused a little variation in its size, its hull thickness being the most affected. The volume and weight of the seed, the expansion coefficient, the equivalent diameter and the sphericity increased linearly with the increase in the seed moisture content. The true density varied nonlinearly in the considered range of moisture content. At the same time, an increase in moisture content yielded a decrease in bulk density trend and a linear increase for the porosity of the bed of grain. Under compression, the seeds rupture force was in the range of 40 – 20 N for vertical and horizontal loading orientation; the seeds were more flexible in the horizontal loading direction, and the rupture under vertical loading direction required less energy than under horizontal loading.

Isik and Izil (2007) determined the physical and mechanical properties of dent corn seeds as a function of moisture content in the range of 11.1 – 24.1 % dry basis (d.b). The average length, width and thickness were 10.9, 8.2 and 4.5 mm, at a moisture content of 11.1 % d.b., respectively. In the above moisture range, the arithmetic and geometric mean diameters and sphericity increased from 7.8 – 8.5 mm, from 7.4 – 8.0 mm and from 0.67 – 0.68 respectively. Studies on rewetted dent corn seeds showed that the thousand seed mass increased from 430 – 542 g, the projected area from 54.5 – 68.9 mm^2, the true density from 995.1 – 1100.1 kg m^{-3}, and the porosity from 29.6 – 44.5 % and the terminal velocity from 6.2 – 7.5 m sec^{-1}. The bulk density decreased from 700.5 – 610.5 kg m^{-3} with an increase in the moisture content range of 11.1 – 24.1 % d.b. The static coefficient of friction of dent corn seeds increased the logarithmic against surfaces of six structural materials, namely, rubber (0.42 – 0.51), aluminium (0.41 – 0.49), stainless steel (0.31 – 0.36), galvanized iron (0.31 – 0.39), glass (0.27 – 0.33) and MDF (medium density fiberboard) (0.28 – 0.35) as the moisture content increased from 11.1 – 24.1 % d.b. The shelling resistance of dent corn seeds decreased as the moisture content increased from 116.1 to 80.4 N.

Effects of moisture content, seed size, loading rate and seed orientation on force and energy required for fracturing cumin seed (*Cuminum cyminum Linn.*) under quasi - static loading was studied by Saiedirad et al. (2008). In the research, fracture resistance of whole cumin seed was measured in terms of average compressive force, seed rupture force and energy absorbed. In this study 10 treatments were performed as randomized complete block design with 20 replications. Cumin seeds were quasi-statically loaded in horizontal and vertical orientations with moisture contents in three levels: 5.7, 9.5 and 15 %; seed size in three levels: small, medium, and large; loading rates in two levels: 2 and 5 mm/min; and two seed orientations: horizontal and vertical. The results showed that the force required for initiating seed rupture decreased from 15.7 to 12.0 N and 58.2 to 28.8 N and the energy absorbed at seed rupture increased from 1.8 to 8.6 mJ and 7.6 to 14.6 mJ, with increase in moisture content from 5.7 % to 15 % d.b. for vertical and horizontal orientations, respectively. This showed that seeds are more flexible in horizontal orientation. Rupture force requires less energy under vertical loading than horizontal loading. Maximum energy absorbed was found to be 15.3 mJ for small seed with 15 % moisture content under horizontal loading. Minimum energy observed was 1.73 mJ for large seed with 5.7 % moisture content under vertical loading. The highest mechanical strength (60 N) is related to a small seed with a moisture content of 5.7 % under horizontal loading and the lowest (10.8 N) is attributable to a large seed with a moisture content of 15 % under vertical loading. Energy absorbed by the small seed at high moisture content increased in horizontal orientations of loading.

Physical and mechanical properties of barley were evaluated by Öztürk and Esen (2008). The physical and mechanical properties were evaluated as a function of moisture content of grain varying from 10 to 14 % (db). In this moisture range, as the bulk density decreased linearly from 647.34 to 623.00 kg/m^3, true density increased linearly from 984.00 to 1013.67 kg/m^{-3}. The porosity and angle of internal friction increased with the increase in the grain moisture content up to 38.50 % and 22.50 %, respectively, at 14 % moisture content. The static coefficient of friction increased from 0.877 to 0.993, 0.773 to 0.920, 0.560 to 0.713 for concrete (BS 30), galvanized steel and wood surfaces respectively.

Moisture dependent physical and mechanical properties of red bean *(Phaseolus vulgaris* L.) grains were investigated by Kiani Deh Kiani et al. (2008). The study was aimed at assessment of some physical properties of red bean grains as a function of moisture content. Based on the results obtained, with increasing moisture content, grain dimensions as well as thousand grain mass increased. In the moisture content range of 10 to 20 % w.b., the surface area, true density, and porosity values increased by 10.6 - 19.7, 4.76 - 6.24, and 17.91 – 21 %, respectively. This increase in moisture content caused a decrease in bulk density values by 8.35 and 9.70 % for the varieties of *Goli* and *Akhtar*, respectively. Coefficient of static friction (*Goli* and *Akhtar*) increased against surfaces of rubber (27.3 and 27 %), galvanized iron (50 and 28.5 %), and plywood (32 and 21.4 %) as the moisture content increased. Mechanical properties were determined in terms of average rupture force, deformation at rupture point, and rupture energy. Deformation and rupture energy of red bean grains generally increased in magnitude with an increase in moisture content, while rupture force decreased.

Moisture-dependent physical and mechanical properties of *Cumin* (*Cuminum cyminum L.*) seed were evaluated by Mollazade et al. (2009) as moisture content changed from 7.24 % to 21.38 % d.b. Increasing moisture content was found to increase the seed length (5.14 - 5.58 mm), width (1.33 - 1.55 mm), thickness (0.97 - 1.05 mm), arithmetic mean diameter (2.48 - 2.73), geometric mean diameter (1.88 - 2.09 mm), surface area (10.34 - 12.66 mm^2), thousand seed weight (2.9 - 3.9 g), porosity (51.22 - 64.11 %), true density (917.8 - 1030.6 kg/m^3), static angle of repose (43 - 49^0), dynamic angle of repose (47 - 56.6^0), and coefficient of static friction on the three surfaces: glass (0.48 - 0.77), galvanized iron sheet (0.36 - 0.73), and plywood (0.57 - 0.69). However, bulk density was found to decrease from 447.66 - 369.88 kg/m^3, and rupture force and rupture energy along with seed length and width were found to decrease from 83.74 - 56.17 N, 132.95 - 84.47 N, 50.66 - 27.52 mJ, and 67.8 to 33.36 mJ, respectively. The sphericity increased from 36.63 to 37.5 % with increase in moisture content from 7.24 to 14.5 % d.b. and then reduced to 37.5 % with further increase in moisture content to 21.38 % d.b.

Ahmadi et al. (2009) worked on the Post harvest physical and mechanical properties of Apricot fruits, pits and kernels (*C.V. Sonnati Salmas*). Properties such as dimensions, geometric mean diameter, sphericity, surface area, bulk density, true density, porosity, volume, mass, true density, bulk density, porosity, 1000 - unit mass, coefficient of static friction on various surface and rupture force in three axes, were determined at 82.34, 16.48 and 13.03 % moisture contents for apricot fruits, apricot pits and apricot kernels respectively. Bulk densities of fruits, pit and kernels were 443.2, 539.4 and 540.1 kg/m^3, the corresponding true densities were 940.7, 1045.5 and 1023.6 kg/m^3 and the corresponding porosities were 52.87, 48.40 and 47.21 %, respectively. The volumes, mass and surface area of fruits were larger than those of pits and kernels. Static coefficient of friction of fruit on all surfaces (wood, glass, galvanized sheet and fiber glass sheet) were measured and static coefficient of friction was less for pits and kernels on glass and their value were 0.474 and 0.188, respectively. Rupture force of fruit, pit and kernel were 10.11, 497.79 and 18.92 N through length, 7.98, 322.59 and 41.97N through width and 7.01, 337.21 and 99.58 N through thickness. Results showed that rupture force through length were minimum. It was further stated in the report that this result is a very important factor in the design of apricot pit crasher machine.

Physico - mechanical seed properties of the common Turkish bean (*Phaseolus vulgaris*) cultivars *'Hinis'* and *'Ispir'* were evaluated by Ozturk et al. (2009). The objective of this study was to determine the geometrical, gravimetrical, frictional, aerodynamic, colour, and mechanical properties of two common bean (*Phaseolus vulgaris*) cultivars *'Hinis'* and *‘Ispir'*, which dominate bean production in *Erzurum*, Turkey. The average length, width, thickness, geometric mean diameter, sphericity, and projected area were found to be: 11.76 and 12.29 mm, 8.85 and 9.10 mm, 7.66 and 7.99 mm, 78.90 and 78.45%, and 92.02 and 99.37 mm^2 for *'Hinis'* and *'Ispir'*, respectively. The average 1000 seed weight, bulk density, and porosity were determined as: 531.3 and 598.9 g, 835.8 and 872.7 kg m^{-3}, and 34.0 % and 33.1 % for *'Hinis'* and *'Ispir'*, respectively. The average angle of repose and terminal velocity were 24.52 and 19.46°, and 11.42 and 11.80 ms^{-1} in *'Hinis'* and *'Ispir'* respectively. The highest coefficient of dynamic friction was obtained with an aluminium surface in both cultivars as 0.227 for *'Hinis'* and 0.199 for *'Ispir'*. This was followed by fibreglass, steel, plywood, and glass surfaces. Both cultivars had white testa. The average value of rupture force, deformation at rupture point, energy absorbed, hardness, and toughness along the X-direction were found to be: 145.9 and 118.4 N, 0.85 and 0.90 mm, 63.8 and 54.0 Nmm, 171.0 and 132.5 N mm^{-1}, and 0.15 and 0.12 mJ cm^{-3} for *'Hinis'* and *'Ispir'*, respectively.

Ahmadi et al. (2009) determined the physical and mechanical properties of Fennel Seed (*Foeniculum vulgare*) as a function of moisture content in the range of 7.78 – 21.67 % d.b. The average length, width and thickness were 58.87, 18.96 and 15.64 mm, at a moisture content of 7.78 % d.b. respectively. In the moisture range from 7.78 % to 21.67 % d.b. Studies on rewetted fennel seed showed that the thousand seed weight increased from 5.5 to 9.2 g, the porosity from 55.91 % to 62.21 %, the static and dynamic angle of repose from 37.6 to 46.6 and 41 to 53.3 respectively, the coefficient of friction on glass, plywood and galvanized iron sheet surfaces from 0.55 to 0.74, 0.45 to 0.63 and 0.43 to 0.66 respectively and deformation on width section increased from 1.68 to 1.86 mm. The bulk density decreased from 413.51 to 352.39 kg m^{-3} and rupture force on both seed length and width sections decreased from 198.93 to 78.68 N, and 600.65 to 186.44 N, respectively, with moisture content in the moisture range of 7.78 to 21.67 % d.b. But there was no regular trend for sphericity, true density, and deformation on length section with increasing moisture content.

Akbarpour et al. (2009) evaluated the mechanical properties of pomegranate seeds as a function of moisture content ranging from 10.06 to 22.91 % (w.b). Length, width, thickness, geometric mean diameter, sphericity and 1000 seed mass increased linearly 3.55, 3.48, 8.87, 5.22, 1.61 and 30.04 % respectively with increasing moisture content (as stated above). Bulk and true densities increased linearly from 569.3 to 646.3 kgm^{-3} and 1057.3 to 1147.2 kgm^{-3}, respectively while porosity decreased from 46.15 to 43.66 %. In the same increasing moisture range, the angle of repose increased from 21.35 to 29.4º, static coefficient of friction increased linearly for concrete (7 %), galvanized iron sheet (7.59 %), plywood (8.05 %) and glass sheet (9.26 %), respectively. The highest static coefficient of friction was observed on concrete and the lowest on glass sheet among the materials tested.

Kibar et al. (2010) worked on the effect of moisture content on physical and mechanical properties of rice *(Oryza sativa* L.). The objective of the study was to investigate some physical and mechanical properties of *Osmancýk - 97* rice variety widespread cultivated in Turkey in order to determine needed designing parameters for handling and storage facilities. In this study, some physical and mechanical properties were evaluated as a function of moisture content in the range of 10 – 14 % d.b. Length, width, thickness, arithmetic and geometric mean diameter ranged from 8.27 to 9.01 mm, 3.10 to 3.48 mm, 2.05 to 2.26 mm, 4.47 to 4.92 mm, 3.75 to 4.13 mm, respectively as the moisture content increased; sphericity, grain volume, surface area, true density and porosity increased from 43 to 45 %, 130.97 to 160.32 mm^3, 38.68 to 46.91 m^2 , 939.0 to 962.1 kgm^{-3}, and 36.61 to 41.97 %; bulk density decreased from 595.5 to 560.5 kgm^{-3} ; the angle of internal friction increased linearly from 29.70 to 32.53° with the increase of moisture content; the static coefficient of friction increased from 0.764 to 0.972, 0.524 to 0.702 and 0.576 to 0.764 for concrete, galvanized steel and wood surfaces, respectively; the poisson ratio and pressure ratio decreased linearly with the increase of moisture content. The report stated that the data obtained from the study will be useful in the structural design of rice bin to calculate loads on bins from the stored material.

Gorji et al. (2010) studied the fracture resistance of wheat grain as a function of moisture content, loading rate and grain orientation. In the research, fracture resistance of wheat grain was measured in terms of grain rupture force and energy. The wheat grains were quasi-statically loaded in horizontal and vertical orientations with moisture content in three levels: 7.8, 15, and 20 %; and loading rate in two levels: 5 and 10 mm min^{-1}. Based on the results obtained, the force required for initiating grain rupture decreased from 77.68 to 35.7 N and 152.11 to 63.99 N, and the energy absorbed at grain rupture increased from 17.8 to 24.34 mJ and 19.32 to 28.35 mJ, with increase in moisture content from 7.8 to 20 % d.b. for vertical and horizontal orientations, respectively. This showed that grains are more flexible in horizontal orientation. Rupture force requires less energy under vertical loading than horizontal loading. Maximum energy absorbed was found to be 32.40 mJ for grain with 20 % moisture content under horizontal loading and 5 (mm min^{-1}) loading rate. The highest mechanical strength (162.61 N) is related to grain with a moisture content of 7.8 % under horizontal loading and 5 mm min^{-1} loading rate. Energy absorbed by the seeds decreased as increased loading rate.

Effects of moisture content and compression positions on mechanical properties of carob pod *(Ceratonia siliqua* L.) were studied by Ekinci et al. (2010). In the study, rupture force, bioyield force, rupture deformation, bioyield deformation, modulus of elasticity and rupture energy were determined for carob pod as functions of moisture content at four different levels of 8.3, 13.2, 14.1, 16.8 % wet basis (w.b.) and compression positions of Horizantal 1 (H1), Horizantal 2 (H2), Vertical 1 (V1), and Vertical 2 (V2). The biological material test device was used to measure the mechanical properties of carob pod. Results showed that rupture force, bioyield force, modulus of elasticity and rupture energy decreased with increase in moisture content of carob pod. The rupture force ranged from 101.0 to 197.0 N while the bioyield force varies between 84.0 and 159.0 N. The modulus of elasticity changed between 22.5 and 43.8 N mm^{-2}. The range of the rupture energy calculated was between 268 and 419 J. The results showed that rupture force measured at the horizontal positions (H1 and H2) were higher than that of the vertical positions (V1 and V2).

3. *Thermal properties*

Some physical properties of fababeans were investigated by Fraser et al. (1978). The specific heat of fababeans, tick beans, (*Vicia faba* L.) was measured at four moisture contents (10·3, 14·5, 19·5 and 25·0 % wet weight basis) and four temperature ranges (− 32 to 20 °C, 0 to 20 °C, 0 to 40 °C and 0 to 60 °C). The specific heat of fababeans varied from 1·35 kJ kg^{-1} K^{-1} at 10·3 % moisture content (in the temperature range − 32 to 20 °C) to 2·25 kJ kg^{-1} K^{-1} at 24·6 % moisture content (in the temperature range 0 to 60 °C). The angle of repose of fababeans measured for four moisture contents varied from 0·36 rad at 8·5 % moisture content to 0·41 rad at 20·9 % moisture content. For the moisture content range of 8·5 to 21·6 %, the static coefficients of friction of fababeans ranged from 0·28 to 0·46 parallel to the plywood grain, 0·32 to 0·55 perpendicular to the plywood grain and 0·32 to 0·38 on galvanized steel. Bulk density decreased with increasing moisture content from 850 kg m^{-3} at 8·5 % moisture content to 730 kg m^{-3} at 34·8 % moisture content. The 1000-kernel weight was 405 g at 8·5 % moisture content, wet weight basis. Though the static coefficient of friction was determined for fababeans on plywood and galvanized sheet, it is necessary to do so for more different engineering material surfaces to enhance an appropriate choice of material for the construction of machine components.

Taiwo et al. (1996) determined the effects of temperature (50–80 ^{0}C) and moisture content 9.1-41.2 % (wet basis) on the specific heat of ground and hydrated cowpea using the method of mixtures. For most of the samples, the specific heat was highest either at 60 °C or 28.6 % moisture content. Further increase beyond these levels resulted in a decrease in the specific heat. Density was determined at room temperature. An initial decrease was observed in density of the samples as moisture level increased from 9.1 % but above 23.1 % moisture content, the density increased with higher moisture levels. Thermal conductivity was determined by the line probe method. The report conclusively stated that thermal conductivity of ground and hydrated cowpea was dependent on moisture content and bulk density but independent of temperature.

The thermal properties, namely specific heat, thermal conductivity and thermal diffusivity of cumin seed were determined by Singh and Goswami (2000). The specific heat increased from 1330 to 3090 J/kg K with increase in temperature from -70 to 50 °C and moisture content from 1.8 to 20.5 % dry basis. The thermal conductivity increased from 0.046 to 0.223 W/m K with the increase in temperature from -50°C to 50°C and moisture content from 1.8 to 20.5 % dry basis. The thermal diffusivity increased from 6.53 x 10^{-8} to 16.64 x 10^{-8} m^2/s with increase of temperature from -50 to 50 °C at the moisture content of 7.8 % dry basis. At a temperature of 10 °C, the thermal diffusivity decreased from 14.72 x 10^{-8} to 12.87 x 10^{-8} m^2/s, with an increase in moisture content from 1.8 to 11.1 % dry basis, and thereafter increased to 13.96 x 10^{-8} m^2/s at 20.5 % dry basis. The specific heat, thermal conductivity and thermal diffusivity displayed second order polynomial relationships with temperature and moisture content.

Thermal conductivity, specific heat capacity and thermal diffusivity of borage (*Borago officinalis*) seeds were determined by Yang et al. (2002) at temperatures ranging from 6 to 20 ^{0}C and moisture contents from 1.2 to 30.3 % w.b. The specific heat capacity ranged from 0.77 to 1.99 kJ $kg^{-1}K^{-1}$ and thermal conductivity ranged from 0.11 to 0.28 $Wm^{-1}K^{-1}$ and increased with moisture content in the range of 1.2 – 30.3 % w.b. The thermal diffusivity ranged from 2.32 x 10^{-7} to 3.18 x $10^{-7} m^2 s^{-1}$. Bulk density of borage seeds followed a parabolic relationship with moisture content. Uncertainty analysis revealed that variation in the thermal conductivity contributed mostly to the accuracy of the thermal diffusivity.

The specific heat of Iranian pistachio nuts was measured as a function of variety (*Ohadi, Momtaz, Sefid,* and *Kalle-Ghochi),* moisture content (initial moisture content, 25, 15 and 5 % (w.b.), and temperature (25, 40, 55 and 70 ^{0}C) by Razavi and Taghizadeh (2007). Specific heat was found to be significantly dependent of the variables studied. The specific heat of each cultivar increased with increase in moisture content and temperature in the range of 0.419 –2.930 kJ/kg K, however, the effect of moisture content was greater than both variety and temperature. Regression models with high R^2 values were developed to predict the specific heat of pistachio varieties as a function of moisture content and temperature individually, and both moisture content and temperature.

Aghbashlo et al. (2008) determined the specific heat and thermal conductivity of *berberis* as well as to develop mathematical models for estimating them. The method of mixtures and hot wire as a heating source was used for measuring the specific heat and thermal conductivity of *berberis* fruit, respectively. The selected variables to simulate variations of *berberis* thermal properties were moisture content and temperature. The measurements were done at 50, 60 and 70 ºC temperature levels and 19.3, 38.5, 55.4 and 74.3 % (d.b) moisture content levels. The results showed that the specific heat and thermal conductivity of *berberis* increased linearly from 1.9653 to 3.2811 kJ/kg ºC and 0.1324 to 0.4898 W/m °C, respectively with increase in the experimental range of the variables. However, the effect of moisture content on increasing the specific heat and thermal conductivity is more than that of temperature. Regression equations were established which could be used to reasonably estimate the values of the specific heat and thermal conductivity as a function of specified moisture content and temperature.

The specific heat, thermal conductivity and thermal diffusivity of whole and ground guna seed and kernel were evaluated and their change with moisture content and temperature investigated by Aviara et al. (2008). The specific heat of whole and ground seed increased from 1391.1 to 3020.13 and from 1459.14 to 3058.15 J kg^{-1} K^{-1}, respectively, as the moisture content and temperature increased from 4.7 to 25.35 % (d.b.)

and 307.12 to 368 K. The specific heat of whole and ground kernel also increased from 2135.15 to 4275.56 and from 2173.4 to 4340.06 Jkg^{-1}K^{-1}, respectively, as the moisture content and temperature increased from 5.6 to 19.13 % (d.b.) and 308 to 368 K. The thermal conductivity of whole seed and kernel increased from 0.0711 to 0.1282 and 0.087 to 0.126 W m^{-1}K^{-1}, respectively, as the moisture content and temperature increased. Thermal conductivity of ground seed and kernel increased also from 0.125 to 0.223 and 0.107 to 0.191Wm^{-1}K^{-1}, respectively, as the moisture content and temperature increased. The thermal diffusivity of whole seed and kernel decreased from 8.5 x 10^{-8} to 9.311 x 10^{-8} and 3.42 x 10^{-8} to 4.397 x 10^{-8} m^{2} s^{-1}, respectively, as the moisture content and temperature increased. The thermal diffusivity of ground seed and kernel decreased from 3 x 10^{-7} to 8.468 x 10^{-8} and 1.768 x 10^{-7} to 4.214 x 10^{-8} m^{2} s^{-1}, respectively, as the moisture content and temperature increased.

Bamgboye and Adejumo (2010) also determined the thermal properties of roselle seeds as a function of moisture content. The initial moisture content of seeds was determined using the ASAE standard. Tests were carried out on the seeds at five moisture content levels from 8.8 to 19 % (d.b.). The specific heat capacity was determined by the mixture method, thermal conductivity by steady state heat of vaporization method and the thermal diffusivity empirically. They reported that specific heat capacity increased in the range 4.04 - 5.63 kJ kg^{-1}K^{-1}, thermal conductivity in the range 1.22 - 1.56 W m^{-1}K^{-1} and thermal diffusivity in the range 4.274 to 4.877 x 10^{-4} m^{2} s^{-1}. They concluded that these values indicated the ability of the material to retain heat which enhances oil recovery.

The specific heat, thermal conductivity, and thermal diffusivity, of peanut pods, kernels, and shells were evaluated as a function of moisture content by Bitra et al. (2010). The specific heat and thermal conductivity were measured using purpose - built vacuum flask calorimeter and transient state heat transfer apparatus, respectively. The specific heat was determined by mixing hot water with sample maintained at ambient temperature in the calorimeter and incorporating temperature - correction into calculations. Thermal conductivity was determined in 60 - min experiments after checking for time - correction in the calculations. Thermal diffusivity was calculated using formula method. Thermal properties, as a function of moisture content, were fitted using linear equations. The specific heats of peanut pods, kernels, and shells increased linearly from 2.1 to 3.3, 1.9 to 2.8, and 2.7 to 4.1 kJ kg^{-1} $^0C^{-1}$, respectively, with the corresponding increase in moisture content from 5.2 to 23.7, 5.0 to 30.6, and 3.5 to 28.7 % (d.b.). The specific heat of shells was the highest, followed by pods and kernels. The thermal conductivity of peanut pods, kernels, and shells increased linearly from 0.12 to 0.16, 0.15 to 0.19, and 0.11 to 0.18 Wm^{-1} $^0C^{-1}$, respectively with increasing moisture content. The thermal conductivity of shells was the lowest, followed by pods and kernels. The thermal diffusivity of peanut pods and kernels decreased from 2.8 x 10^{-7} to 2.3 x 10^{-7} and 1.1 x 10^{-7} to 1.0 x 10^{-7} m^2 s^{-1}, respectively, with an increase in m.c. But, the diffusivity of shells increased from 5.9 x 10^{-7} to 6.7 x 10^{-7} m^2 s^{-1}. The thermal diffusivity of shells was the highest, followed by pods and kernels.

CHAPTER 3
METHODOLOGY

3.1 Collection and preparation of sample

Samples were collected from Araromi axis of Saki West Local Government, Oyo State, Nigeria (Lat. 8° $39^{'}$ N, Long. 3° $24^{'}$ E) as shown in figure 3.1. The location is densely populated with *Parkia bioglobosa* trees existing naturally. Locust bean processors are predominant in the area. Collection of samples from this area was preferred to buying pre-processed (from harvest to pulp-removal) seeds from the markets in order to ensure the origin of the samples and monitor the pre-processing stages. The trees were carefully selected with the help of an experienced locust bean processor and farmer who was able to identify old, prime-aged and healthy trees.

3.1.1 Preliminary study

A preliminary assessment of the production process was carried out in the area in order to determine the nature and current state of the process. Oral interviews with some of the processors were carried out and each of the stages involved in the production process was carefully observed and reported.

3.1.2 Harvesting. The pods were picked from the ground (fallen matured pods) and also plucked from the trees with long bamboo pole with a hook at the tip which looked like a sickle. The tool is commonly referred to as ‘go-to-hell.’ The pods collected were sun dried for three days to facilitate easy pod shelling. The pods were split open to collect the pulp-coated seeds. This was done in accordance with the processors’ cultural processing method and handling.

3.1.3 Shelling of pods. The pods were manually split open using bare hands and sometimes stones. Some of the pulp-coated fresh seeds were preserved in polythene bag to maintain the moisture content which was later determined using the oven-drying method. This was done in order to know the moisture content of the seeds at the point of harvest.

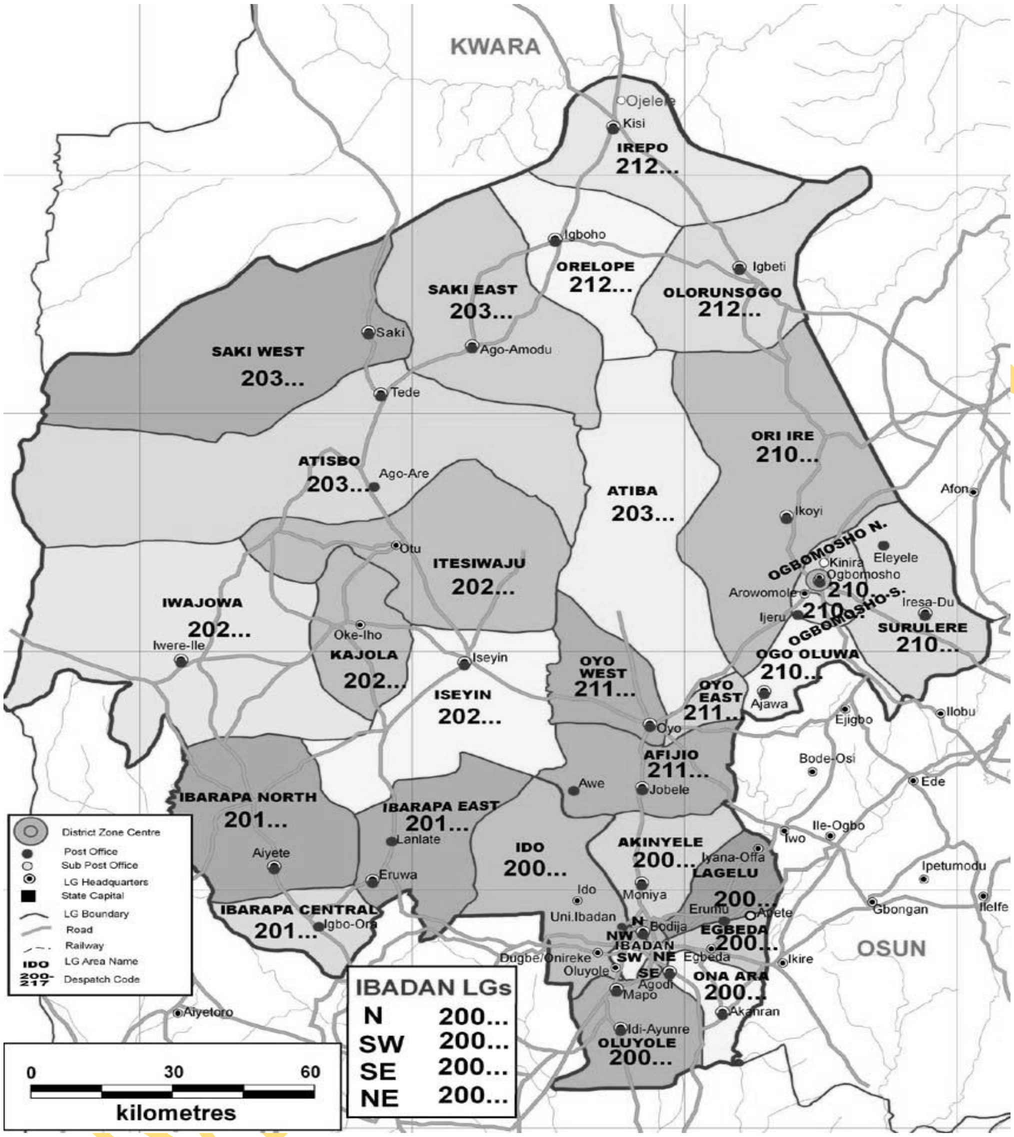

Fig. 3.1 Map of Oyo State, showing Saki West Local Government Area.

3.1.4 Pulp removal. Seeds with pulp coating were first soaked in water for 30 minutes, washed and dried for six (6) hours in the sun. They were again soaked in water for ten minutes and pounded in mortar with little coarse sand to enhance pulp removal. The clean seeds were finally dried in the sun for 5 days. Culturally, the seeds are dried for at least 3 days until a desired and safe storage level of dryness or low moisture level is reached which was considered fit for market sales. For the purpose of this work, the seeds were dried until they compared well with the regular seeds sold in the market in appearance and colour. This was done by visual estimation. The dried seeds were brought in polythene bags into the laboratory (Department of Agronomy, University of Ibadan), for experimental work.

3.2 Determination of samples' Moisture Content. The initial moisture content of the dried seeds was determined by using the oven-dry method, at 103 ± 1 ^{0}C for 72 hours (ASAE, S 352.2). The samples at other desired moisture content levels were prepared by adding calculated amounts of distilled water using equation 3.1.

$$Q = \frac{W_i\,(m_f - m_i)}{100 - m_f} \qquad \_\_\_\_\_3.1 \qquad \text{(Mohsenin, 1986)}$$

where Q = mass of added water in grams (g);
W_i = initial mass of seed sample in grams (g);
m_f and m_i = final and initial moisture contents respectively (wet basis).

The whole bulk of seeds was cleaned manually to remove all foreign matter, broken and immature seeds. The seeds were divided into five sample lots of equal weight before adding distilled water to each lot as desired and calculated. One of the sample lots was left without addition of water in order to retain the moisture content level after drying, when the pulp was removed. Distilled water was added to another sample lot to attain the initial moisture content level at harvest after pod shelling. Water was added to other sample lots to get varying desired higher moisture content levels as calculated. Each sample lot was packaged in doubled, low density polythene bags to preserve the moisture content. All sample lots were stored afterwards in a refrigerator with the thermostat set to 5 ^{0}C for five days (Davies, 2010; Akbarpour et al., 2009) to allow for uniform distribution of moisture within the seed mass in each sample lot. For each experiment, the required quantity of seeds is taken out from each sample lot in the refrigerator for 2 hours to equilibrate with room temperature.

3.3 Determination of physical properties

3.3.1 Seed axial dimensions. The true axial dimensions of each of 30 randomly selected seeds from each sample lot were measured. The axial dimensions were: length, width and thickness. A vernier calliper with 0.02 mm accuracy was used for taking the measurements. The mean values of the length, width and thickness for each group of 30 seeds from the sample lots were determined (Zewdu and Solomon, 2008; Nablandi *et al*., 2010; Tunde – Akintunde and Akintunde, 2007; Andrejko and Kaminska, 2005).

3.3.2 Principal dimensions. The principal dimensions are the arithmetic (D_a) and geometrical (D_g) mean diameters which were calculated according to equations 3.2 and 3.3 respectively from the values of the three axial dimensions for each seed.

$$D_a = \frac{(L + W + T)}{3} \qquad \_\_\_\_\_\_\_\_\_\_ \; (3.2)$$

$$D_g = (LWT)^{1/3} \; \_\_\_\_\_\_\_\_\_\_ \; (3.3)$$

(Mohsenin, 1986)

where L = length; W = width; T = thickness in mm.

3.3.3 Surface area. The surface area of locust bean seeds was determined by analogy with a sphere of the same geometric means diameter using equation 3.4.

$$S = \pi D_g^2 \qquad \_\_\_\_\_\_\_\_\_ \; (3.4)$$

(Mohsenin, 1986; Sacilite et al, 2003: Tunde – Akintunde and Akintunde, 2004; Altuntas et al., 2005; Kiani Deh kiani et al., 2008). Where S = surface area and D_g = geometric mean diameter. Mean values of surface area for each sample lot (group of 30 seeds) were calculated.

3.4 Determination of Gravimetric Properties

3.4.1 Individual seed mass. The mass of individual seed was determined by weighing 50 g of seeds and counting the number of seeds in the 50 g mass. The mass was divided by the respective number of seeds in the 50 g mass to determine the mass of individual seed. This was replicated 5 times and the mean value determined for each sample.

3.4.2 Seed volume Seed volume was determined using the liquid displacement method stated by Mohsenin (1986). The volume of individual seed was determined by pouring 20 g of seeds into 30 ml of toluene (C_7H_8) in a measuring cylinder. The difference between the initial and final level (or volume) of toluene in the measuring cylinder, represented the volume displaced by the seeds. The volume displaced was divided by the respective number of seeds to determine the volume of a seed. This was replicated five times. Toluene was used in place of water, because it is absorbed by seeds to a less extent. Also, its surface tension is low and its dissolution power is low (Milani et al., 2007).

3.4.3 Thousand Grain mass. The mass of a thousand grains was determined by counting randomly selected hundred seeds and weighing them on an electronic balance. The result was multiplied by 10 to obtain the mass for 1000 seeds. The experiment was replicated five times and the means determined for each sample. (Tunde – Akintunde and Akintunde, 2007).

3.4.4 True density. The true density was determined for each sample mass as described in section 3.4.2 using the toluene displacement method. Instead of dividing the volume of toluene displaced by the number of seeds in 20 g of seed mass, the mass of seeds (20 g) was divided by the volume of toluene displaced. True density is therefore the ratio between the mass of locust bean seeds (20 g) and the true volume of the seeds. The experiment was also replicated 5 times and the mean calculated for each sample (Isik, 2007; Shafiee *et al*., 2009; Tavakoli *et al*., 2009; Nalbandi *et al*., 2010).

3.4.5 Bulk density. The bulk density is the ratio of the mass of a sample of a seed to total volume (Shafiee et al., 2009). Bulk density for all the samples were determined by filling an empty 300 ml beaker with locust bean seeds and weighing it (Mohsenin, 1986). The weight of the seeds was obtained by deducting the weight of the empty beaker from the weight of the seed-filled beaker. To achieve uniformity in bulk density, the beaker was tapped 10 times for the seeds to consolidate in the beaker (Ahmadi et al, 2009). The beaker was filled with seeds dropped from a 15 cm height and a sharp – edged, flat metal file was used to remove excess seeds to level the surface at the top of the graduated beaker (Nalbandi et al, 2010). Bulk density was calculated using equation 3.5

$$\rho_b = m/v \quad \_\_\_\_\_\_ \ (3.5) \qquad\qquad \text{(Mohsenin, 1986)}$$

where ρ_b= bulk density, m = mass of seeds; v = volume of beaker (also taken as volume of seed sample). This was replicated 5 times and the mean calculated for each sample.

3.4.6 Porosity. Porosity is the ratio of free space between grains to total mass of bulk grains, determined by

$$P = [(\rho_t - \rho_b) / \rho_t] \times 100 \quad \_\_\_\_\_ \ (3.6) \qquad \text{(Mohsenin, 1986; Heidarbeigi et al, 2008)}$$

where P = porosity, ρ_t = true density , ρ_b = bulk density.

This was calculated for each replicate of samples using their respective values of bulk and true densities. The mean value of porosity for each sample was determined.

3.5 Friction Properties

3.5.1 Static coefficient of friction. The static coefficient of friction of locust bean seeds was determined in seven surfaces viz; plywood, rubber, galvanized sheet, stainless steel, mild steel, aluminum and glass. These test surfaces were placed on a tilting surface one after the other. The tilting surface was designed and fabricated (in the pattern shown in fig. 3.2) for the purpose of this experiment. A topless, bottomless and hollow cylinder of 50 mm diameter and 50 mm height was placed on the test surface and filled with seed sample. The hollow cylinder was raised slightly so as not to touch the surface. The surface with the cylinder resting on it was inclined gradually with a screw device until the cylinder began to slide. At this point, the angle of the inclined surface was read off and the tangent of the angle is static coefficient of friction (Nalbandi et al., 2010).

3.5.2 Static angle of repose. This is often referred to as emptying angle of repose (Razavi et al., 2009). The static angle of repose was measured using a wooden box half full of locust bean seeds, mounted on a tilting surface as in figure 3.1 except for test surfaces. The tilting surface is slowly and gradually titled until the seeds began to move, leaving the inclined surface. The angle of tilted surface was at this point measured as the static angle of repose for each sample (Mohsenin, 1986; Ghasemi et al., 2008; Nalbandi et al,, 2010). The experiment was replicated 5 times and the mean value calculated for each sample.

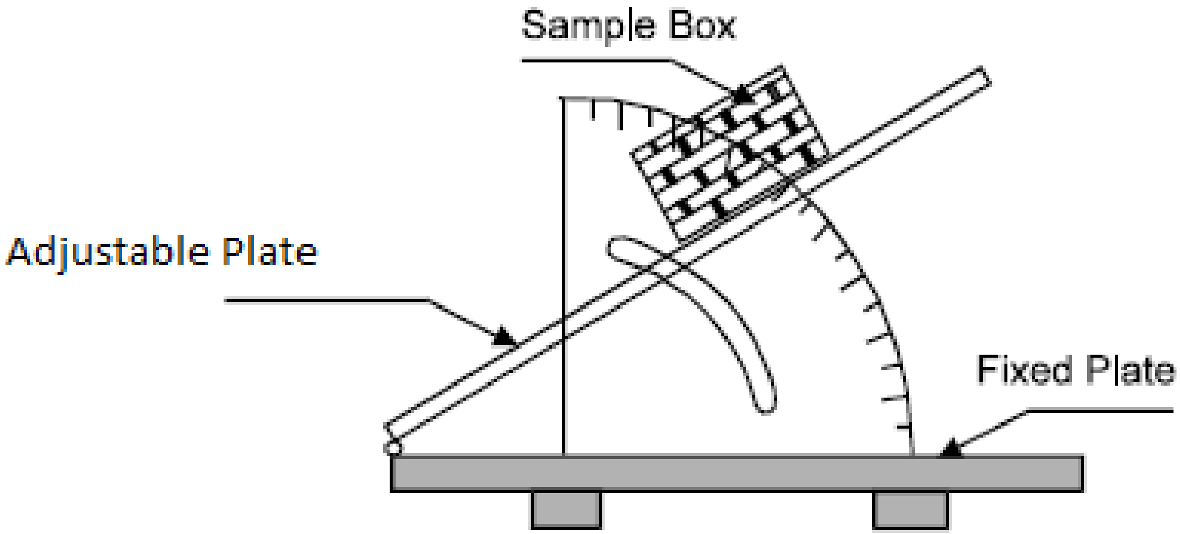

Fig. 3.2 Measuring device for static angle of repose and static coefficient of friction.

3.5.3 Dynamic Angle of repose. This was determined using a hollow cylinder and applying trigonometry rules (Mohsenin, 1986; Ahmadi *et al*., 2009; Razavi *et al*. (2009). The dynamic angle of repose is referred to as the filling angle of repose and is defined as the angle made with the horizontal at which the material will stack when piled. A topless and bottomless cylinder of 15 cm diameter and 25 cm height was placed at the center of a raised circular plate, having a diameter of 35 cm. The cylinder was filled with locust bean seeds and raised slowly until it formed a seed cone on the circular plate. The height and base (diameter) of the cone was measured and the filling or dynamic angle of repose was determined using the following equation:

$$\theta_r = \tan^{-1} (2H / D) \quad \_\_\_\_\_\_\_\_\_\_ (3.7) \qquad \text{(Mohsenin, 1986)}$$

where H, D and θ_r are height, diameter and dynamic angle of repose of the seed cone respectively in mm. The experiment was replicated 5 times and the means calculated for each sample (Milani *et al*., 2007; Akbarpour *et al*., 2009).

3.5.4 Coefficient and angle of internal friction. This refers to the friction of grain against grain (Irtwange, 2000). It was measured, using a rectangular guide frame of size 11 x 9 x 5 cm which was put under a cell of size 7 x 5 x 5 cm as stated by Stepanoff (1969) and adopted by Irtwange (2000). The guide frame and cell were filled with sample. The cell was tied with a cord passing over a frictionless pulley attached to the pan. Weights (w_2) were put into the pan to cause the cell to just slide. After this, the cell was made empty and weights (w_1) were also put into the pan to cause the empty cell to slide over the guide frame. The coefficient of internal friction was calculated as:

$$\mu_i = (w_2 - w_1 \quad) / W \quad \_\_\_\_\_\_\_ (3.8) \quad \text{(Stepanoff, 1969)}$$

where μ_i = coefficient of internal friction;

$w_2 - w_1$ = weight required to slide the sample materials in grams;

W = weight due to the sample material in the cell = volume of cell (cm^3) x bulk density of sample materials (g/cm^3)

The angle of internal friction was calculated as

$$\theta_i = \tan^{-1} \mu_I \quad \_\_\_\_\_\_ (3.9) \quad \text{(Stepanoff, 1969)}$$

where θ_i = angle of internal friction (degree);

μ_i = coefficient of internal friction

Five replications were made and mean values computed for each sample.

3.6 Flow properties

3.6.1 Coefficient of mobility. Coefficient of mobility represents the fluidity or freedom of motion of the substance. Coefficent of mobility was calculated using the formula given by Stepanoff (1969) as cited by Irtwange (2000).

$$m_1 = 1 + 2\mu_I^2 - 2\mu_I \ (1 + \mu_i^2)^{1/2} \qquad \_\_\_\_\_\_\_ \ (3.10) \ \ (\text{Stepanoff, 1969})$$

where m_1= coefficient of mobility;

$\mu_I = \tan \theta_i$ = coefficient of internal friction

3.6.2 Hopper side wall angle (Slope). Irtwange (2000) quoted Stepanoff (1969) that the slope angle of the side wall of a hopper must be greater than the angle of internal friction of a material for easy flow of the material and it is calculated using equation 3.11:

$$\beta = 45^o + \phi_I /2 \qquad \_\_\_\_\_\_\_ \ (3.11) \ \ (\text{Stepanoff, 1969})$$

where $\phi_{I\,=}$ angle of internal friction of sample material side wall slope (degree);

β = side wall slope.

3.7 Mechanical properties

3.7.1 Normal stress and shear stress. The experimental set up or apparatus for measurement of shear stress (τ) for different values of normal stress (σ) is similar to that of coefficient and angle of internal friction except for a normal load on top of the rectangular cell. The measurements were carried out for 200, 300, 400 and 500 g loads and three replications were taken for each sample and load. The normal stress (g/cm^2) was calculated as:

$$\sigma = (w_3 + w_4) / A = \rho h \qquad \_\_\_\_\_\_\_\_ \ (3.12) \qquad (\text{Stepanoff, 1969; Irtwange, 2000})$$

where w_3 = weight of the cell (g);

w_4 = weight due to the load on top of the cell (g);

A = Area of the cell (cm^2);

h = height of the sample materials in the cell (cm);

ρ = density of the sample materials (gcm^{-3})

The shear stress (τ) was calculated as:

$$\tau = [w_5 \ (1 - w\sqrt{2}\,)] / A \qquad \_\_\_\_\_ \ (3.13)(\text{Stepanoff, 1969; Irtwange, 2000})$$

where w = coefficient of friction of pulley = 0.5;

w_5 = weight required to slide the sample material with load - weight required to slide the empty cell (g)

3.7.2 Determination of maximum rupture force and deformation. A preparatory tension/compression-testing machine (Universal Testing Machine - U.K. model) was used to determine maximum rupture force and deformation of locust bean samples. This was done in the Department of Material Science Engineering, Faculty of Engineering (Spider House), Obafemi Awolowo University, Ile-Ife. Maximum load employed was 151 kg and test for each sample was replicated 5 times. Individual seed was loaded between two parallel plates of the machine and compressed along its thickness until rupture occurred as denoted by a rupture point in the force deformation curve. The rupture point is a point on the force deformation curve at which the loaded specimen shows a visible or invisible failure in the form of breaks or cracks. This point was detected by a continuous decrease of load in the force-deformation diagram while the rupture point was detected, when the loading was stopped. Mean value of 5 replications for each sample was calculated. Same method was adopted by Tavakoli, M. et al., (2009) and Tavakoli, H. et al., (2009).

3.7.3 Rupture energy. The mechanical behavior of locust bean samples were expressed in terms of rupture force and rupture energy required for initial rupture. Energy absorbed by the sample at rupture was determined by calculating the area under the force - deformation curve from the following relationship.

$$E_r = (F_r D_r) / 2 \quad \_\_\_\_\_\_\_\_ (3.14) \qquad \text{(Braga et al., 1999).}$$

where E_r = rupture energy (Nmm);

F_r = rupture force (N) and

D_r = Deformation at point of rupture (mm).

Same method was used by Kiani Deh Kiani *et al*. (2008); Tavakoli et al., (2009); Ahmadi et al., (2009).

3.8 Thermal properties

3.8.1 Specific heat capacity of locust bean. The specific heat capacity of locust bean was determined using the method of mixtures as described by Aviara and Haque (2001) which involved a calibrated copper calorimeter placed inside a flask, similar to figure 3.3. The calorimeter was calibrated. A mass of water, m_w, was poured into the calorimeter. At the relatively constant temperature of the water (T_w), a mass of hot water m_{hw} at a temperature of T_h (maximum of 70 ^{0}C), was added. The temperature of the hot and cold water mixture at equilibrium (T_e) was recorded. The respective masses of hot and cold water were adjusted until a final temperature of the mixture that is close to the room temperature was obtained. The system was assumed to be adiabatic. Therefore, the heat capacity of the calorimeter was determined by equation 3.15.

$$C_c = \frac{m_{hw}\, c_w\, (T_h - T_e)}{(T_e - T_w)} - m_{cw}c_w \quad \text{\_\_ (3.15)}$$

(Mohsenin, 1980; Aviara and Haque, 2001)

Where C_c = Specific heat capacity of calorimeter (J/kg °C);

M_{cw} = Mass of cold water (g);

M_{hw}= Mass of hot water (g);

C_w = Specific heat of water (J/kg °C);

T_w = Temperature of cold water (°C);

T_h = Temperature of hot water (°C); and

T_e = Temperature of equilibrium cold water (°C).

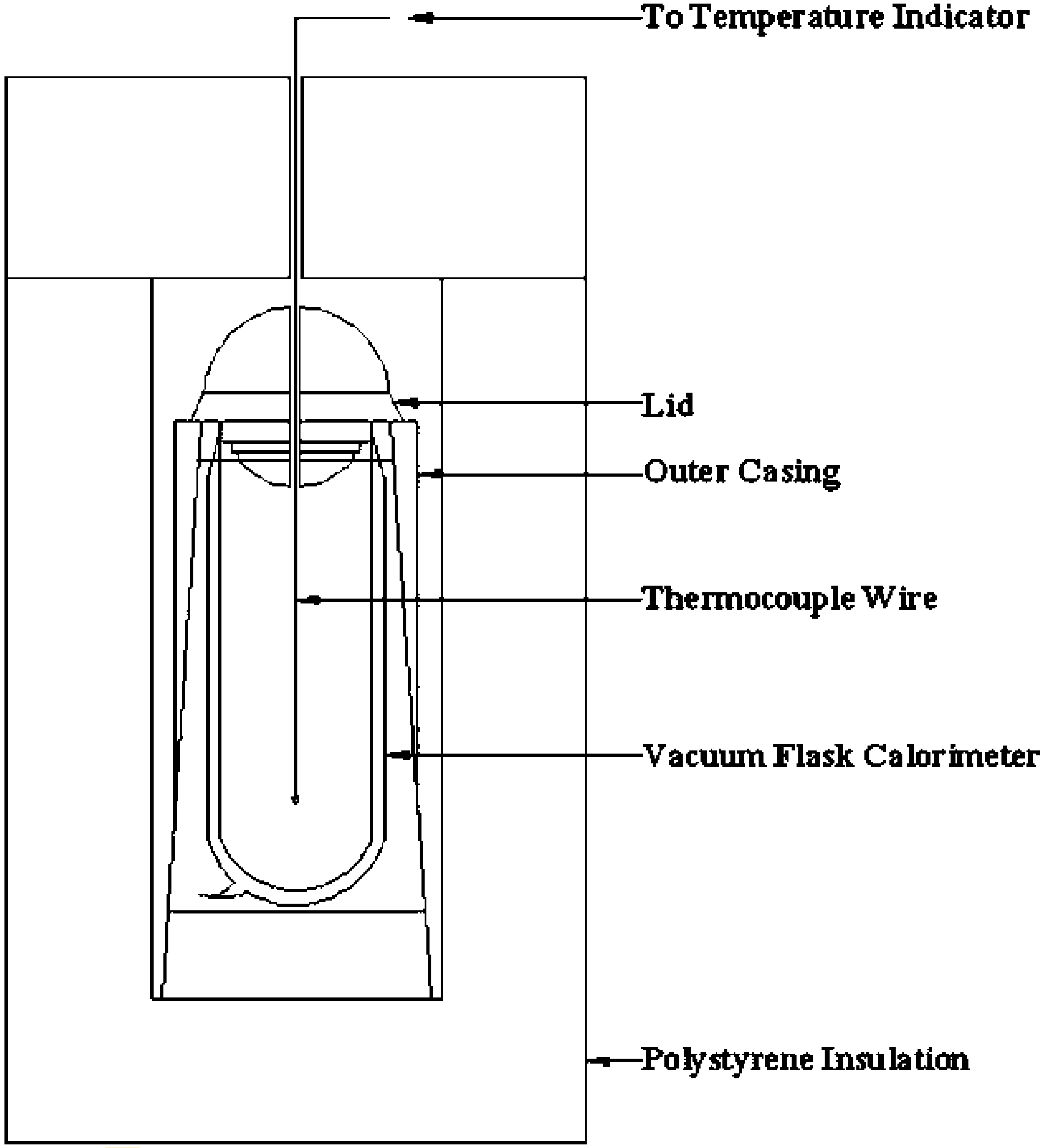

Fig. 3.3 Apparatus for determining specific heat capacity (method of mixtures)

The calibration was replicated five times. The average value of the specific heat capacity of calorimeter was found to be 393.3 ± 23.83 J/kg ^{0}C. To determine the specific heat capacity of locust bean, a sample of known weight, temperature and moisture content was dropped into the calorimeter containing water of known weight and temperature. The mixture was stirred continuously using a copper stirrer and the temperature was recorded at an interval of 1 minute using a digital thermometer with a probe – thermocouple. At equilibrium, the final or equilibrium temperature was recorded and the specific heat was calculated using the equation.

$$C_s = \frac{(m_c c_c + m_w c_w)\,[T_w - (T_e + t'R')]}{m_s[(T_e + t'R') - T_s]} \quad (3.16)$$

(Mohsenin, 1980; Aviara and Haque, 2001)

where: C_c, C_s and C_w = specific heats of calorimeter, sample and water, respectively (kJ kg^{-1} ^{0}C^{-1});

m_c, m_s and m_w = masses of calorimeter, sample and water (kg) respectively;

R' = the rate of temperature fall of the mixture after equilibrium (^{0}C s^{-1});

T_e = the equilibrium temperature of the sample and water mixture (^{0}C),

T_s and T_w = the initial temperatures of sample and water, respectively (^{0}C) and

t' = the time taken for the sample and water mixture to come to equilibrium (s).

The term $t'R'$ accounts for the heat of hydration and heat exchange with the surroundings. At each moisture level of the samples, (five levels from 5.9 to 28.2 %) the experiment was replicated three times and the average values of the specific heat were recorded.

3.8.2 Thermal conductivity. Thermal conductivity of locust bean was determined using the steady-state heat flow method. A guarded hot-plate apparatus similar to the one described by Drusas et al. (1986) and employed by Aviara and Haque (2001) was used. It consisted of an upper (hot) 120 mm plate and 9 mm thick with a rod-handle attached to its centre. The heating chamber was made of two, 300 mm tall concentric cylinders (120 and 150 mm in diameter) which were welded on a 9 mm thick and 150 mm diameter circular mild-steel plate. The circular plate covered one end of both cylinders. The hollow between the cylinders was lagged with fibre glass to prevent heat loss. The base was also lagged and had a small hole at its centre to accommodate the probe thermocouple from the digital thermometer. The hot plate was heated electrically and this was controlled using a power stabilizer. Measurements were made using indicating ammeter, voltmeter and thermometer. The apparatus was first calibrated using maize and wheat seeds of known thermal conductivity before using it for locust bean.

To determine the thermal conductivity of locust bean, a sample at specified moisture content was put in a 75 mm diameter, circular plastic-ware plate and 10 mm thickness. The sample assumed the size of the plate. The probe thermocouple pierced through the cylinder bottom and through the plastic but slightly penetrating into the sample to avoid touching the hot plate directly. The plastic dish containing the sample was placed at the base of the cylinder. The hot plate was lowered down the cylinder gently until it touched the sample. The temperature of the hot plate was pegged around 70 ^{0}C. The fluctuations in temperature of the hot plate and the changes in temperature of the sample were monitored and recorded for 1 hour at 5 minutes interval. At the equilibrium condition, the temperature difference and heat flux were recorded and used in calculating the thermal conductivity of the sample from equation 3.17. The experiment was replicated three times at each moisture level and the mean values determined.

$$q = k\frac{dT}{L} \qquad \text{\_\_\_\_\_\_ (3.17)}$$

(Mohsenin, 1980; Aviara and Haque, 2001)

where: k = thermal conductivity (W m^{-1} ^{0}C);
dT = temperature difference at equilibrium conditions ^{0}C;
L = thickness of sample material (m) and
q = heat flux (Wm^{-2})

3.8.3 Thermal diffusivity. The thermal diffusivity was calculated using experimental values of specific heat, thermal conductivity and bulk density using equation 3.18.

$$\infty = k / (\rho_b C_s) \quad \_\_\_\_\_\_\_ \quad (3.18) \qquad \text{(Mohsenin, 1980; Aviara and Haque, 2001)}$$

where ∞ = thermal diffusivity ($m^{-2}\ s^{-1}$);

k = thermal conductivity ($W\ m^{-1}\ {}^0C$);

ρ_b = bulk density ($kg\ m^{-3}$) and

c_s = specific heat capacity ($kJ\ kg^{-1}\ {}^0C$)

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Traditional method of processing Locust bean into ‘*Iru*’ (fermented locust bean): the preliminary study.

The processing of *iru* is mainly carried out by women. The traditional method usually involves harvesting and shelling of the pods, sorting of seeds from broken pod shells or chaffs, washing off the pulp from seeds, cooking of seeds, dehulling, seed cleaning, parboiling of seeds and fermentation. Some stages in the process slightly differ from one locality to the other especially in the South – Western part of Nigeria which is largely influenced by the people’s cultural beliefs, technological know – how, conservative processing tradition and available processing utensils and materials. In the processing family, there are those who major in harvesting and shelling of the pods, washing and drying the seeds and getting them ready for market sales as raw material for further processing into the fermented form (*Iru*). The other set of processors buy the washed and dried seeds from the markets and process them into fermented form. Very few processors carry out the processing from harvesting to fermentation because of the amount of labour involved. Hence in such cases, the amount of seeds handled is very small. The following is the detail of the assessment of the production process of *iru*.

4.1.1 Harvesting

This is the first step in the process. Most times, processors buy shelled and washed seeds from people who go into the bushes or forests to harvest the pods. Cadbury Nigeria PLC, the maker of *Dadawa* cubes which makes use of locust bean (*Parkia biglobosa*) as its major raw material also buys shelled and de–pulped (removal of the pulp) seeds from villages around Ogbomosho axis in Oyo state, Nigeria. Harvesting of locust bean commences usually at the beginning of rains, from March to June/July. Busson (1965) reported that men climb the *parkia* tree to pluck the pods by hand while Gakou et al. (1994), Sabiiti and Cobbina (1992) reported that harvesting is done with the use of long poles and stakes that have curved iron, sickle–like heads by climbing the tree or from the ground. The pole is commonly known as ‘go-to-hell’. Direct picking of fallen pods is another method of harvesting. This is possibly as a result of fruit (pod) abscission when it is very ripe. The binding force between the pod and its stalk becomes reduced with time as pod matures or ripens until a little shaking of the tree, wind or animal movement cause it to drop. Sometimes the pod drops on its own when the binding force becomes extremely weak and its weight can no longer be sustained. The pods are then gathered for shelling (Sharland, 1989: Guinko and Pasgo, 1992). Picking pods from the ground and use of 'go-to-hell' were used at Araromi, Saki for this work.

4.1.2 Pod shelling

Shelling is the breaking open or shattering of the pods to remove the seeds embedded in them. The manner in which this is done varies from locality to locality depending on the skill possessed, individual knowledge and the availability of manpower. A method of pod shelling is by stacking up the pods in heaps under trees and allowing them to dry to an extent before beating them with heavy sticks. In this method, the number of damaged seeds and pods is high because blows are directly applied without any form of regulation of the applied force and without any cushioning effect. The method primarily depends on magnitude and frequency of blows. Also some seeds and pods will fly off due to the impact of force applied, hence there is seed loss leading to relatively low efficiency of the method. The second method of pod – shelling is by bagging the dried pods using woollen sacks and beating the sacks with sticks. In this case the blows are cushioned by the sacks slightly, thereby minimizing the amount of damage done to the seeds and pods. The sacks also prevent the materials from flying off during beating. Though this method may be slower than the previous one, it is more efficient and effective.

Another method of pod-shelling is by taking the dried pods one by one and splitting them open with bare hands to remove the seeds. Sometimes it involves using a stone to crack open stubborn pods. This method is slow, time consuming and could be injurious to the hands. Nevertheless, it is the most effective and efficient among the three methods especially when the pods are very dry. When packing the seeds from the floor sometimes, impurities are packed along with them. Less winnowing and sorting of the seeds are done afterwards since they are done concurrently with shelling. The chaffs or broken pods are either thrown away or sold for the purpose of making herbal concoction. It can be inferred from the three methods described above that moisture content of the pods at the point of shelling plays a great role in shelling efficiency. The drier the pods, the more brittle they become and shatter easily with low magnitude of force applied on them. Most times the pods are sprinkled with water at reasonable time intervals during drying to allow the expansion of the pod case or shell thereby creating clearance between the seeds and the inner walls of the pod. The pod case becomes brittle. This will allow easy shattering of the pods without damaging the seeds depending on the magnitude of the blow or force applied on the pods. This phenomenon enhances effective and efficient shelling. Pods are usually sun-dried.

4.1.3 Sorting: Sorting is the removal of dirt, broken or shattered pod - shells from the seed bulk which is usually done by winnowing. The seeds at this stage are covered with yellow pulp (Kon et al., 1973). The whole bulk of seed and dirt or debris is poured from a considerable height (from a basin to a basin or on a mat) against the direction of the movement of ambient air current. When the bulk of debris is removed by winnowing, the remnants of the debris or dirt are removed by handpicking (Plate 2.3 a).

4.1.4 Pulp removal and pre – cooking for dehulling

Removal of pulp is carried out by washing the seeds in a sieve immersed in a bigger bath or container filled with water. In some areas or locality, the seeds are washed in a basket immersed in running water (e.g. stream or river). Sometimes the seeds are first soaked in water for some minutes before washing in water to enhance pulp removal. In some other cases, the seeds are partially cooked and pounded with some coarse sand in a mortar to also facilitate pulp removal. When pulp is finally removed, the seeds are sun–dried and made ready and available in the markets for further processing into fermented form by other processors. Generally after pulp removal, the seeds are first soaked overnight (about 10 hours) before cooking them for 8 hours with the addition of wood ash, in preparation for dehulling. Some other processors soak the seeds for 3–4 days and afterwards cook them for 3 hours, which reduces the total amount of fuel (mainly wood) consumed. Cooking helps to soften the hard testa to enhance efficient dehulling, while soaking alone does it slowly. Reichert et al. (1979), Kon et al. (1973) and Deshpande et al. (1982) among others carried out wet dehulling of various soaking duration of cowpea and found out that the duration of soaking alone did not seem to have significant effect on dehulling efficiency. Water temperature and soaking time were found to increase

(a) (b)

(a) *Parkia biglobosa* seeds embedded in yellow pulp being sorted manually after shelling.
(b) Cooking the seeds for dehulling.

(c) (d)

(c) Dehulling by foot in a mortar. (d) Cleaning after dehulling

(e) (f)

(e) Parboiling of clean seeds before fermentation. (f) Fermented locust bean (the end product)

Plate 4.1 Production process of fermented locust bean (‘*Iru*’).

efficiency of dehulling (Forbus and Smith (1971). The period of cooking depends largely on the intensity of heat applied and the quantity of seeds to be cooked. The wood ash is first sieved, poured back in the sieve and added to the seeds being cooked by immersing the bottom of the sieve in the cooking water in the pot. The wood ash helps in quickening the softening of the testa. The pot is filled with water up to a level above the seeds. When the water goes down, the pot is refilled as many times as possible until the testa is softened and splits open easily. At this stage, the seeds are ready for dehulling. Stubborn seeds (uncooked seeds) from previous cooking are normally added to the next batch of seeds to be cooked at the beginning of cooking. Cooking of seeds bleaches the testa and the coloured water is soaked–in by the cotyledons which is responsible for their colour change from milky–white to deep brown after dehulling.

4.1.5 Seed dehulling and cleaning.

Dehulling is the removal of the testa in order to obtain the cotyledon. After cooking when the testa splits open, the cooked seeds are left till the following day (approximately 12 hours). It is believed that if the seeds are dehulled while still hot, more damage will be done to the cotyledons. The cotyledons are softer when hot than cold. The cooled seeds are packed into a mortar and a pestle to pound or human feet are used to rub the seeds together to remove the testa (dehulling). Depending on the processing method adopted, seeds are sometimes mixed with little coarse sand in the mortar for more efficient dehulling (Plate 4.1c). The roughness of the coarse sand during pounding enables easy removal of the testa. The testa has considerable weight as does the cotyledon which causes the dehulled testa to settle down with the cotyledon thereby making it difficult to separate the cotyledons from the dehulled testa (Audu et. al., 2004). The separation which is also called cleaning is usually done with the use of basket dipped in a flowing stream or a large sieve made of aluminium or plastic in a large basin (Plates 4.1d). The sieve or basket is with holes, large enough to permit the passage of the dehulled testa but not the cotyledon. This is because the softened testa becomes flabby and small when empty, that is, when it’s not housing the cotyledon. In some cases, the testa is shredded into fragments during dehulling, hence its easy passage through the sieve openings.

A lot of water is required in separating the testa from the cotyledon. Generally, in the traditional method, dehulling rate depends on softness of the seed after cooking, amount of energy applied, number of people involved, inclusion or non – inclusion of coarse sand. To ensure good cleaning, the seeds are rinsed thrice. Water used for the third rinsing is often used for cooking fresh seeds because it is believed that it hastens cooking, hence cooking duration is reduced. After cleaning by rinsing, the remnant of the dehulled testa and other present impurities are finally removed by handpicking.

4.1.6 Parboiling and fermentation

The clean cotyledons are returned to the cooking pot to be parboiled using fresh water. Parboiling is done for about 40 – 50 minutes depending on the intensity of heat applied (Diawara et al., 2000). At this point, part of the parboiled cotyledons may be collected which is called *'Iru Woro'* in *Yoruba* language (meaning the non – marshy type). The rest is further parboiled for about 15 or 20 minutes while Potassium carbonate solution (K_2CO_3) is added to it to form a final product called *'Iru pete'* also in Yoruba language (the marshy type) after fermentation. The non – marshy and marshy types of the parboiled cotyledons are spread into wooden trays or flat, wide calabashes (about 15 mm deep) after parboiling. A covered tin is placed at the centre of the tray before covering the tray with a basket tray or perforated wooden tray. The reason for the tin is to ensure that the cover tray does not collapse in the tray and gives room for good fermentation. The tray and cover are wrapped up properly with a number of thick clothes to provide required temperature for necessary bacterial activity for effective fermentation to take place. Fermentation period is usually about 2 – 3 days (48 – 72 hours). Satisfactory fermentation occurs within a temperature of 30 – 35 ºC (Alabi et al., 2005).

The end product of fermentation of the cotyledons is a strong ammoniac smelling mass which can easily be moulded into desired shapes. The addition of K_2CO_3 enables the softening and the sticky ability of the cotyledons. The fermentation process involves a lot of proteolytic changes in the substrate, due to bacterial action among which are notable ones referred to as *Bacillus Substilis, B. lincheniform* and a few *Staphylococcus sp.* (Deshpande et al., 1982). Successful, effective or complete fermentation in this traditional method is often judged by the ammoniac smell, mucilaginous surface, viscous texture and dark colour of the final product. Beaumont (2002) reported that spices and additives such as salt are incorporated into the fermented locust bean before moulding it, while sun – drying is employed to facilitate its stabilization.

4.1.7 Packaging

Packaging is still largely done manually. The final product is moulded with bare hands, especially into balls and set on wide leaves (e.g. Banana and Cocoyam leaves) in wide, flat containers ready for sale. A preliminary assessment of locust bean (*Parkia biglobosa*) processing, as discussed above reveals that the whole process is still largely done manually with traditional tools hitherto. The traditional method is still very unhygienic. This definitely calls for the engineering design and development of relevant machines or equipment for the process. Since the process involves hydration in some of the stages, it is necessary to study the behavior of the seeds as regards their engineering properties under the influence of moisture content. A chart providing a quick glance at the traditional processing method is shown in figure. 4.1.

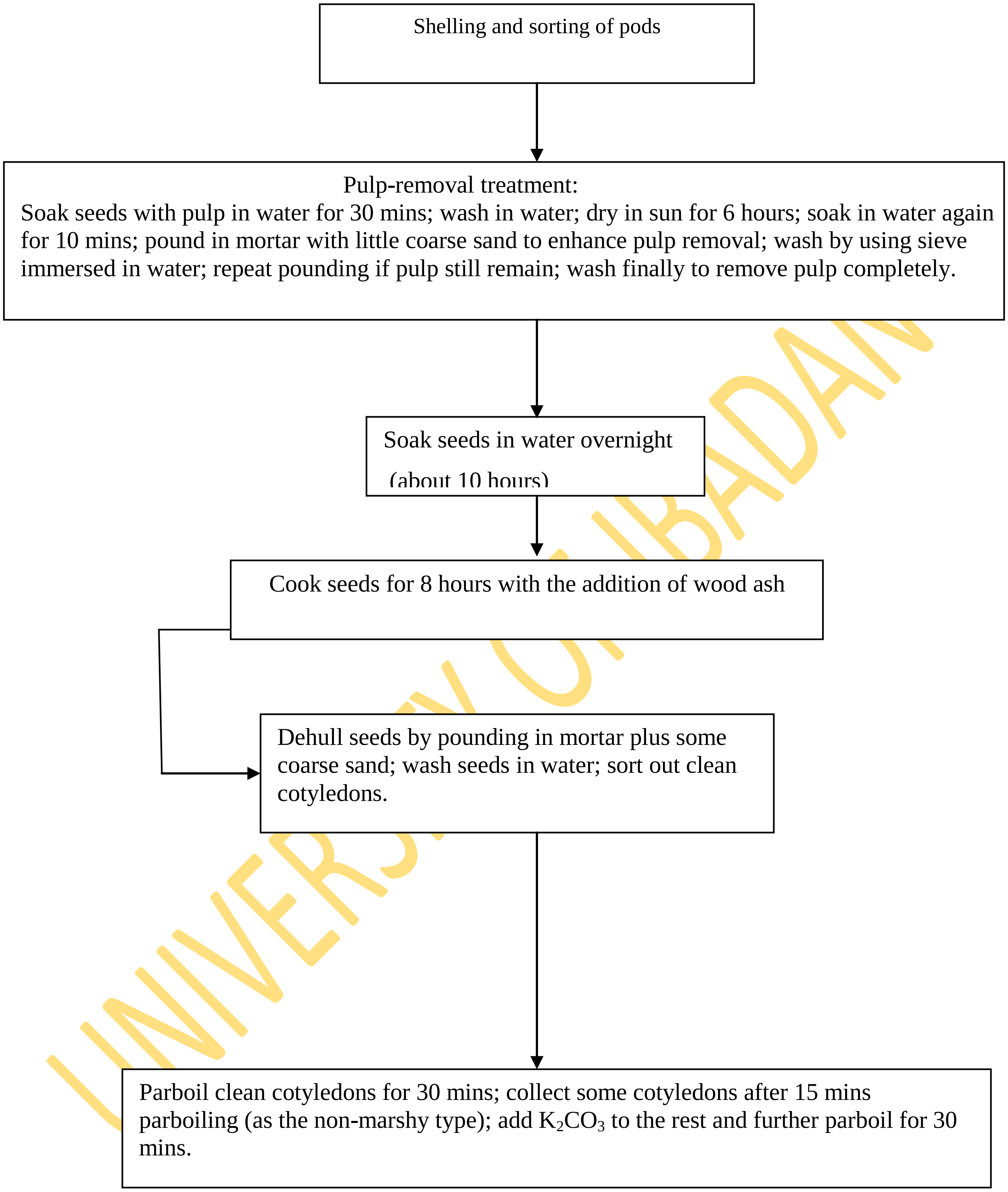

Fig. 4.1 Chart showing different stages of lcust bean processing

4.2 Physical properties of locust bean seed

4.2.1 Seed moisture content.

The initial moisture content of the seed at harvest was found to be 14.26 % wet basis (w.b) [11.1 % dry basis (d.b.)] while the seed moisture content after washing off the pulp and drying was determined to be 5.6 % w.b (5.9 % d.b). The three other moisture levels obtained by conditioning (re-wetting) the seeds were 10, 18 and 22 %, all in wet basis (16.6, 22 and 28.2 % d.b respectively).

4.2.2 Seed size and shape

Generally, the variation of the seed length, width, thickness, arithmetic mean diameter, geometric mean diameter, sphericity and surface area with seed moisture content is displayed in table 4.1. Table 4.1 shows that length, width, surface area, geometric mean diameter and arithmetic mean diameter increased significantly while thickness and sphericity decreased significantly ($p<0.05$) with increase in seed moisture content between 5.9 and 28.2 % d.b. The length, width, geometric mean diameter, arithmetic mean diameter and surface area increased from 10.24 to 11.29 mm, 8.45 to 9.08 mm, 7.78 to 8.12 mm, 8.06 to 8.54 mm and 191.15 to 208.29 mm^2, respectively. The seed thickness decreased from 5.49 to 5.26 mm while sphericity also decreased from 0.75 to 0.71. Geometric and Arithmetic mean diameters decreased from 5.9 to 11.1 % moisture content and gradually increased between 16.6 - 28.2 % moisture content.

Table 4.1 Variations of principal dimensions, sphericity and surface area with moisture content

MC (%)	L (mm)	W (mm)	T (mm)	GD (mm)	ARD (mm)	SFA (mm^2)	SPH
5.9	10.24b (1.02)	8.45b (0.83)	5.49a (0.43)	7.78b (0.49)	8.06b (0.56)	191.15b (24.61)	0.75a (0.04)
11.1	10.49b (0.73)	8.33b (0.78)	5.11b (0.51)	7.61b (0.46)	7.97b (0.47)	182.96b (22.34)	0.72b (0.03)
16.6	10.60b (0.85)	8.44b (0.79)	5.14b (0,58)	7.69b (0.48)	8.06b (0.51)	186.95b (25.20)	0.72b (0.04)
22	10.69b (0.64)	8.55b (0.79)	5.2ab (0.62)	7.73b (0.38)	8.16b (0.43)	191.91b (22.68)	0.72b (0.03)
28.2	11.29a (0.85)	9.08a (0.56)	5.26ab (0.62)	8.12a (0.03)	8.34a (0.49)	208.29a (26.36)	0.71b (0.03)

MC = moisture content, L = Length, W=width, T = Thickness, GD=Geometric diameter; SPH = Sphericity, SFA = Surface area; ARD = Arithmetic diameter. Values in parentheses are standard deviation; values in the same column with different letters (a-c) are significant ($p<0.05$).

1. *Seed length, width and thickness*: The linear increase in length and width and the decrease observed in the thickness with increase in seed moisture content (figure 4.2) implies that the size gained by locust bean seed due to increase in moisture content is along its length and width axes. The increasing trend in axial dimensions of seeds with increasing moisture content is due to the filling of capillaries and voids in the seed with moisture, hence there is subsequent swelling (Seifi and Alimardani, 2010). The direction of size gained is also due to the cell arrangement in the seeds (Nalbandi et al., 2010). A similar trend was reported by Mohammad et al., (2010), on sunflower seed (SHF8190). In their report, the three axial dimensions of sunflower seed first decreased with increase in moisture content from 4 - 12 %, then length started to increase in the moisture range 12 – 22 %. However, width and thickness decreased further. A similar case was also reported for coriander seeds by Coskuner and Karababa (2007) in which there was a linear decrease in the length in the moisture content range of 7.1 - 18.94 % while thickness and width increased in a polynomial trend within the same moisture range.

A linear increase in all the three axial dimensions for locust bean (*Parkia filicoidea*) was reported by Sobukola and Onwuka (2010) within a moisture range of 7.37 - 28.09 % (dry basis). It was stated in the report that seed length, width and thickness increased from 10 - 11.72; 7.80 – 9.22 and 4 - 4.85 mm respectively. This means that two varieties of the same seed will likely behave differently when subjected to moisture intake in terms of their axial dimensions which implies that they may have different cell arrangement. Therefore the filling of the capillaries and voids in the seeds by moisture will lead to swelling of the seed varieties in different directions of their axial dimensions. A significant increase in length and thickness but significant decrease in width of two varieties of beniseed was reported by Tunde Akintunde et al., (2007) in the moisture range of 3.5% - 25% (dry basis). ANOVA results for length, width and thickness for *parkia biglobosa* seeds (Appendix 8) showed that the differences between moisture levels were statistically significant ($p<0.05$) for the three axes. The relationship between moisture content and length, width is linear while it is polynomial with thickness (figure 4.2) and can be expressed with the following regression equations;

$L= 0.0418M + 9.9609 \quad R^2 = 0.8893$ ____________ (4.1)

$W = 0.0273M + 8.1127 \quad R^2 = 0.6568$ ___________ (4.2)

$T = 0.0019M^2 - 0.0693M + 5.7706 \quad R^2 = 0.6363$ ____________ (4.3)

Where L, W, T and M are length, width, thickness and moisture content respectively

These equations therefore imply that, for every unit increase in moisture content of *Parkia biglobosa* seed, there will be a unit increase in the length and width but a decrease in the thickness of the seed.

2. *Geometric and arithmetic mean diameters*: These describe the size of seed and they are important in the design of aperture in screens mostly used in separating machines. Both arithmetic and geometric mean diameters of locust bean followed the same pattern on the graph. They both had a sharp decrease at 11.1 % moisture content of seed before gradually increasing from 16.6 - 28.2 % thus taking a polynomial curve on the graph. The sharp decrease recorded at 11.1 % moisture level is due to the very sharp decrease in thickness and width recorded also at 11.1 % moisture content of the seed. This is as a result of the dependence of arithmetic and geometrical mean diameters on the three axial dimensions of the seeds. The relationship between moisture content of locust bean (*Parkia biglobosa*) seeds and their average diameters (figure 4.3) can be expressed with the following second degree polynomial equations:

$A_d = 0.0021M^2 - 0.0502M + 8.2826 \quad R^2 = 0.9881$ _______ (4.4)

$G_d = 0.0024M^2 - 0.0676M + 8.0898 \quad R^2 = 0.9617$ ________ (4.5)

where A_d, G_d and M are Arithmetic mean diameter, Geometric mean diameter and moisture content of seeds respectively. The very high coefficient of determination (R^2) show that the equations are perfect representations of the relationship between moisture content and the average diameters of *Parkia biglobosa* seeds. This is in agreement with the report of Tavakoli *et al*. (2009) on the moisture dependent physical properties of Barley grains and with the report of Akbarpour *et al*. (2009) on pomegranate seeds.

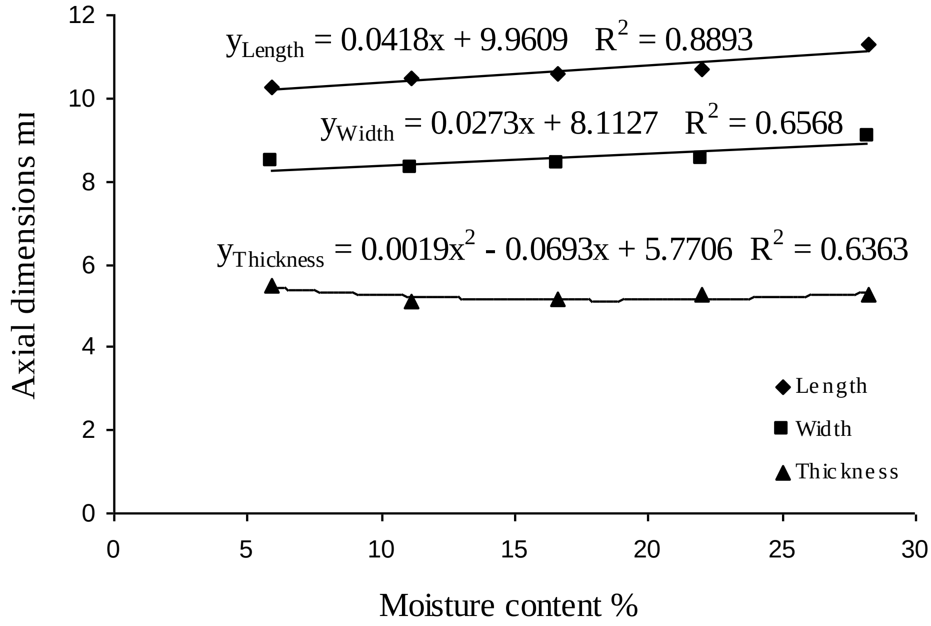

Figure 4.2 Graph of axial dimensions against moisture content of locust bean

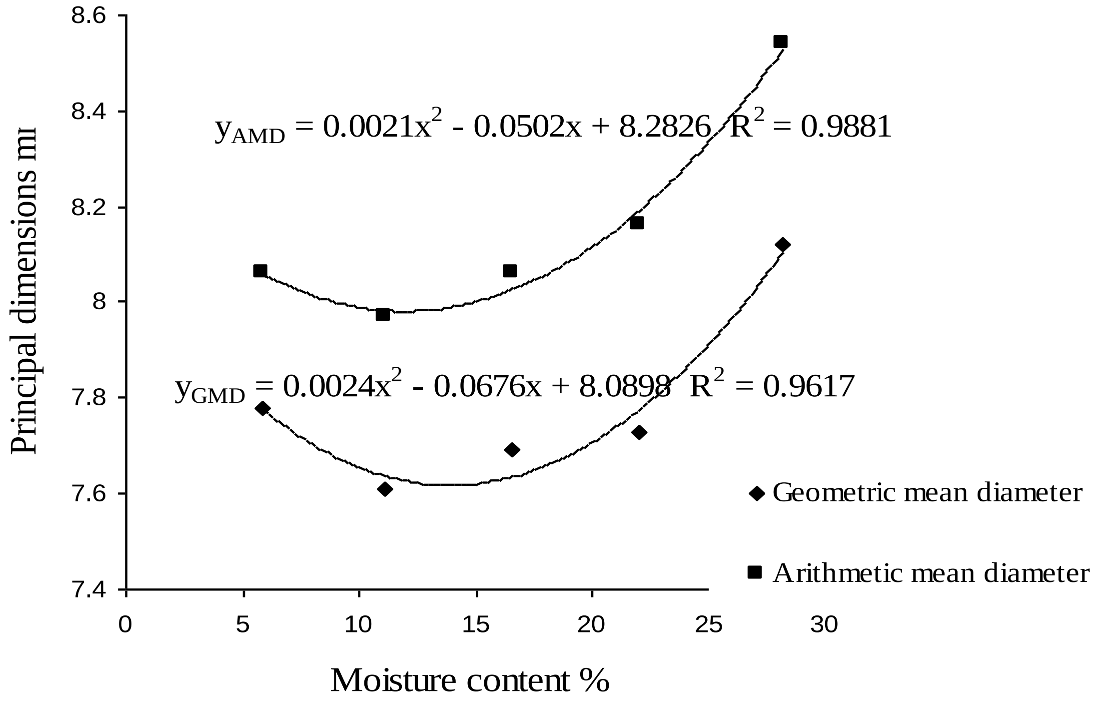

Figure 4.3 Graph of principal dimensions and moisture content of locust bean

3. *Sphericity*: The sphericity value for most agricultural seeds, as stated by Mohsenin (1986) is in the range 0.32 – 1.00. Though the sphericity for *parkia biglobosa* seeds decreased from 0.75 to 0.71 as moisture increased from 5.9 to 28.2 % (d.b), it still falls within the standard range and relatively high. The closer the sphericity is to 1.00, the higher the tendency to roll about any of the three axes. Therefore locust bean seeds will roll easily on any of its axes because of its high sphericity but that ability will reduce as moisture content of the seed increases. Sphericity is considered in the design of the shape of holes or aperture on screens in the design of separating and cleaning machines. Furthermore, size and shape of seed determine the clearance between beaters (or hammers) and screen as found in separating and reduction machines. If the beater-screen clearance is larger than the seed, efficiency of the machine is largely reduced. If the clearance is smaller than seeds' size and shape, there'll be losses due to seed breakage.

The decrease in sphericity with increase in moisture content might be as a result of the decrease in the thickness of the seed as the seed increased in length and width with increase in moisture content. The relationship between moisture content and sphericity is expressed by graph and regression equation in form of a polynomial curve of the third degree (figure. 4.4):

$$\phi = -0.0033M^3 + 0.0329M^2 - 0.1038M + 0.824 \quad R^2 = 0.9938 \quad \_\_\_ \ (4.6)$$

where ϕ = Sphericity; M = Moisture content.

Similar result was reported by Zewdu and Solomon (2008) for Grass pea in which sphericity decreased polynomially from 93.53 - 92.46 within a moisture range of 8.5 - 30.66 % (w.b). The effect of moisture content of locust bean seed on its sphericity was statistically significant ($p<0.05$) as shown in the ANOVA result (Appendix 8). Decreasing sphericity trends was also reported by Tekin et al; (2006) for Bambara bean.

4. *Surface Area*: The surface area is a function of the geometric diameter which is also dependent on the axial dimensions of the seed. The surface area of a grain 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 grain during cleaning by pneumatic means (Omobuwajo et al, 1999). The surface area for *Parkia bioglobosa* seeds first decreased from 191.1 to 182.9 mm^2 as moisture content increased from 5.9 to 11.1 %.

Afterwards the surface area increased gradually to 208.2 mm^2 as moisture content increased to 28.2 %, hence the relationship between moisture content and surface area is a second order polynomial (figure 4.4). The regression equation expressing the relationship is given as:

$$A_s = 3.5786M^2 - 17.161M + 204.4 \quad R^2 = 0.9814 \qquad \_\_\_\_\_\_ (4.7)$$

where A_s = Surface area and M = moisture content.

The initial decrease in surface area was due to the initial sharp decrease in the thickness of the seeds at 11.1 % moisture level. A similar result was reported for coriander seeds by Coskuner and Karababa (2009), where a polynomial curve represented the relationship between moisture content and surface area though there was no sharp decrease at any moisture level. On the other hand, Sobukola and Onwuka (2010) reported a linear increase in surface area for *Parkia filicoidea* from 121.77 to 177.24 mm^2 as moisture content increased from 7.96 to 28.09 % (d.b.).

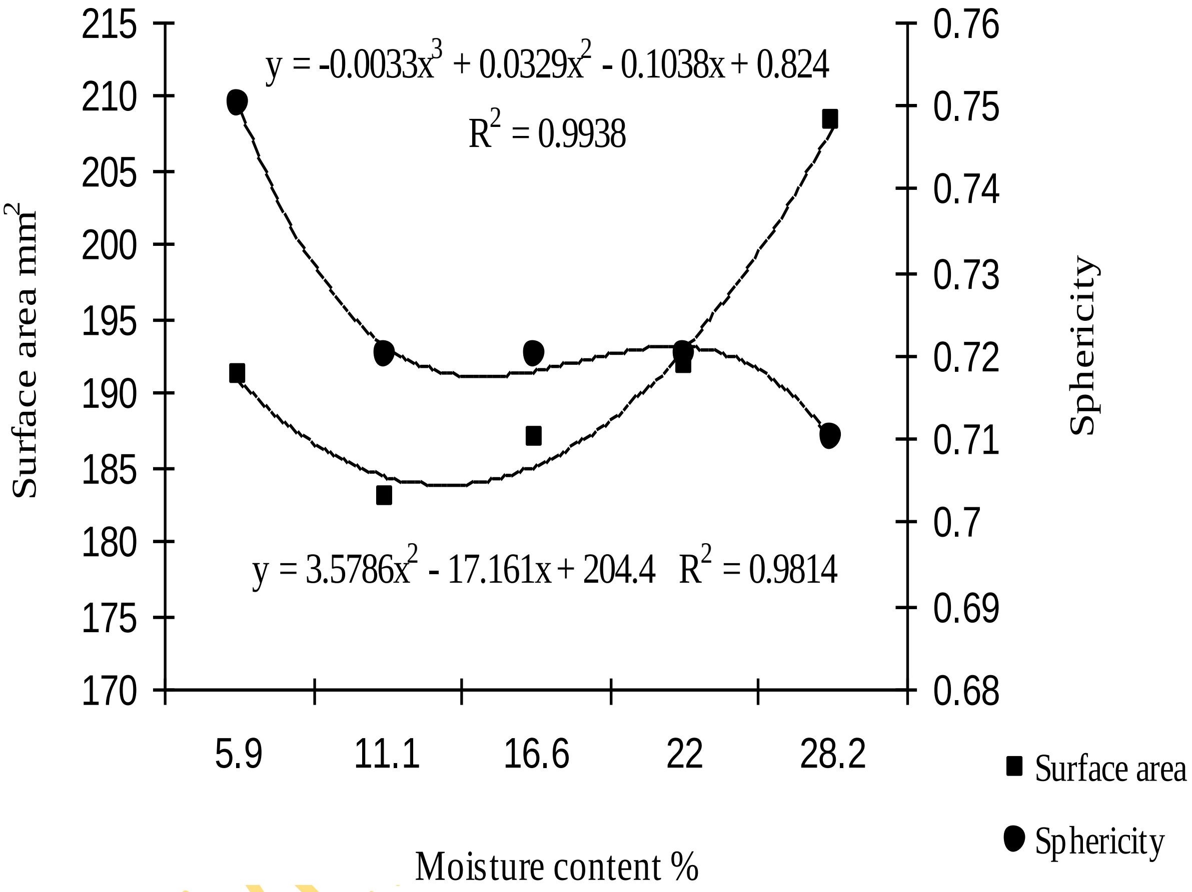

Figure 4.4 Sphericity and surface area of locust bean as affected by moisture content

4.3 Gravimetric properties

4.3.1 Seed mass, volume and thousand-grain mass.

The ANOVA result (Appendix 9) showed that seed moisture effect was statistically significant on thousand grain mass only, but further separation of means using Duncan Multiple Range Test (DMRT) as represented in table 4.2 showed a statistically significant effect of seed moisture content on thousand grain mass, seed volume and seed mass as seed moisture content increased from 5.9 to 28.2 % ($p < 0.05$).

1. *Seed Mass* Seed mass is the average mass of individual seed. Seed mass has practical applications in unit operations such as conveying as well as cleaning. The seed mass gradually increased from 0.24 to 0.26 g with increase in moisture content in a third order polynomial trend (figure 4.4) but the effect of seed moisture on seed mass became statistically significant at 22 % moisture content. There was an initial increase between 5.9 and 11.1 % moisture levels (though not statistically significant) followed by a gradual increase in the seed mass up to 28.2 % moisture content. This might be due to the fact that drier seeds will take in moisture more rapidly than wet seeds. The faster the colloids in the seed get saturated with water, the slower the rate of water intake. Since the intake of water increases the mass of the seed, there must be an initial increase in the seed mass at the very early moisture content. Higher seed mass was still recorded at higher moisture contents but more gradual and slower compared to the early moisture levels. For *Parkia biglobosa* seeds, the relationship between moisture content and seed mass is a third order polynomial with the highest value at 28.2 % moisture level. The relationship is expressed by the equation:

$M_s = -9E\text{-}16M^3 - 0.0007M^2 + 0.0093M + 0.232 \quad R^2 = 0.9184$ _______ (4.8)

Where M_s = seed mass; M = moisture content

2. *Seed volume*: Seed volume considerations have practical application in separation and product loading. Seed volume had an appreciable increase at the initial stage as moisture increased from 5.9 to 11.1 % but gradually decreased as moisture content increased to 28.2 %, though the final volume at 28 % moisture content was still higher than the initial volume at 5.9 % moisture content. The initial increase in seed volume was statistically significant. Therefore the relationship between moisture content and seed volume for locust bean (*Parkia biglobosa*) was expressed by a polynomial equation of the third degree (Eqn. 4.9).

$$V_s = 2.1083M^3 - 21.946M^2 + 68.945M + 146.84 \quad R^2 = 0.9607 \quad \_\_\_\_\_ \quad (4.9)$$

Where V_s = seed volume: M = Moisture content

Comparing the volume and mass of locust bean, it was observed that the seed volume decreased with increasing moisture content (after the initial increase in volume) while seed mass increased with increasing moisture content. It therefore implies that seed density will increase as moisture content increases. Weight and volume are also useful in mathematical and computer modeling of handling and processing operations where the behavior of the bulk system is predicted from the microscopic behavior especially of individual seed (Rong et al., 1995; Raji and Favier, 2004).

3. *Thousand grain mass*: Thousand grain mass (TGM) is the total mass of 1000 seeds. For locust bean, TGM increased from 247.6 g to 284.2 g with increasing seed moisture content from 5.9 % to 28.2 % but the increment was only statistically significant from 5.9 % to 11.1 % moisture content. This phenomenon is also due to the fact that dry seeds readily take in moisture and faster than wet seeds. When most of the colloids in the seed get filled with moisture, the moisture intake becomes gradual or slower, thus a more appreciable increase in mass of the bulk grain may not occur as the seed moisture content increases. The relationship between seed moisture content and TGM is a polynomial relationship shown in figure 4.5 and expressed in equation 4.10. This is important in the design of conveyors, transport and storage equipment.

$$TGM = 0.0695\,M^2 + 3.9273M + 227.64 \quad (R^2 = 0.9823) \quad \_\_\_\_\_\_\_ \quad (4.10)$$

where M = moisture content.

Table 4.2 Some gravimetric properties of locust beans as affected by moisture

Mc (%)	SM (g)	SV (mm^3)	TGM (g)
5.9	0.24b (0.004)	195.6b (9.39)	247.6c (9.88)
11.1	0.25ab (0.003)	215.26a (7.56)	263.6b (8.61)
16.6	0.25ab (0.01)	210.96a (9.10)	275.4ab (15.63)
22	0.26a (0.01)	207.78ab (15.02)	277.4a (6.42)
28.2	0.26a (0.008)	206.1ab (8.56)	284.2a (4.76)

Mc = moisture content, SM = seed mass, SV = Seed volume, TGM = Thousand grain mass. Values in parentheses are standard deviations; values in the same column followed by different letters (a-c) are significant ($p<0.05$).

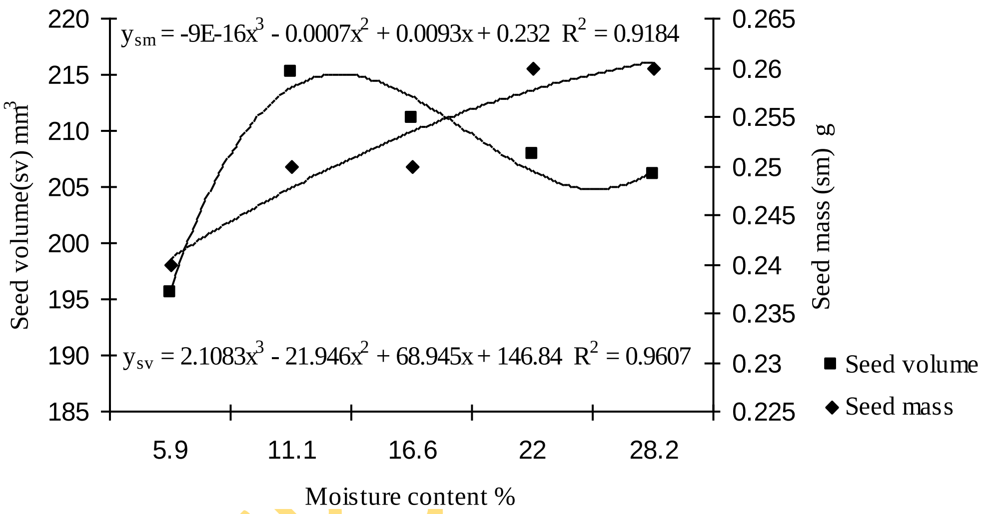

Figure 4.5 Effect of moisture variation on seed mass and volume

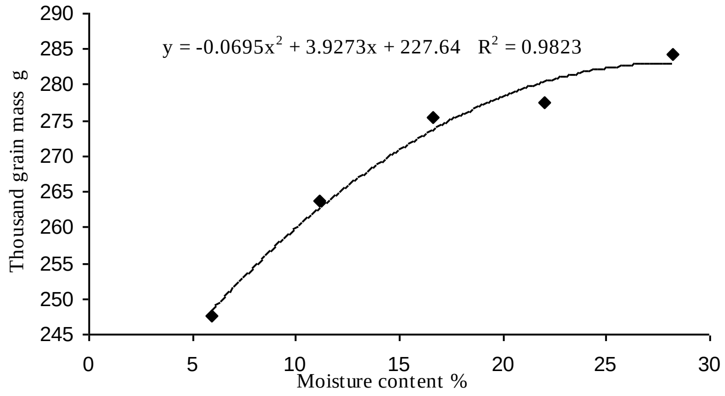

Fig. 4.6 Effect of moisture variation on thousand grain mass

4.3.2 Bulk density, true density, and porosity

From ANOVA results for gravimetric parameters (Appendix 9), table 4.3, figures 4.6 and 4.7, it could be inferred that bulk density increased linearly and significantly ($p<0.05$) with increasing moisture content (from 5.9 to 28.2 %) while true density did not show significant effect of the seed moisture content. Porosity decreased significantly but in a polynomial trend ($p<0.05$) within seed moisture range of 5.9 - 28.2 % d.b. from 48.4 to 41.9 %. It first increased at 22 % moisture content and further decreased at 28.2 % moisture content.

1. *Bulk and True densities*: Bulk density is the ratio of a bulk mass of a material to the volume it occupies. Bulk density for locust bean (*Parkia biglobosa*) seeds increased with increasing moisture content of seeds. The reason for increase in bulk density was due to mass of seed increasing more rapidly than the volume of seeds. Precisely, seed volume for locust bean (*Parkia bigloboс*a) started decreasing after the initial increase thereby giving rise to bulk density since bulk density is the ratio of the mass of bulk grain to the volume occupied.

2. *True density*: is the actual density of a grain bulk determined by the ratio of a specific mass of the bulk grain to the actual or true volume of toluene displaced. For true density of locust bean, analysis of variance (ANOVA in appendix 9) showed that moisture content had no statistically significant effect on true density. Nevertheless, the decrease in true density implies that volume occupied by the bulk grain increased at a faster rate than increase in its mass. The increase and decrease in bulk and true densities respectively was also due to structural properties of the seeds (Milani et al; 2007). Decrease in both bulk and true densities was found for *Parkia filicoidea* by Sobukola and Onwuka, (2010). Igbozulike and Aremu, (2009) reported an increase in bulk density and a decrease in true density for *Garcinia* Kola seeds as moisture content increased. Equations 4.11 and 4.12 express the relationship between moisture content and both (bulk and true densities) of *parkia biglobosa* seeds.

$$\rho_b = - 2.6747M + 642.05 \quad (R^2 = 0.8174) \qquad \_\_\_\_\_\_\_ \ (4.11)$$

$$\rho_t = - 6.0338M^3 + 1.8297M^2 - 30.092M + 1373.3 \ (R^2 = 0.9792) \ \_\_\_ \ (4.12)$$

where ρ_b = bulk density; ρ_t = true density and M = moisture content.

3. ***Porosity*****:** Since porosity depends on bulk and true densities, variation in the magnitude of these two parameters will affect the magnitude of porosity (Milani et al; 2007). The porosity for *Parkia biglobosa* was found to decrease with increase in seed moisture content. In practical terms, porosity describes the ratio of pore spaces (voids) in a grain bulk to the space occupied by the whole grain mass. This simply implies that increase or decrease in porosity will be determined by the magnitude of pore spaces in a grain mass. For *Parkia biglobosa*, the decreasing porosity with increasing moisture content therefore implies that pore spaces within the bulk seeds especially when stacked up in storage will reduce with increasing moisture content of the seeds. It means that the seeds got swollen as moisture content increased (increased in size) and the pores reduced. Also, the seeds became very wet and sticky at high moisture content thereby filling some of the voids with the sticky fluid film on the seed surface; therefore porosity decreased. A decrease in porosity was reported for *Parkia filicodiea* by Sobukola and Onwuka, (2010). Tunde-Akintunde and Akintunde (2007) also reported a decrease in porosity for beniseed. They further stated that porosity decreases because an increase in moisture content results in a more significant swelling of the seed along its axial dimensions (precisely length and width). This will reduce the air spaces in the grain bulk, and give a more compact arrangement of seeds. On the other hand, it therefore suggests that if locust bean is stored when wet, aeration will be reduced and moulding will occur. The regression equation expressing the relationship between porosity and moisture content for *parkia biglobosa* is given as;

$$\varepsilon = -\ 0.0215M^2 - 1.0054M + 53.358\ (R^2 = 0.9993) \qquad \_\_\_\_\ (4.13)$$

where ε = Porosity and M = moisture content

This property is important in packaging of the grains and it affects the resistance to airflow through bulk grain.

Table 4.3 Effect of moisture on Porosity, Bulk and True densities

MC (%)	BLKD (kgm^{-3})	TRD (kgm^{-3})	Porosity (%)
5.9	644.98c	1251.96a	48.40a
	*(7.92)	(55.50)	(2.14)
11.1	678.54b	1220.6a	44.36b
	(9.79)	(40.25)	(1.93)
16.6	700.28a	1220.6a	42.58b
	(8.62)	(40.25)	(1.64)
22	702.48a	1239.22a	43.10b
	(9.92)	(85.88)	(3.71)
28.2	708.06a	1222.2a	41.91b
	(12.05)	(62.16)	(3.78)

MC= Moisture content, BLKD = Bulk density, TRD = True density * Values in parentheses are standard deviations. Values in the same column followed by different letters (a-c) are significant ($p<0.05$).

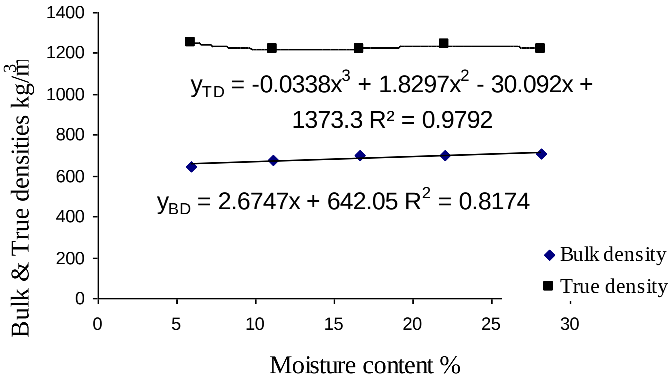

Fig. 4.7 Influence of moisture content on bulk and true densities of locust bean

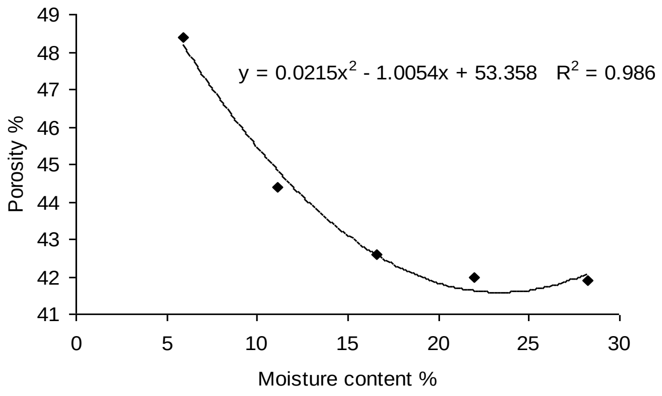

Fig. 4.8 Porosity of locust bean as affected by moisture content

4.4 Frictional properties

4.4.1 Static coefficient of friction

Static friction is a force parallel to two opposing surfaces that are stationary. To initiate movement in a stationary object, you must put in enough energy to overcome the static friction which is holding it still. The ANOVA results for static coefficient of friction on seven surfaces (Appendix 10) reveal that the effect of seed moisture content on static coefficient of friction was statistically significant ($P<0.05$) on rubber, plywood, glass and mild steel surfaces only. Further separation of means by use of DMRT as represented in Table 4.4, showed that the effect of seed moisture on static coefficient of friction was also statistically significant (a decrease) on stainless steel but between 22 and 28.2 % seed moisture content. Comparing the magnitude of static coefficient of friction literarily at the two endpoints of the moisture range (i.e. 5.9 and 28.2 %), there was a general increase for all the structural surfaces except aluminium and stainless steel on which a decrease was recorded. Highest value of coefficient of friction was found in plywood (0.60) and rubber (0.60) both at 28.2 % moisture content.

Aluminium had a decrease in coefficient of static friction with increase in moisture content of seeds but there was an increase at 16.6 % moisture content but a further decrease between 22 - 28.2 % moisture content. After an initial decrease between 5.9 - 11.1 % moisture content, stainless steel also experienced an increase between 16.6 – 22 % moisture levels before a further decrease at 28.2 % moisture content. The various regression equations and trend patterns expressing the relationship between moisture content and static coefficient of friction of locust bean seeds (*Parkia biglobosa*) on different surfaces are presented in figures 4.9 through 4.12. Static coefficient of friction is needed in the choice of structural material for the design of machine components involving the flow of bulk granular materials. The increase in static coefficient of friction was due to increased adhesion between the wet seeds' surfaces and the rough surfaces of the test materials (like plywood and rubber) while the decrease was due to the smoothness and more polished surfaces of aluminium and stainless steel in comparison with other test surfaces.

Linear increase in static coefficient of friction for *Parkia biglobosa* seeds was found on plywood only, while its increase on glass, mild steel, galvanized sheet and rubber were in a polynomial trend. Plywood recorded the highest value of static coefficient of friction (0.61), followed by rubber (0.60) at 28.2 % moisture level while rubber also recorded the lowest at 5.9 % moisture level. It therefore means that more energy or force will be required to initiate motion of locust bean seeds on some surfaces (like plywood) as seed moisture content increases while energy requirement for motion in the seeds will be less for others like aluminium as the seed moisture content increases. Sobukola and Onwuka, (2010) recorded the highest static coefficient of friction for *Parkia filicoidea* on plywood surface (1.00). Equations expressing the relationship between moisture content and the different surfaces for *Parkia biglobosa* are as follow:

$\mu_{\text{Plywood}} = 0.0051M + 0.4449 \qquad R^2 = 0.9469$ _______ (4.14)

$\mu_{\text{Glass}} = -0.0005M^2 + 0.0221M + 0.3099 \quad R^2 = 0.9931$ _____ (4.15)

$\mu_{\text{Mild steel}} = 2E\text{-}05M^4 - 0.0014M^3 + 0.0341M^2 - 0.3314M + 1.552 \qquad R^2 = 1$ ___ (4.16)

$\mu_{\text{Galvanized sheet}} = -3E\text{-}05M^3 + 0.0019M^2 - 0.0295M + 0.6226 \quad R^2 = 0.7123$___ (4.17)

$\mu_{\text{Rubber}} = -0.0003M^2 + 0.0156M + 0.3409 \quad R^2 = 0.7824$ ______ (4.18)

$\mu_{\text{Aluminium}} = 1E - 05M^4 - 0.0007M^3 + 0.0167M^2 - 0.158M + 1.0231 \quad R^2 = 0.2482$ ___ (4.19)

$\mu_{\text{Stainless steel}} = -5E\text{-}05M^3 + 0.0024M^2 - 0.033M + 0.672 \quad R^2 = 0.9998$______ (4.20)

Table 4.4 Seed moisture content and static coefficient of friction of locust bean on different material surfaces.

	Moisture content (%)				
Material	5.9	11.1	16.6	22	28.2
Plywood	0.48c	0.50bc	0.53b	0.54b	0.60a
	(0.02)	(0.04)	(0.03)	(0.03)	(0.01)
Glass	0.40b	0.50b	0.54a	0.55a	0.54a
	(0.05)	(0.04)	(0.03)	(0.07)	(0.01)
Mild steel	0.52a	0.46b	0.55a	0.52a	0.54a
	(0.04)	(0.07)	(0.02)	(0.009)	(0.02)
Galvanized Iron	0.51a	0.47a	0.51a	0.51a	0.52a
	(0.04)	(0.03	(0.02)	(0.04)	(0.03)
Rubber	0.41d	0.50c	0.56ab	0.51bc	0.60a
	(0.04)	(0.03)	(0.03)	(0.04)	(0.05)
Aluminum	0.54a	0.52a	0.56a	0.53a	0.52a
	(0.02)	(0.04)	(0.043)	(0.06)	(0.04)
Stainless steel	0.55ab	0.53ab	0.55ab	0.56a	0.50b
	(0.025)	(0.05)	(0.041	(0.02)	(0.04)

Standard deviations in parentheses. Values in the same row followed by different letters (a-c) are significant ($p<0.05$).

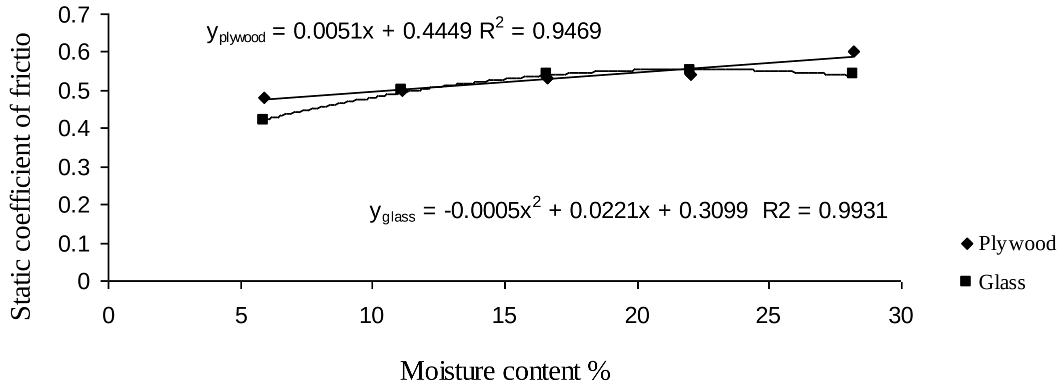

Fig. 4.9 Moisture content effect on static coefficient of friction of locust bean on plywood and glass surfaces

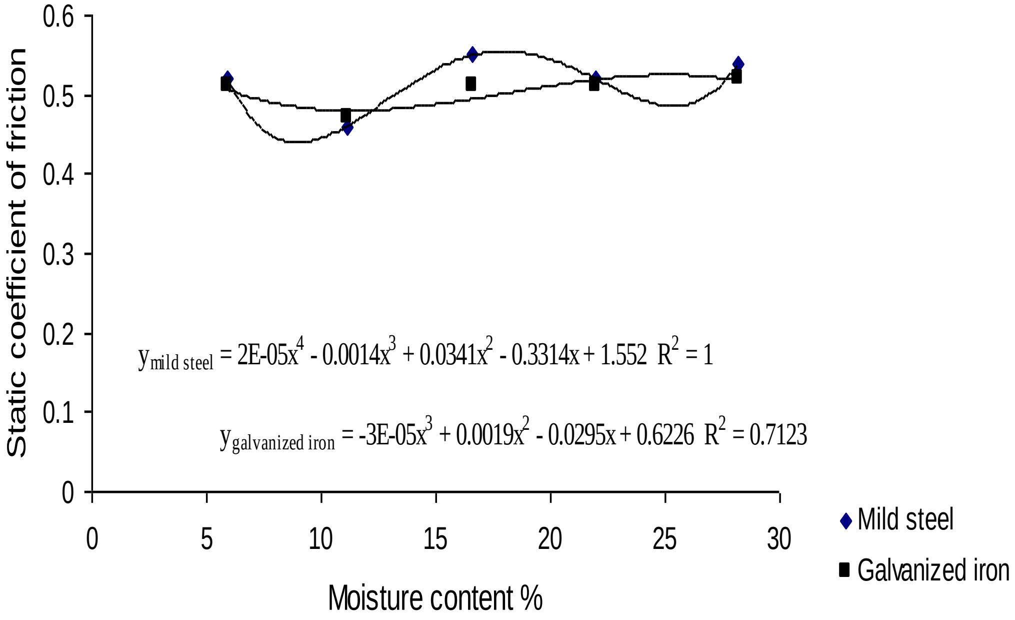

Fig. 4.10 Static coefficient of friction of locust bean on mild steel and galvanized iron against moisture content

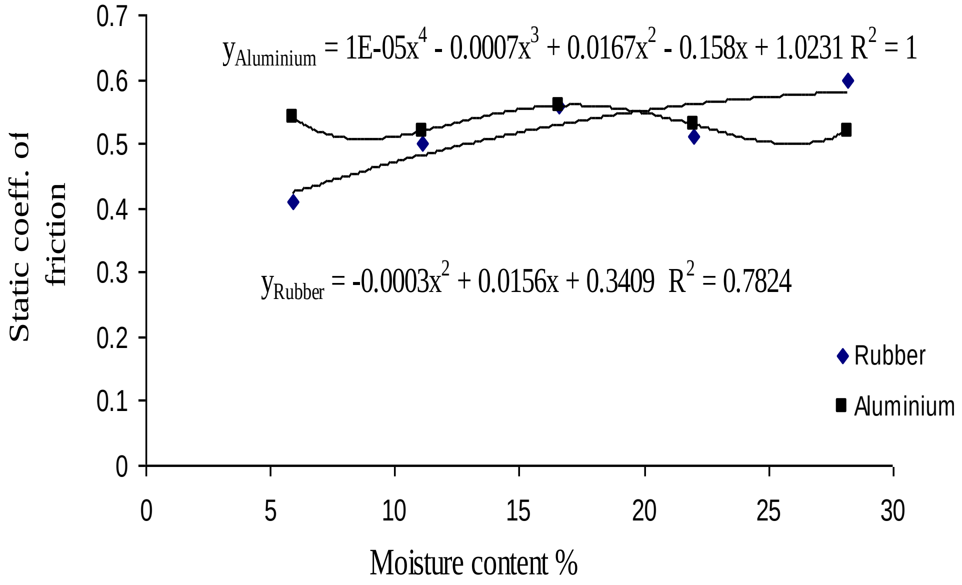

Fig. 4.11 Static coefficient of friction on rubber and aluminium as a function of moisture content

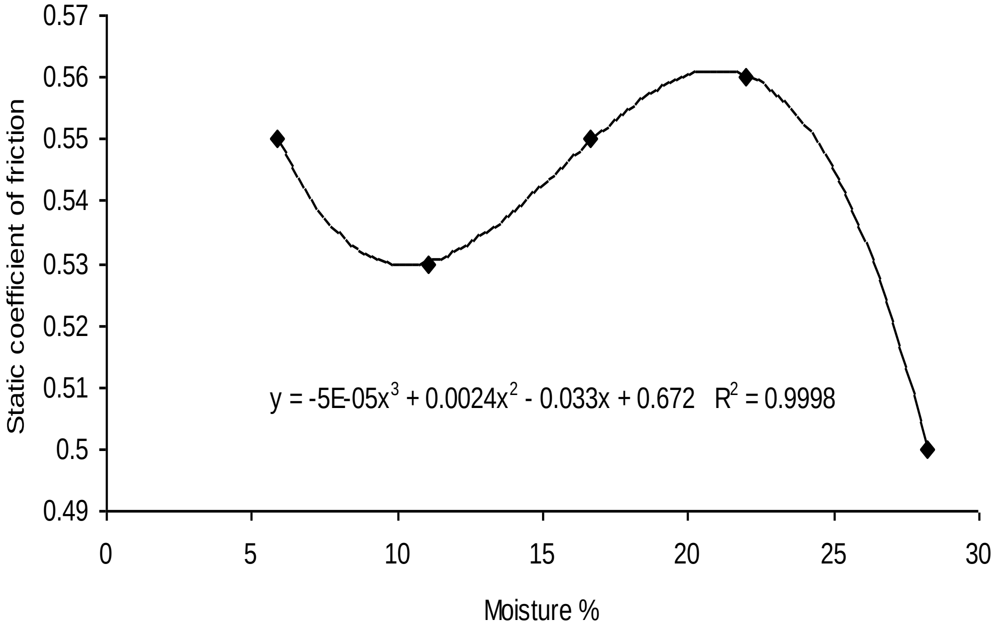

Fig. 4.12 Static coefficient of friction of locust bean on stainless steel surface as a function of moisture content

4.4.2 Coefficient and angle of internal friction

The coefficient of internal friction is simply the friction of grain against grain. The seed moisture content increased in the range of 5.9 - 28.2 % d.b (Table 4.5) which gave increase in coefficient of internal friction (0.30 – 0.53) and angle of internal friction (17.0 - 28.2^o). Increase in both parameters was of the same trend. A decrease was recorded for both parameters between 16.6 and 22 % moisture levels before further increase at 28.2 % moisture content. Highest value was recorded at 11.1 % moisture level for both coefficient (0.61) and angle (31.4^o) of internal friction.

Both coefficient and angle of internal friction increased in a polynomial trend as moisture content of the seeds increased (figure. 4.13). Since the angle of internal friction is the arc-tangent of the coefficient of internal friction, it follows that both angle and coefficient of internal friction will have the same trend. The angle of internal friction was higher than the coefficient of internal friction at all moisture levels. At higher moisture content levels, locust bean seeds stick together, resulting in enhanced stability and less flow ability. This definitely increased the value of coefficient of internal friction, which in turn increased the value of angle of internal friction. The angle and coefficient of internal friction are important in the design of hoppers and flow channels in processing machines and equipment for seeds. Both angle and coefficient of internal friction for locust bean are highest at 11.1 % moisture content. There is significant ($p<0.05$) effect of moisture content of seeds on both coefficient and angle of internal friction (Appendix 10.2). Equations for the relationship between moisture and coefficient and angle of internal friction are as follow;

$$\theta_i = 1.7675M^3 - 17.715M^2 + 54.308M - 21.188 \quad R^2 = 0.9811 \_\_\_ (4.21)$$

$$\mu_i = 0.0408M^3 - 0.4054M^2 + 1.2238M - 0.556 \quad R^2 = 0.9864 \_\_\_ (4.22)$$

where θ_i , μ_i , M are angle, coefficient of internal friction and moisture content.

Table 4.5 Effect of moisture content on coefficient and angle of internal friction

Moisture content %	Coefficient of Internal friction	Angle of Internal friction (degree)
5.9	0.30c	17.0c
	(0.07)	(3.62)
11.1	0.61a	31.4a
	(0.14)	(5.49)
16.6	0.55ab	28.9ab
	(0.03)	(1.50)
22	0.48b	26.5b
	(0.04)	(2.22)
28.2	0.53ab	28.2ab
	(0.02)	0.976

Values in parentheses are standard deviations. Values in the same column followed by different letters (a-c) are significant ($p<0.05$).

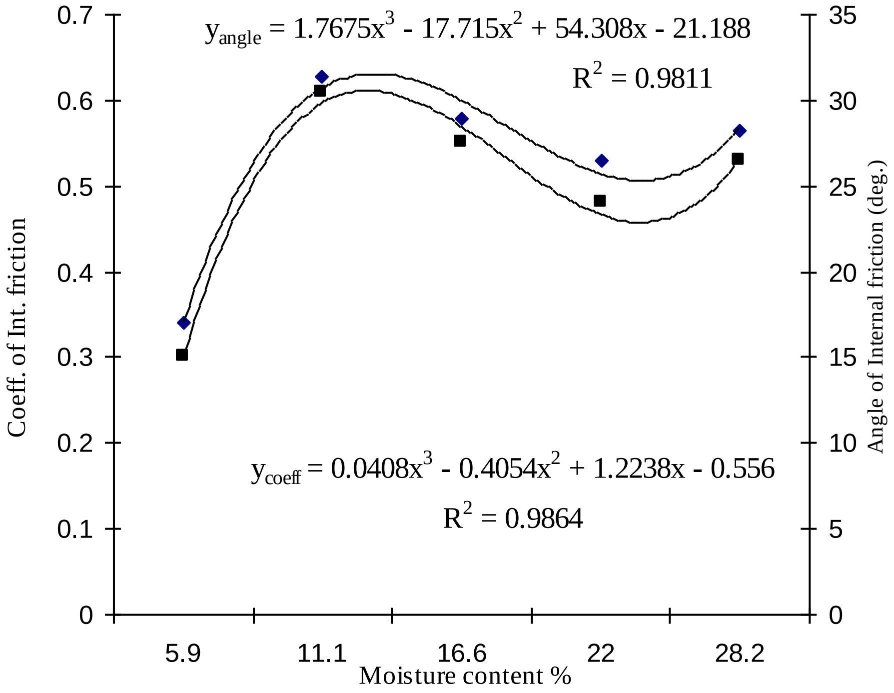

Fig. 4.13 Effect of moisture content on coefficient and angle of internal friction of locust bean

4.4.3 Static and dynamic angles of repose

The static angle of repose increased linearly from 48.4 to 56° with increase at each moisture level in the moisture range of 5.9 - 28.2 % (d.b). The dynamic angle of repose also increased with increase in moisture in the same moisture range but with a decrease at 22 % moisture content after which an increase was experienced again at 28.2 % moisture content. Both static and dynamic angles of repose of *parkia biglobosa* increased linearly with increase in the seed moisture content in the range of 5.9 - 28.2 % (d.b). ANOVA (appendix 10.2) and the DMRT results (Table 4.6) for the angles of repose show the significant effect ($p<0.05$) of seed moisture content in the range of 5.9 - 28.2 % (d.b.) on the dynamic and static angles of repose. The static angle of repose was higher at each moisture content level than the dynamic angle of repose (figure 4.14). It would be recalled from section 4.1.2(3) that the sphericity for *parkia biglobosa* seeds decreased with increasing moisture content hence the ability of the seeds to easily roll over one another is reduced as moisture content increased. This accounts for the increase in the magnitude of the angles of repose as moisture content increased. The higher the sphericity is, the higher the ability to roll over therefore, the lower the angle of repose.

Another reason for high angles of repose is the sticky nature of the seeds at high moisture content. At high moisture levels, the seeds of *Parkia biglobosa* tend to stick to one another because of the presence of water films on their surfaces. This hinders their free flow therefore, angle of repose will increase. The dryer the seeds, the less they stick together and the more easily they slide and roll over one another, and hence a low angle of repose. The relationship between the angles of repose and moisture content are given as:

$\theta_{Static} = 0.3324M + 46.269 \quad R^2 = 0.9625$ _______ (4.23)

$\theta_{Dynamic} = 0.2051M + 23.763 \quad R^2 = 0.6663$_____ (4.24)

Table 4.6 Effect of moisture content on the angles of repose

Moisture content %	Dynamic angle of repose (degree)	Static angle of repose (degree)
5.9	25.3c (1.502)*	48.4d (0.894)
11.1	25.8c (0.894)	50.4c (1.140)
16.6	28.0b (1.048)	50.8c (1.303)
22	26.2c (1.035)	53.6b (1.516)
28.2	30.7a (1.199)	56a (1.414)

*Values in parentheses are standard deviations (deg) degrees. Values in the same column followed by different letters (a-c) are significant ($p<0.05$).

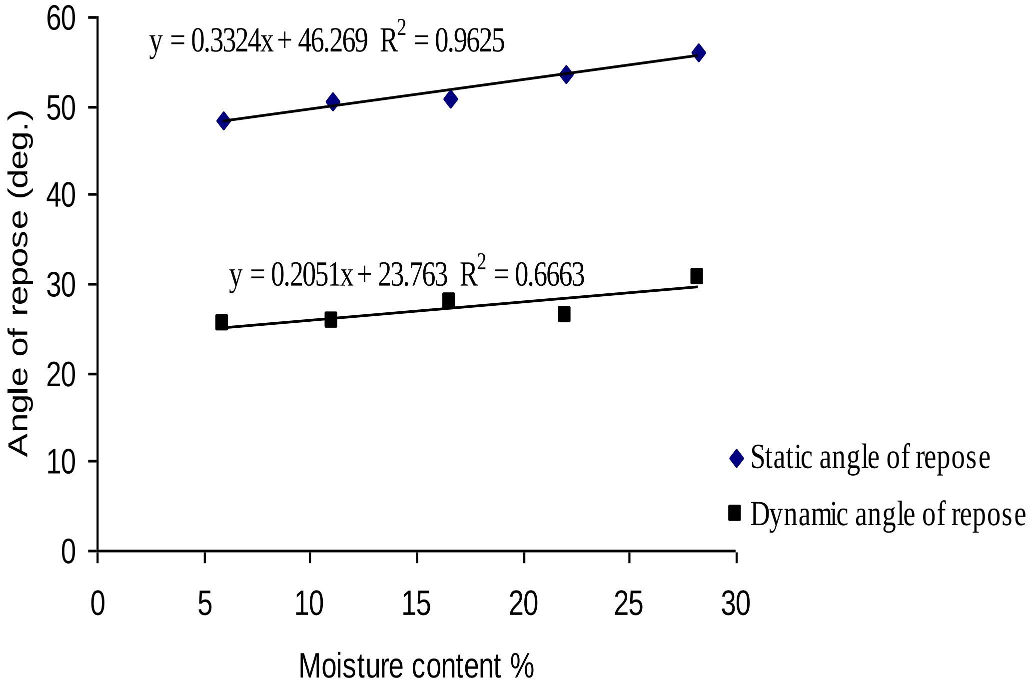

Fig. 4.14 Moisture content effect on the angles of repose of locust bean.

4.5 Flow properties

4.5.1 Coefficient of mobility and hopper side - wall flow

From the ANOVA (appendix 10.3) and DMRT results (Table 4.7), it is shown that the effect of moisture on coefficient of mobility and hopper side wall slope is statistically significant ($p<0.05$). Coefficient of mobility decreased from 0.55 to 0.35 while hopper side wall slope increased from 53.49 to 59.11^{o} as seed moisture content increased from 5.9 to 28.2 % d.b. Coefficient of mobility was highest at 5.9 % moisture content while hopper side wall slope was highest at 11.1 % moisture content. Hopper side wall slope was higher than the coefficient of internal friction of locust bean at every moisture level. The decrease in coefficient of mobility is in a polynomial trend as shown on the graph while hopper side wall slope for locust bean also had an increase in a polynomial trend (figure 4.15).

1. *Coefficient of Mobility* Coefficient of mobility represents the fluidity or the freedom of motion of a material or substance (Irtwange, 2000). From the results, it was observed that the coefficient of mobility for *parkia biglobosa* seeds decreased (a polynomial trend) from 0.55 to 0.35 with increase in moisture content in the range 5.9 - 28.2 % (d.b). The decrease in coefficient of mobility was due to the sticky surfaces of the seeds at high moisture content which hinders the freedom of the seeds to move easily. At high moisture contents, the seeds also tend to adhere to the surface on which they are. This also constitutes a hindrance to the fluidity of the seeds. Therefore at high moisture levels, the ability of locust bean seeds to move easily is reduced. The relationship between coefficient of mobility and moisture content can be expressed as

$$M_1 = 0.03M^3 + 0.3M^2 - 0.92M + 1.198 \quad (R^2 = 0.9922) \quad \_\_\_\_ \ (4.25)$$

2. *Hopper side wall angle (slope)*: Irtwange, (2000) quoted Stepanoff, (1969) in his report that ‘for easy flow of material, the slope angle of the side wall of hoppers must be greater than the angle of internal friction of the material’. Since the angle of internal friction of *Parkia biglobosa* seeds increased with increasing moisture content of the seeds, the hopper side wall angle also (though non-linear) increased, following the same pattern with the angle of internal friction as earlier shown in fig. 4.13. The hopper side wall slope at each moisture content level therefore suggests the angle for which the hopper side walls should be designed for *parkia biglobosa* seeds at the specified moisture levels or range.

For locust bean within moisture content range of 5.9 - 28.2 % and a range of angle of internal friction of 16.99 - 28.24°, hopper side wall slope or angle ranges between 53.49 - 59.11°. The following equation expresses the effect of moisture on hopper side wall angle for locust bean:

$$\beta = 0.8833M^3 - 8.8714M^2 + 27.245M + 34.34 \ (R^2 = 0.9789) \_\_\_\_ \ (4.26)$$

where β = hopper side wall slope; M = moisture content

Table 4.7 Effect of moisture content on coefficient of mobility and Hopper side wall slope

Moisture content %	Coefficient of mobility	Hopper side wall slope / angle (deg.)
5.9	0.55a	53.5c
	(0.07)*	(1.815)
11.1	0.318c	60.81a
	(0.066)	(2.668)
16.6	0.347bc	59.46ab
	(0.02)	(0.766)
22	0.393b	58.22b
	(0.033)	(1.096)
28.2	0.357bc	59.11d
	(0.013)	(0.481)

Values in the same column followed by different letters (a-d) are significant ($p<0.05$).
Values in parentheses are standard deviations.

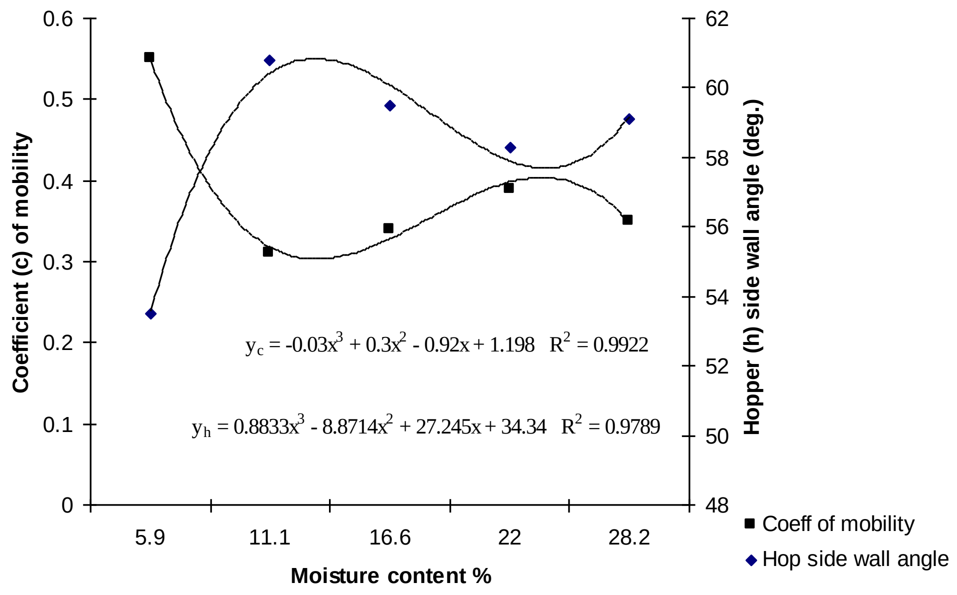

Fig. 4.15 Coefficient of mobility and Hopper side wall angle of locust bean as affected by moisture content

4.6 Mechanical properties

4.6.1 Normal and shear stresses

Tables 4.8 and 4.9 show that the effect of moisture content of locust beans on their normal and shear stresses is significant ($p<0.05$). From the graphs of normal and shear stresses against moisture content (figures 4.16 and 4.17) it is shown that the relationship between moisture content and normal stresses is linear for all the loads, while the relationship between moisture content and shear stress is polynomial for the same loads. In comparison, normal stress was higher at all moisture content levels than shear stress for all the load levels. Both stresses increased with increase in moisture level for all the loads. This is due to the ability of locust bean seeds to stick together at high moisture content levels thereby increasing the normal and shear stresses within the grain bulk. As a result of low porosity at high moisture levels, the magnitude of pore spaces within the bulk grain is decreased, hence the normal and shear stresses of the bulk grain is increased.

1. *Normal stress*: Normal stress was constant for all replicates of each sample lot; therefore the values of normal stress could not be analyzed for significance of moisture effect. But from Table 4.8, it is shown that normal stress increased with load (200 – 500 g) having an increase at every load point and moisture content level at a moisture range of 5.9 - 28.2 % d.b. Normal stress increased by 8.38 - 8.69 g/cm^2, 9.39 - 9.70 g/cm^2, 10.40 - 10.71 gcm^{-3}, 11.41 - 11.72 gcm^{-2} for 200, 300, 400 and 500 g respectively.

2. *Shear stress*: Effect of moisture content on shear stress at different load points 200 g – 500 g as seen in table 4.8 is significant ($p<0.05$) for a moisture range of 5.9 % to 28.2 % (d.b). The highest values of shear stress for each load were: 1.023 (16.6 %), 1.22 (11.1 %), 1.231 (11.1 %) and 1.545 gcm^{-2} (11.1 %) for 200, 300, 400 and 500 g respectively. Peak value of shear stress was observed for 500 g load at 11.11 % moisture level while the lowest shear stress value was observed at 5.9 % moisture level under 200 g load. The following equations show the effect of moisture content on shear and normal stress under the specified loads.

$\sigma_{200} = 0.0132M + 8.3673$ $R^2 = 0.8142$ ____ (4.27)

$\tau_{200} = 0.0004M^3 - 0.0223M^2 + 0.3725M - 0.9298$ $R^2 = 0.9104$___ (4.28)

$\sigma_{300} = 0.0132M + 9.3773$ $R^2 = 0.8142$____ (4.29)

$\tau_{300} = 0.0027M^2 + 0.0995M + 0.2792$ $R^2 = 0.6782$ ___ (4.30)

$\sigma_{400} = 0.0024M^2 + 0.099M + 0.236$ $R^2 = 0.6789$____ (4.31)

$\tau_{400} = 0.0024M^2 + 0.099M + 0.236$ $R^2 = 0.3758$ ___ (4.32)

$\sigma_{500} = 0.0132M + 11.397$ $R^2 = 0.8142$ ____ (4.33)

$\tau_{500} = -0.0042M^2 + 0.1651M - 0.0408$ $R^2 = 0.7761$ ___ (4.34)

Table 4.8 Values of normal stress at different loads and moisture contents

Load (g)	Moisture content level %				
	5.9	11.1	16.6	22	28.2
200	8.38	8.55	8.65	8.67	8.69
300	9.39	9.56	9.68	9.68	9.70
400	10.4	10.57	10.67	10.69	10.71
500	11.41	11.58	11.68	11.7	11.72

Table 4.9 Shear stress mean values under different load and moisture levels

Load (g)	Moisture content (%)				
	5.9	11.1	16.6	22	28.2
200	0.589c	0.954ab	1.023a	0.696c	0.845b
	*(0.07)	(0.079	(0.081)	(0.006)	(0.088)
300	0.688c	1.22a	1.16ab	1.036b	0.996b
	(0.086	(0.083)	(0.124)	(0.105)	(0.056)
400	0.638b	1.231a)	1.228a	1.086a	1.213a
	(0.034)	(0.118)	(0.142	(0.012)	(0164)
500	0.666c	1.545a	1.44ab	1.45bab	1.359b
	(0.064)	(0.049)	(0.088)	(0.058)	(0.028)

*Values in parentheses are standard deviations. Values in the same column followed by different letters (a-c) are significant ($p<0.05$).

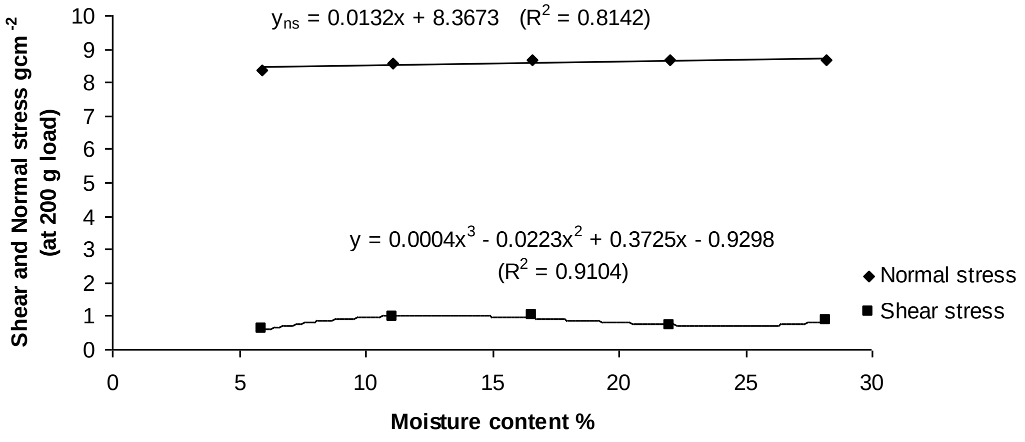

Fig. 4.16 Graph of normal, shear stresses at 200 g load.

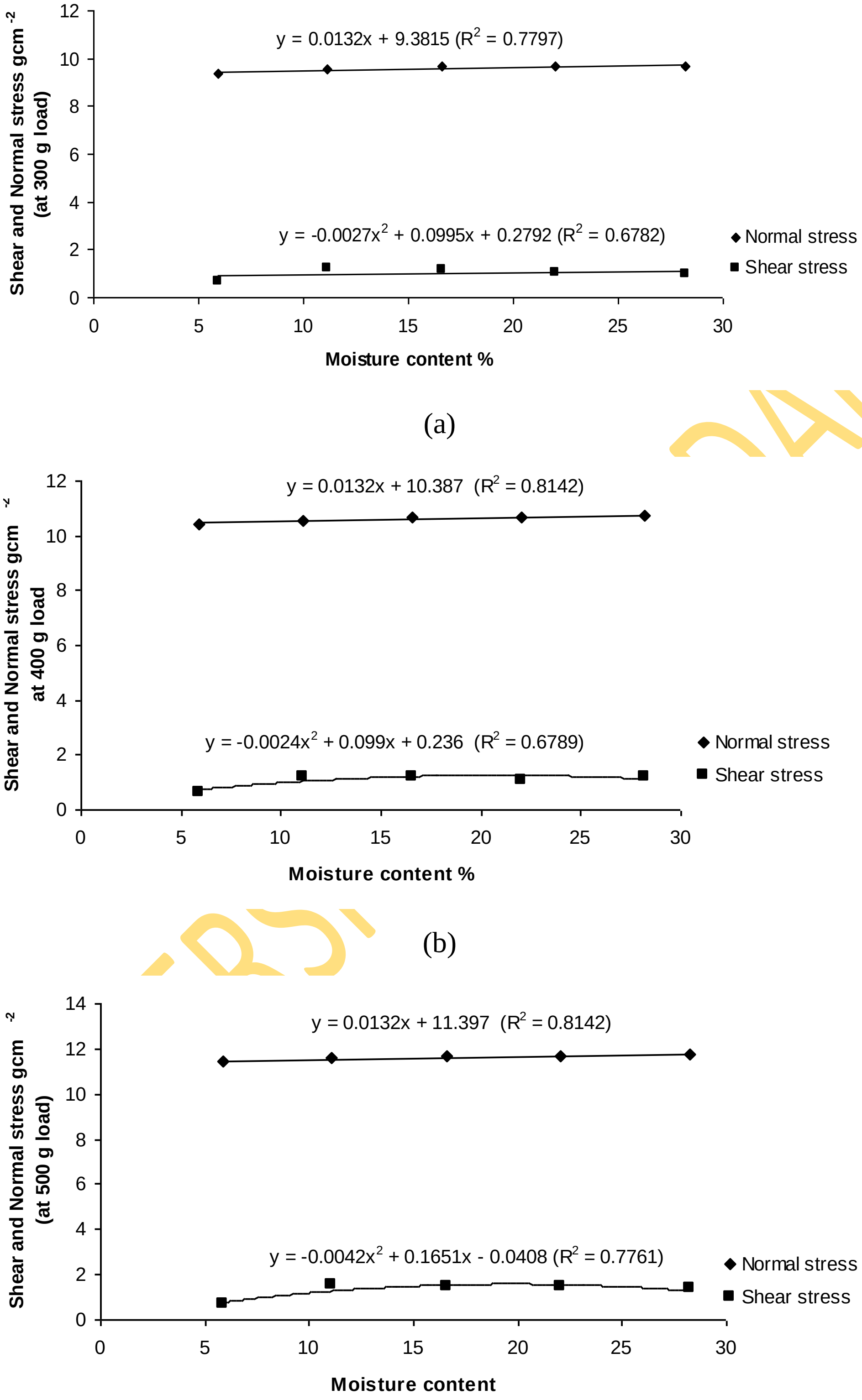

Fig. 4.17 Graphs of normal, shear stresses under (a) 300; (b) 400 and (c) 500 g load against moisture content

4.6.2 Rupture force, deformation and rupture energy

From the results (Table 4.10), it is shown that rupture force decreased from 214.4 to 129.9 N in the moisture range 5.9 - 28.2 %. Though the effect of moisture on rupture force was not statistically significant, it showed a linear trend (figure 4.18). Higher forces were observed at low moisture content level while lower forces were observed at higher moisture content levels. Moisture content effect on deformation is significant ($p<0.05$). Deformation initially decreased slightly (0.98 - 0.97 mm) with moisture content increase from 5.9 - 11.1 %, increased at 16.63% moisture level and decreased again at 28.2 % moisture content thus, it follows a polynomial trend (figure 4.18). But comparing 5.9 % and 28.2 % moisture content levels, there was an appreciable increase in deformation. Highest deformation was recorded at 22 % moisture content. Rupture energy decreased with increase in moisture content from 109.17 - 73.46 Nmm. Effect of moisture content of locust bean on its required rupture energy followed a polynomial trend as seen in figure 4.19.

1. *Rupture force*: For *Parkia biglobosa* seeds, the lower rupture forces were obtained at higher moisture contents. This might have resulted from the fact that *Parkia biglobosa* seeds have soft texture at high moisture content levels. Similar results were reported by Tavakoli et al. (2009) for Soybean grains, Atluntas and Yidiz, (2007) for faba beans, Olaniyan and Oje (2002) for shea nut, Ekinci et al. (2010) for carob pod, Ahmadi et al. (2009) for apricot fruits. The relationship between moisture content and rupture force is given as: $y = -22.348M + 240.69 \quad R^2 = 0.9796$ _________ (4.35)

where y = rupture force (N) and M = moisture content.

2. *Deformation*: Deformation in *Parkia biglobosa* was found to increase gradually from 0.98 to 1.61 mm as seed moisture content increased from 5.9 to 22 % and dropped at 28.2 % to 1.13 mm. The increase in deformation with decrease in rupture force as moisture content increased might be due to the soft texture of the seeds at high moisture content. Though there was a decrease in deformation at 28.2 % moisture level, the magnitude was higher than deformation magnitude at the lowest moisture level (5.9 %). The relationship between moisture content and deformation is expressed as a polynomial curve (third degree) having the following equation:

$\varepsilon_d = -0.0942M^3 + 0.7918M^2 - 1.794M + 2.09 \qquad R^2 = 0.9527$ _______ (4.36) where ε_d = deformation; M = moisture content.

3. *Rupture energy*: Rupture energy for *Parkia biglobosa* decreased from 109.17 Nmm to 73.46 Nmm as moisture content increased from 5.9 to 28.2 % in a linear trend (figure 4.19). This is a result of the soft texture developed by the seed as moisture content increased. Energy required to rupture locust bean is needed for the design of dehullers, pod shellers and for pulp removal, especially in the determination of the power requirement of the equipment. The equation expressing the relationship between moisture content and rupture energy is given as:

$R_E = -0.1514M^2 + 3.7811M + 89.739 \qquad R^2 = 0.9281$ _____ (4.37)

where M = moisture content and R_E = rupture energy (Nmm).

Table 4.10 Significance of moisture content on rupture force, deformation and rupture energy

Moisture Content (%)	Rupture Force (N)	Deformation (mm)	Rupture Energy (Nmm)
5.9	214.42a	0.98b	109.17a
	(82.29)	(0.14)	(59.42)
11.1	1999.32a	0.97b	109.09a
	(109.32)	(0.30)	(78.91)
16.6	179.69a	1.21ab	108.67a
	(50.19)	(0,21)	(38.80)
22	144.96a	1.61a	105.77a
	(40.79)	(058)	(41.33)
28.2	129.86a	1.13ab	73.46a
	(51.87)	(0.43)	(38.86)

Values in parenthesis are standard deviation. Values in the same column followed by different letters (a-b) are significant ($p<0.05$).

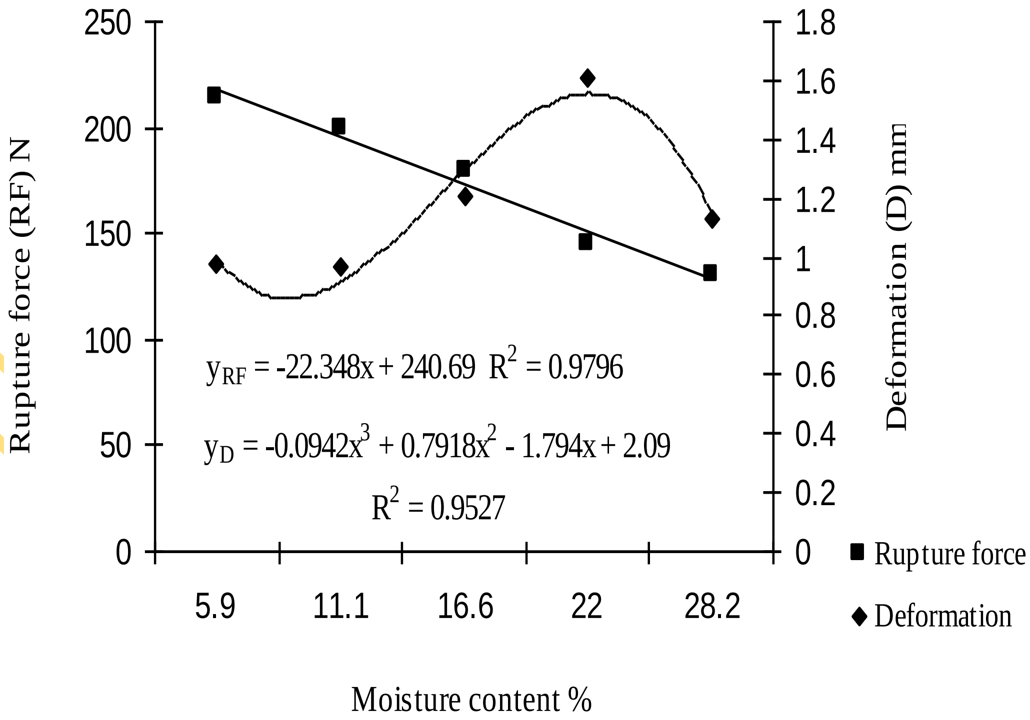

Fig. 4.18 Effect of moisture content on rupture force and deformation

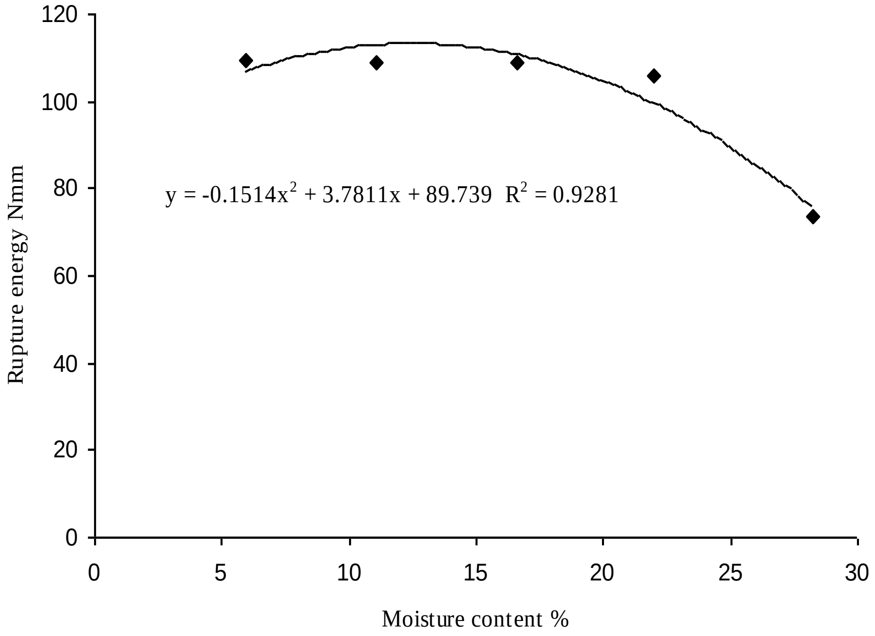

Fig. 4.19 Relationship between rupture energy and moisture content of locust bean

4.7 Thermal properties

4.7.1 Specific heat capacity: Specific heat capacity is the property needed in estimating the amount of energy required to raise the temperature of a material. This property of locust bean is important in developing equipment for its processing that involves drying, heating and parboiling especially during pulp removal, dehulling and parboiling. The specific heat capacity of *Parkia biglobosa* seeds increased from 2.74 to 4.38 kJ/kg ^{o}C with increase in seed moisture content from 5.9 to 28.2 % d.b. Table 4.11 shows the significant effect of moisture content on the specific heat capacity of locust bean. The significance was more pronounced at the lower moisture levels than the higher levels. The rate of increase was more rapid at lower moisture levels (5.9 – 16.6 %) with the peak at 22 % before gradually dropping between 22 and 28.2 %. Increased specific heat with increasing moisture content might be due to the high specific heat value of water compared to the dry material; the water having occupied its air-filled pores at lower moisture contents.

The relationship between moisture content and specific heat capacity of *Parkia biglobosa* seeds is a second order polynomial as shown in figure 4.20. Similar trend was reported by Singh and Goswani (2000) for Cumin seed, Tang et al. (1991) for lentil seeds, Chakrabarfy and Johnson (1972) for Tobacco, Wang and Brennan (1993) for Potato and Razavi et al. (2007) for Pistachio nuts. Other researchers who reported a non-linear behaviour are Kazarian and Hall (1965) for some grains, Murata et al. (1987) for cereal grains and Dutta et al. (1988) for grain. Taiwo *et al*. (1996) and Aviara *et al*. (2008) noted that specific heat capacity of ground cowpea and soybean seed, respectively, increased with increase in moisture content and temperature up to a certain level, and decreased with further increase in temperature and moisture content. Fasina and Sokhansanj (1995) noted the existence of a polynomial relationship of the second order between the specific heat of alfalfa pellets and moisture content. Similar results were obtained for millet grains and flours by Subramanian and Viswanathan (2003). The specific heat of locust bean at any moisture content level can be estimated from the following equation:

$$C_s = -0.2493M^2 + 1.9387M + 0.962 \qquad R^2 = 0.9728 \quad \_\_\_\_\_ \ (4.38)$$

where Cs = specific heat capacity of locust bean in kJ/kg ^{0}C

M = moisture content.

4.7.2 Thermal Conductivity: With increase in moisture in the range of 5.9 – 28.2 % d.b., thermal conductivity of *Parkia* seeds increased from 0.052 to 0.118 W/m^{0}C in a second order polynomial regression equation as revealed in figure 4.20. Similar result was reported for cumin seed by Singh and Goswami (2000). The result of thermal conductivity of locust bean seeds is in agreement with the findings of Chandra and Muir (1971) for wheat. Table 4.11 also show a statistically significant effect of moisture on the thermal conductivity of locust bean seeds.

Thermal conductivity is the possibility of transmission of heat within seeds in a bulk. The increase in thermal conductivity of locust bean seeds with increasing moisture content might be due to high thermal conductivity of water compared to dry locust bean seeds which is associated with air-filled pores. For locust bean seeds, bulk density increased with increasing moisture content while porosity decreased thereby reducing the air-filled pores in the bulk, thus resulting in increasing thermal conductivity of the seeds. Thermal conductivity of locust bean ranged from 0.052 to 0.118 W m^{-1} ^{o}C with increase in moisture content. The significant effect is more pronounced between 5.9 and 16.6 % moisture content statistically than at higher moisture levels though an increase in thermal conductivity was observed at higher moisture levels.

The relationship between thermal conductivity and moisture content of locust bean is expressed by the following regression equation:

$k = -0.0041M^2 + 0.0417M + 0.0134 \quad (R^2 = 0.9935)$ ______ (4.39)

where k = thermal conductivity and Wm^{-1} ^{0}C

M = moisture content.

4.7.3 Thermal Diffusivity Thermal diffusivity of *Parkia biglobosa* seeds increased from 2.93 x 10^{-8} to 3.79 x 10^{-8} m^2/s with an increase in moisture content in the range 5.9 – 28.2 % d.b., though the seed moisture effect on this property was not statistically significant (Table 4.11). The relationship between moisture and thermal diffusivity of *parkia* seeds is linear as shown in figure 4.21, showing that the rate of heat transfer increases with increase in moisture content. This is due to decrease in porosity of *parkia* with increasing moisture content which is also affected by increase in its bulk density. Since porosity decreases with increase in moisture content, the seeds are packed together reducing the air-filled pores within the bulk thereby making it possible for the seeds to easily transmit heat and retain it. It therefore means that *parkia biglobosa* seed has high ability to gain and retain heat as moisture content increases which is necessary in the design of steamers and dehullers for processing of locust bean. A linear relationship between moisture content and thermal diffusivity was reported for Sheanut kernels by Aviara and Haque (2001). Bamgboye and Adejumo (2010) also reported similar result for Roselle seeds.

The relationship between moisture content and thermal diffusivity for locust bean is given as:

$\alpha = 0.0352M + 2.7041 \qquad R^2 = 0.9349$ ___________ (4.40)

where α = thermal diffusivity (m^2/s) and

M = moisture content (%).

Table 4.11 Effect of moisture content on thermal properties of locust bean

Moisture content (%)	Specific heat capacity kJ kg^{-1} ^{0}C	Thermal conductivity W m^{-1} ^{0}C	Thermal diffusivity x 10^{-8} m^{2}s^{-1}
5.9	2.74a	0.052a	2.93a
	(0.043)	(0.006)	(0.285)
11.1	3.62b	0.077ab	3.14a
	(0.475)	(0.028)	(1.063)
16.6	4.67c	0.104b	3.25a
	(0.686)	(0.017)	(0.963)
22	4.77c	0.113b	3.36a
	(0.364)	(0.028)	(0.709)
28.2	4.38bc	0.118b	3.79a
	(0.385)	(0.018)	(0.286)

Values in parenthesis are standard deviation. Values in the same column followed by different letters (a-c) are significant ($p<0.05$).

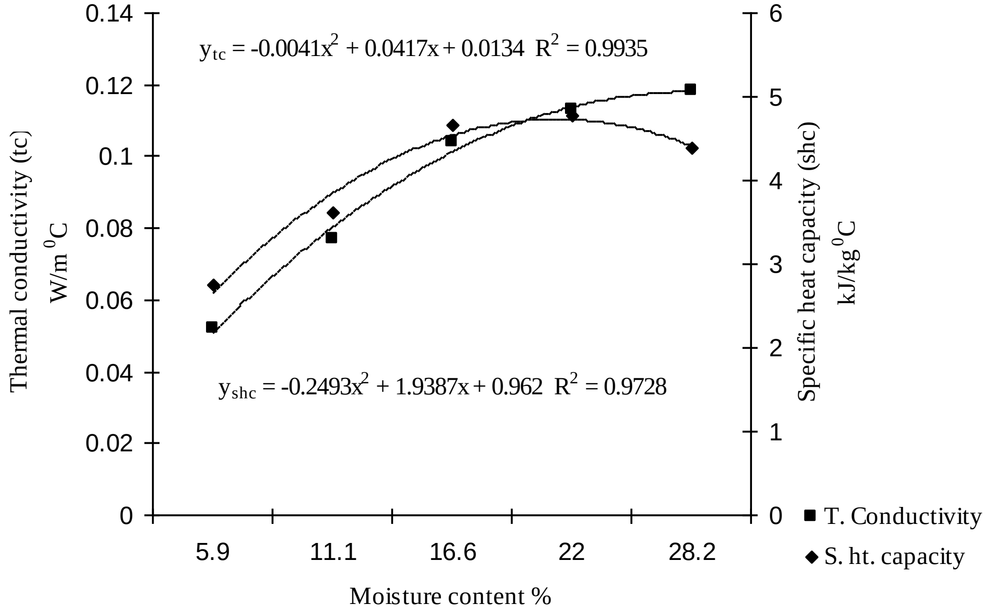

Fig. 4.20 Relationship between moisture content and thermal conductivity and specific heat capacity.

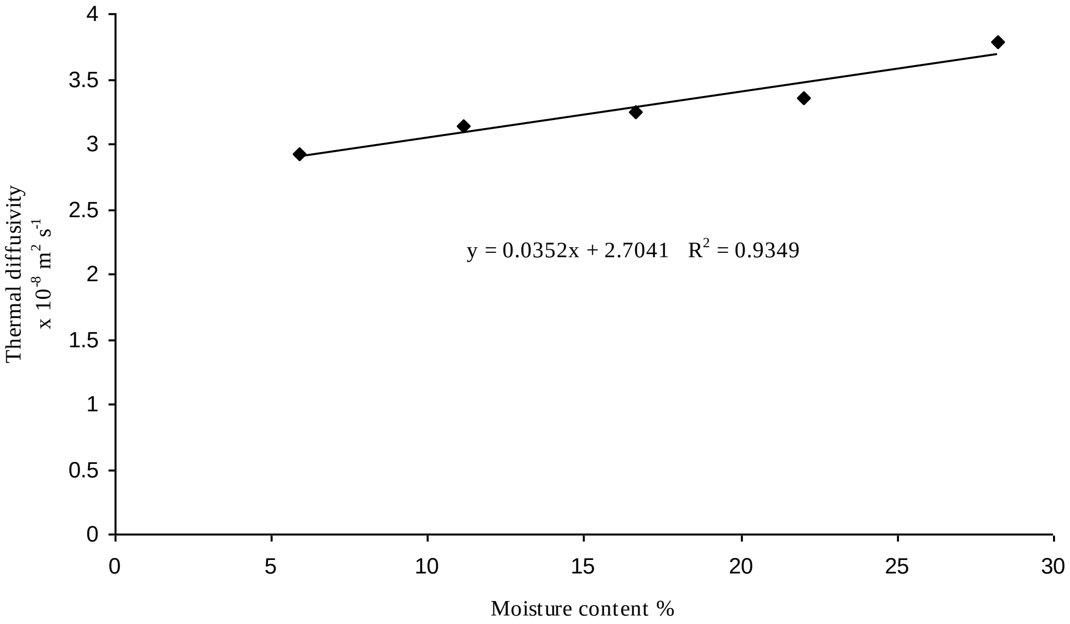

Fig. 4.21 Relationship between moisture content and thermal diffusivity

CHAPTER FIVE

CONCLUSIONS AND RECOMMENDATIONS

This study was carried out to determine some engineering properties of locust bean (*Parkia biglobosa*) such as seed shape and size, gravimetric, frictional, flow, mechanical and thermal at 5.9, 11.1, 16.6, 22 and 28.2 % (dry basis) moisture levels. The relationship between the properties and the variation in seed moisture content was examined. The following are the conclusions and recommendations made in the study:

A. Conclusions:

1. The effect of seed moisture content on most of the engineering properties of locust bean (*Parkia biglobosa*) was significant ($P<0.05$), such as seed length, width, arithmetic and geometric mean diameters, surface area, sphericity, bulk and true densities, porosity, static coefficient of friction (on plywood, glass, mild steel and rubber surfaces), coefficient and angle of internal friction, dynamic and static angles of repose, coefficient of mobility, hopper wall angle, shear stress (under 200, 300, 400 and 500 g loads), thermal conductivity and specific heat capacity.

   Seed moisture content effect was not significant on other properties.

2. Some of the properties increased (in either polynomial or linear trend) between 5.9 and 28.2 % seed moisture content (d.b) such as seed length (10.24 – 11.29 mm), geometric mean diameter (7.78 – 8.12 mm), surface area (191.15 – 208.29 mm^2), bulk density (644.98 – 708.06 kgm^{-3}), static angle of repose (48.4 – 56^0). Increase in static coefficient of friction on plywood (0.48 – 0.60^0) and rubber (0.41 – 0.60^0) surfaces, hopper wall angle (53.5 – 59.11^0) were recorded. Coefficient (0.30 – 0.53) and angle (17.0^0 – 28.2^0) of internal friction, deformation (0.98 – 1.13 mm), specific heat capacity (2.74 – 4.38 kJ kg^{-1} ^0C) also increased. Others decreased, such as seed thickness (5.49 – 5.26 mm), porosity (48.4 – 41.91 %), static coefficient of friction on aluminium (0.54 – 0.52^0) surface, rupture force (214.42 – 129.86 N). The corresponding high R^2 (coefficient of determination) values in the regression equations

indicate that the graphs perfectly describe the relationship between seed moisture content and the engineering properties that were examined.

3. A baseline data for the development of necessary equipment for the production process of locust bean have been generated.

B. Recommendations

1. The same study can be conducted on two or three varieties of *parkia* to examine the effect of seed moisture and variety on the engineering properties of locust bean.
2. A wider range of moisture content variation of the seeds can be used in the study to capture a broader view of the behaviour of *parkia biglobosa* seeds.

REFERENCES

Abdullah, M.H.R.O., Ch'ng, P.E., Lim, T.H. 2011. Some physical properties of *parkia speciosa* seeds. International Conference on Food Crops and Biotechnology IPCBEE vol 9 IACSIT Press, Singapore.

Aghbashlo, M., Kianmehr, M.H. and Hassan-Beygi, S.R. 2008. Specific heat and thermal conductivity of berberis fruit (*Berberis vulgaris*). *American Journal of Agricultural and Biological Sciences* 3.1: 330-336

Ahmadi, H., Fathollahzadeh, H and Mobli, H. 2009. Post harvest physical and mechanical properties of Apricot fruits, pits and kernels (C.V. *Sonnati salmas*) cultivated in Iran. *Pakistan Journal of Nutrition*. 8: 264-268. Retrieved on June 18, 2010, from http://scialert.net/abstract/?doi=pjn.2009.264.268

Ahmadi, H., Mollazade, K., Khorshidi, J., Mohtasebi, S.S. and Rajabipour, A. 2009. Some physical and mechanical properties of Fennel seed (*Foeniculum vulgare*). *Journal of Agricultural Science*. 1. 1: 66-75. Retrieved on June 18, 2010, from www.ccsenet.org/journal.html

Akaiimo, D.I. and Raji, A.O. 2006. Some physical and engineering properties of *Prosopis Africana* seed. *Biosystems Engineering* 95. 2: 197-205. Retrieved on May 20, 2008 from www.sciencedirect.com

Akbarpour, V., Milani, J. and Hemmati, k. 2009. Mechanical properties of Pomegranate seeds affected by moisture content. *American-Eurasian Journal of Agriculture and Environmental Science*. 6. 4: 447-453

Alabi, D.A. 1993. *Parkia biglobosa*, an endangered specie. *Nigerian Forestry Proceeding on Conservation of Threatened Species in Nigeria*. 265-285

Alabi, D.A.; Akinsulire, O.R. and Sanyaolu, M.A. 2005. Qualitative determination of chemical and nutritional composition of *Parkia biglobosa* (Jacq.) Benth. *African Journal of biotechnology*. 4. 8: 812-815. Retrieved Mar. 17, 2004, from wwwuniv.academicjournals.org/AJB

Altuntas, E. and Demirtola, H. 2007. Effect of moisture content on physical properties of some grain legume seeds. *New Zealand Journal of Crop and Horticultural Science*. 35. 4: 423-433

Altuntas, E., Ozgoz, E. and Taser, F. 2005. Some physical properties of Fenugreek (*Trigonella foenum-graceum L.*) seeds. *Journal of Food Engineering* 71: 37-43. Retrieved on May 14, 2009 from www.sciencedirect.com

Altuntas, E. and Yildiz, M. 2007. Effect of moisture content on some physical and mechanical properties of Faba bean (*Viciafaba L.*) grains. *Journal of Food engineering*. 78: 174-183

Amin, M.N., Hossain, M.A. and Roy, K.C. 2004. Effect of moisture content on some physical properties of lentil grains. *Journal of Food Engineering* 65: 83-87

Andrejko, D. and Kaminska, A. 2005. Selected properties of yellow lupine seeds formed by hydration. *Electronic Journal of Polish Agricultural Universities*. 8. 4: 82-88. Retrieved on June 10, 2010 from www.ejpau.media.pl/volume8/issue4/art-82.html

Anonymous. 2001. A Natural ingredient for a good health and palatability. www.ceromic.co.uk/main.htm. August 20.

ASAE. 1999. Moisture measurement – unground grain and seeds. American Society of Agricultural Engineers. St. Joseph. Michigan (1997) revised version, S352.2

ASAE. 2001. Resistance to airflow of grains, seeds, other agricultural products and perforated metal sheets. www.asabe.org April 21, 2003.

Asoegwu, S., Ohanyere, S., Kanu, O. and Iwueke, C. 2006. Physical properties of African oil bean seed (*Pentaclethra macrophylla)Agricultural Engineering International: the CIGR Ejournal*. 8: 2-16

Audu, I., Oloso, A. and Umar, B. 2004. Development of concentric cylinder locust bean dehuller. *Agricultural Engineering Int.: the CIGR Journal of Scientific Research and Development*. 6. 1-11

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

Aviara, N.A., Haque, M.A. and Ogunjimi, L.A.O. 2008. Thermal properties of guna seed. *International Agrophysics*, 22: 291-297

Aydin, C. 2007. Some engineering properties of peanut and kernel. *Journal of Food Engineering*. 79.3: 810-816

Bamgboye, A.I., Adejumo, O.I. 2010. Thermal properties of Roselle seed. *International Agrophysics*. 24:85-87

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

Baumler E, Cuniberti A, Nolasco S.M, Riccobene I.C. 2006. Moisture dependent physical and compression properties of safflower seed. *Journal of Food Engineering* 72: 134–140.

Beaumont, M. 2002. Flavouring composition prepared with bacillus spp. *Int. Journal of Food Microbiology.* 75: 189-196

Bitra, V.S.P., Banu, S., Ramakrishna, P., Narender, G. and Womac, A.R. 2010. Moisture dependent thermal properties of peanut pods, kernels and shells. *Biosystems Engineering.*106: 503-512

Booth, F.E.M. and Wickens, G.E. 1988: Non-timber uses of selected arid zone trees and shrubs in Africa. *FAO Conservative Guide*. 19. FAO, Rome, pg. 176.

Braga, G.C., Couto, S.M., Hara, T. and Neto, J.T.P.A. 1999. Mechanical behaviour of macadamia nut under compression loading. *Journal of Agricultural Engineering Research,* 72: 239–245.

Busson, F.1965 Food plants of West Africa: A botanical, biological and chemical study *Méd. Tropica.* 9: 696–717.

Campbell – Platt, G. 1980. African locust bean (*Parkia species)* and its West African fermented food product, *Dawadawa. Ecology of Food and Nutrition*, 9:123-132.

Chakrabarty, S. M., and Johnson, W. H. 1972. Specific heat of flue cured tobacco by differential scanning calorimetry. *Transactions of the ASAE*, 15. 5: 928-931

Chandra, S., and Muir, W. E. 1971. Thermal conductivity of spring wheat at low temperatures. *Transactions of the ASAE,* 14. 4: 644-646

Coskuner, Y. and Karababa, E. 2007. Physical properties of coriander seeds (*Coriandrum sativum* L.) *Journal of Food Engineering.* 80: 408-416

Dalziel, J.M. 1937. *The useful plants of west tropical Africa*. Crown Agents, London. 217-220.

Davies, R.M. 2010. Engineering Properties of three varieties of melon seeds as potentials for Development of melon processing machines. *Advanced Journal of Food Science and Technology*. 2.1:63-66

Deshpande, S. S., Sathe, S. K., Salunke, D. K., and Cornforth, D. P. 1982. Effects of dehulling on phytic acid, polyphenols, and enzyme inhibitors of dry beans (*Phaseolus vulgaris* L.) *Journal of Food Science*. 47:1846.

Diawara, B., Sawadogo, L., Amoa-Awua, W.F. and Jakobsen, M. 2000. Capability building for research and development in quality assurance and fermentation technology for African fermented foods. HACCP system for traditional African fermented foods: soumbala. WAITRO.

Drusas, A., Tassopoulos, M., & Saravacos, G. D. 1986. Thermal conductivity of starch gels. In M. Le Maguer, & P. Jelen, *Food Engineering and Process applications volume 1: transport phenomena.* Essex: Elsevier Applied Science (Chapter 13).

Dutta, S.K., Nema, S. and Bharduraj, R.K. 1988. Physical properties of grain. *Journal of Agricultural Engineering Research*. 23: 40-45.

Ekinci, K., Yılmaz, D., Ertekin, C. 2010. Effects of moisture content and compression positions on mechanical properties of Carob pod (*Ceratonia siliqua*). *African Journal of Agricultural Research* 5.10:1015-1021. Retrieved on August 12, 2010 from http://www.academicjournals.org/AJAR

FAO, Rome. 1988. Traditional food plants. *Food and Nutrition Paper*, 47: 590-593.

FAO, 2001. *Parkia Biglobosa* Plant. www.ecoport.org/ep?Plant=8323

Fasina, O.O. and Sokhansanj, S. 1995. Bulk thermal properties of alfalfa pellets. *Canadian.Agricultural Engineering*, 37: 91-95.

Figueiredo, A.K., Baumler, E., Riccobene, I.C. and Nolasco, S.M. 2010. Moisture dependent engineering properties of sunflower seeds with different structural characteristics. *Journal of Food Engineering.* 8.3: 31-38

Firouzi, S., Naghi, M., Vishgaei, S. and Kaviani, B. 2009. Some physical properties of groundnut (Arachis hypogaea L.) kernel cv. NC2 as a function of moisture content. *American-Eurasian Journal of Agricultural and Environmental Science.* 6.6: 675-679

Forbus, W. R., & Smith, R. E. (1971). Pecan conditioning methods for increased shelling efficiency. *Transactions of the ASAE*, 14.3: 596.

Fraczek, J., Hebda, T., Slipek, Z., Kurpaska, S. 2005. Effect of seed coat thickness on seed hardness. *Canadian Biosystems Engineering*. 47:4.1-4.5

Fraser, B.M., Verma, S.S. & Muir, W.E. 1978. Some physical properties of fababeans. *Journal of Agricultural Engineering Research*, 23, 53–57.

Gakou, M., Force, J.E., McLaughlin, W.J. 1994. Non-timber forest products in rural Mali: a study of villager use. *Agroforestry Systems* 28: 213-226

Garnayak, D. K., Pradhan, R.C., Naik, S.N., Bhatnagar, N. 2008. Moisture-dependent physical properties of jatropha seed (*Jatropha curcas L.*). *Industrial Crops and Products*, 27: 123-129

Ghadge, P.N., Vairagar, P.R. and Prasad, K. 2008. Physical properties of chick pea split (*Cicer arietinum L.*). *Agricultural Engineering International: the CIGR Ejournal* 10: 1-9

Ghasemi Varnamkhasti, M., Mobli, H., Jafari, A., Keyhani, A.R., Heidari Soltanabadi, M., Rafiee, S., Kheiralipour, K. 2008. Some physical properties of rough rice (*Oryza Sativa*) grain. *Journal of Cereal Science*. 47: 496－501.

Ghasemi Varnamkhasti, M., Mobli, H., Jafari, A., Keyhani, A. R., Rafiee S., Heidari Soltanabadi, M. and Kheiralipour K. 2007. Some engineering properties of paddy (*var. Sazandegi*). *International Journal of Agriculture and Biology*. 9.5: 763-766

Gorji, A., Rajabipour, A., Tavakoli, H. 2010. Fracture resistance of wheat grain as a function of moisture content, loading rate and grain orientation. *Australian Journal of Crop Science*. 4.6: 448-452

Guinko, S. and Pasgo, L.J. 1992. Harvesting and marketing of edible products from local woody species in Zitenga, Burkina Fasso. *Unasylva* 43: 16-19

Hagos, T.H. 1962: A revolution of genus *Parkia R. Br. (Mim.)* in Africa. *Acta Botanica Neer-Landica*, 11: 231-265

Hall J B, Tomlinson H F, Oni P I, Buchy M., Aebischer, D.P. 1997. *Parkia Biglobosa a Monograph.* Bangor, UK: School of Agriculture and Forest Sciences, University of Wales.

Heidarbeigi, K., Ahmadi, H., Kheiralipour, K and Tabatabaeefar, A. 2008. Some physical and mechanical properties of Iranian wild pistachio (*Pistachio mutica L.*). *American-Eurasian Journal of Agricultural & Environmental Science* 3.4: 521-525

Heidarbeigi, K., Amadi, H., Kheiralipour, K and Tabatabaeefar, A. 2009. Some physical and mechanical properties of Khinjuk. *Pakistan Journal of Nutrition.* 8.1: 74-77

Hopkins, H.C. 1983: Taxonomy, reproductive biology and economic potential of parkia (*Leguminosae: mimosoideae)* in Africa and Madagascar. *Botany Journal of the Linnean Society,* 87: 135-167

Igbozulike, A.O., Aremu, A.K. 2009. Moisture dependent physical properties of *Garcinia Kola* seeds. *Journal of Agricultural Technology*. 5.2: 239-248

Irtwange, S.V. 2000. Effect of accession and moisture content on some engineering properties of African Yam bean. Ph.D thesis, Department of Agricultural and Environmental Engineering, University of Ibadan, Nigeria. 65-102

Isik, E. 2007. Some engineering properties of Soybean grains. *American Journal of Food Technology* 2.3: 115-125

Isik, E. and Izil, N. 2007. Moisture dependent physical properties of Dent corn (*Zea mays var. Indentata* Sturt) seeds. *American Journal of Food Technology* 2: 342-353

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

Karababa, E. and Coskuner, Y. 2007. Moisture dependent physical properties of dry sweet corn kernels. *International Journal of Food Prpperties.* 10.3: 549-560.

Karimi, M., Kheiralipour, K., Tabatabaeefar, A., Khoubakht, G.M., Naderi, M. and Heidarbeigi, K. 2009. The effect of moisture content on physical properties of wheat. *Pakistan Journal of Nutrition.* 8.1: 90-95

Kazarian, E. A., & Hall, C. W. 1965. The thermal properties of grains. Transactions of the ASAE, 31, 33-37/40.

Kessler, J.J. (1994). Agroforestry in Burkina Faso: a careful balance. *Agro- Siev,* 6: 4-5.

Kheiralipour K, Karimi M, Tabatabaeefar A, Naderi M, Khoubakht G, Heidarbeigi K. 2008. Moisture-dependent physical properties of Wheat (*Triticum aestivum* L.). *Journal of Agricultural Technology*. 4.1: 53－64.

Khodabakhshian, R., Emadi, B. and Abbaspour Fard, M.H. 2010. Gravimetric properties of Sunflower seeds and kernels. *World Applied Sciences Journal*. 8.1: 119-128

Khodabakhshian, R., Emadi, B. and Abbaspour Fard, M.H. and Saiedirad, M.H. 2009. Moisture dependent geometrical properties of Sunflower seed, *arzagol* variety as a case study. *Chemical, Biological and Environmental Engineering.* 7.2: 375-378

Kiani Deh Kiani, M, Minaei, S., Maghsoudi, H. and Ghasemi Varnamkhasti, M. 2008. Moisture dependent physical properties of red bean. *International Agrophysics* 22: 231-237

Kibar, H., Ozturk, T. and Esen, B. 2010. The effect of moisture content on physical and mechanical properties of rice (*Oryza sativa* L.). *Spanish Journal of Agricultural Research* 8.3; 741-749

Klanjcar, J., Kopac, M., Kosem, D. and Kozlovic, K. (2002): *Dawadawa* www.bf.uni-lj.si/zt/biotech/seminar-absract/zivil/

Kon, S., Brown, A. H., Ohanneson, J. G., and Booth, A. N. 1973. Split peeled beans: Preparation and some properties. *Journal of Food Science.* 38: 496.

KoochekiA., Razavi S.M.A., Milani E.,MoghadanT.M., Abedini, M., Alamatiyan S., and Izadikhah S., 2007. Physical properties of watermelon seed as a function of moisture content and variety. *International. Agrophysics*, 21, 349-359.

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

Mabille, F., Gril, J. and Abecassis, J. 2001. Mechanical properties of Wheat seed coats. *Cereal Chemist.* 78.3: 231-235

Milani, E., Seyed, M., Razavi, A., Koocheki, A., Nikzadeh, V., Vahedi, N., MoeinFard, M., GholamhosseinPour, A. 2007. Moisture dependent physical properties of cucurbit seeds. .*International Agrophysics.* 21: 157-168

Mohammad, R.S. and Reza, A. 2010. Moisture-dependent physical properties of sunflower seed (SHF8190). *Modern Applied Science*. 4.7: 135-143

Mohsenin, N. N. 1980. *Thermal properties of food and agricultural materials.* Gordon and Breach Science Publishers. New York, U.S.A.

Mohsenin, N.N. 1986: *Physical properties of plant and animal materials.* 2nd Edition (revised). Gordon and Breach Science Publishers, New York, U.S.A.

Mollazade K, Ahmadi H, Khorshidi J, Rajabipour A, Mohtasebi S S. 2009. Moisture-dependent physical and mechanical properties of cumin (*Cuminum cyminum* L.) seed. *International Journal of Agriculture*. & *Biological Engineering*, 2.2: 49－56.

Murata, S., Tagawa, A., and Ishibashi, S. 1987. The effect of moisture content and temperature on specific heat of cereal grains measured by DSC. *Journal of the Japanese Society of Agricultural Machinery*, 46. 6: 547-554.

Nalbandi, H., Ghassemzadeh, H.R. and Seiiedlou, S. 2010. Seed moisture-dependent physical properties of *Turgenia latifolia*: criteria for sorting. *Journal of Agricultural Technology*. 6.1: 1-10. Retrieved on January 12, 2011 from http://www.ijat-rmutto.com

Odunfa, S.A., 1985 *Dawadawa* Introduction to Legume – based Fermented Foods. CRC Press Inc. Boca Raton, Florida. 173-189

Odunfa, S.A. and Adesomoju, A.A. 1985. Effects of fermentation on the free fatty acids of African locust bean during *Iru* production. *Journal of Plant Food*. 6: 111-115

Ogunjimi, L.A.O., Aviara, N.A., Aregbesola, O.A. 2002. Some engineering properties of locust bean seed. *Journal of Food Engineering*. 55(2): 95 – 99.

Oje, K. 1993. Some physical properties of locust bean seeds relevant to dehulling and seed processing. *Journal of Food Science and Technology*. 30(4): 253 – 255.

Okpala, J.O., 1990. Analysis of some macro nutrients and food substances in the matured fruit parts of *Parkia biglobosa*. *Nigeria Journal of Botany*. 3: 209-14.

Olaniyan, A.M., Oje, K. 2002. Some aspect of the mechanical properties of shea nut. *Biosystems Engineering*, 81, 413–420.

Olayanju, T.M. 2002. Design, fabrication and evaluation of a Beni-seed oil expeller. Ph.D thesis, Department of Agricultural and Environmental Engineering, University of Ibadan, Nigeria. 91-97

Omobuwajo, T.O., Akanda, E.A. Sanni, L.A. 1999. Selected physical, mechanical and aerodynamic properties of African breadfruit (*Treculla Africana*) seeds. *Journal of Food Engineering*. 40: 241–244

Oni, K.C. 1990. Shelling machine related properties for African locust bean fruit. *Transactions of the American Society of Agricultural and Biological Engineers*.

33(2): 572 - 576

Oni, P.I. 1997. *Parkia biglobosa* (Jacq) Benth in Nigeria: A revenue assessment Ph.D.Thesis, University of North Wales, Banger, United Kingdom.

Oni PI, Hall J,B. and Ladipo, D.O. 1998. The ecology of a key African multipurpose tree species; *Parkia biglobosa* (Jacq) Benth: the current state of knowledge.) *Nigerian Journal of Ecology* 1: 59-77.

Ozarslan, C. 2002. PH – Postharvest technology:physical properties of Cotton seed. *Biosystems Engineering* 83.2: 169-174

Ozturk, I., Kara, M., Elkoca, E. and Ercilsi, S. 2009. Physico-chemical grain properties of new common bean cv. *Elkoca-05. Scientific Research and Essay*. 4.2: 088-093

Ozturk, I., Kara, M., Yildiz, C. and Ercilsi, S. 2009. Physico-chemical seed properties of the common Turkish bean (*Phaseolus vulgaris*) cultivars '*Hinis*' and '*Ispir*'. *New Zealand Journal of Crop and Horticultural Science*. 37.1: 41-50

Öztürk T., Esen B. 2008. Physical and mechanical properties of barley. *Agricultura Tropica et subtropica* 41.3:117-121

Pradhan, R.C., Naik, S.N., Bhatnagar, N., Swain, S.K. 2008. Moisture-dependent physical properties of Karanja (*Pongamia pinnata*) kernel. *Industrial Crops and Products,* 28.2: 155-161.

Raji, A. O. and Favier, J. F. 2004. Model for the deformation in agricultural and food particulate materials under bulk compressive loading using discrete element method—II: compression of oilseeds. *Journal of Food Engineering*, 64:373–380

Razavi, M.A. and Fathi, M. 2009. Moisture-dependent physical properties of grape (*Vitis vinifera* L.) seed. *The Philippine Agricultural Scientist*, 92.2: 201-212

Razavi, S. M. A., & Taghizadeh, M. 2007. The specific heat of pistachio nuts as affected by moisture content, temperature, and variety. *Journal of Food Engineering,* 79: 158-167.

Razavi, S.M.A., Rafe, A. and Akbari, R. 2007. Terminal velocity of pistachio nut and its kernel as affected by moisture content and variety. *African Journal of Agricultural Research.* 2.12: 663-666. Retrieved on Mar. 17, 2010 from www.academijournal.org/AJAR

Razavi, S.M.A. and Milani, E. 2007. Some physical properties of the water melon seed. *African Journal of Agricultural Research.* 1.3: 65-69

Razavi, S.M.A., Yeganehzad, S. and Sadeghi, A. 2009. Moisture dependent physical properties of canola seeds. *Journal of Agricultural Science and Technology*, 11:309-322

Reichert, R.D., Oomah, B.D. and Youngs, C.G. 1979. Factors affecting the abraisive-type dehulling of grain legumes investigated with a new intermediate-sized batch dehuller. *Journal of Food Science*, 49: 267-272

Rong, G., Negi, S.C. and Jofriet, J.C. 1995. Simulation of the flow behavior of bulk solids in bins—Part 2: shear bands, flow, corrective inserts and velocity profile. *Journal of Agricultural Engineering Research*, 62, 257–269

Sabiite, E.N. and Cobbina, A.J. 1992. *Parkia biglobosa:* A potential multipurpose fodder tree legume in West Africa. *International Tree Crops Journal*, 7: 113-139.

Sacilik, K., R. Ozturk, and R. Keskin. 2003. Some physical properties of hemp seed. *Biosystems Engineering* 86.2: 191–198.

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

Seifi, M.R., Alimardani, R. 2010. Moisture-dependent physical properties of sunflower seed (SHF8190). *Mordern Applied Science*. 4(7): 135-143

Seyed, M.A.R. and Elnaz Milani. 2006. Some physical properties of the water melon seeds. *African Journal of Agricultural Research*. 1(3): 65 – 69

Seyed, M.A.R. and Fathi, M. 2009. Moisture – dependent physical properties of grape (*Vitis vinifera*). *Agricultural Scientist*. 92(2): 201 - 212

Shafiee, S., Motlagh, A., Minaee, S., Haidarbigi K. 2009. Moisture dependent physical properties of dragon’s head seeds (*Lallemantia iberica*). *Agricultural Engineering International: the CIGR Ejournal.* 11: 1-10

Sharland, R. 1989. Using indigenous knowledge in relation to subsistence sector etension: interaction between the agricultural and wild environments in Moru Agriculture in southern Sudan. Ph.D Thesis. Agricultural Extension and Rural Development Department, University of Reading, U.K.

Singh, K.K., Goswami, T.K. 2000. Thermal properties of Cumin seed. *Journal of Food Engineering*. 45:181-187

Sobukola, O.P. and Onwuka, V.I. 2010. Effect of moisture content on some physical properties of locust bean seed (*Parkia fillicoidea* L.). *Journal of Food Process Engineering*, 10: 14-20

Stepanoff, A.J. 1969. *Gravity flow of bulk solids and transportation of solids in suspension.* Wiley Publishers. New York, U.S.A.

Subramanian, S., and Viswanathan, R. 2003. Thermal properties of minor millet grains and flours. *Biosystems Engineering*, 84.3: 289-296.

Tabatabaeefar, A., 2003. Moisture-dependent physical properties of wheat. *Int. Agrophysics*, 17: 207–11

Taiwo, K. A., Akanbi, C. T., & Ajibola, O. O. 1996. Thermal properties of ground and hydrated cowpea. *Journal of Food Engineering*, 29: 249-256.

Tang, J., Sokhansanj, S., Yannacopoulos, Y., and Kasap, S. O. 1991. Specific heat capacity of lentil seeds by differential scanning calorimetry, DSC. *Transactions of the ASAE*, 34. 2: 517-522.

Tavakoli, H., Mohtasebi S.S., Rajabipour A., Tavakoli, M. 2009. Effect of moisture content, loading rate and grain orientation on fracture resistance of barley grain. *Research Journal of Agricultural Engineering* 55.3: 85-93

Tavakoli H., Rajabipour A. and Mohtasebi S.S. 2009. Moisture-dependent Engineering properties of soybean grains. *Agricultural Engineering International: the CIGR Ejournal*. 11: 1-10

Tavakoli, M., Tavakoli, H., Rajabipour, A., Ahmadi, H. and Gharib-Zahedi, S.M.T. 2009. Moisture-dependent physical properties of barley grains. *International Journal of Agriculture and Biological Engineering.* 2.4: 84-91. Retrieved on Mar. 17, 2010 from http:/www.ijabe.org

Tekin, Y., E. Işik, H. Ünal, and R. Okursoy. 2006. Physical and mechanical properties of Turkish Göynük Bombay Beans (*Phaseolus vulgaris L.*). *Pakistan Journal of Biological Sciences*, 9.12: 2229–2235.

Tunde-Akintude, T.Y. and Akintude, B.O. 2004. Some physical properties of sesame seed. *Biosystems Engineering*, 88: 127-129.

Tunde-Akintunde, T.Y. and Akintunde, B.O. 2007. Effect of moisture content and variety on selected properties of Beniseed. *Agricultural Engineering International: the CIGR Ejournal*. 9: 1-14

Tunde-Akintunde, T.Y., Olajide, J.O. and Akintunde, B.O. 2005. Mass-volume-area related and mechanical propertiesof soybean. *International Journal of Food Properties.* 8.3: 449-456

Varnamkhasti, M.G., Mobli, H., Jafari, A., Rafiee, S., Heidarysoltanabadi, M. and Kheiralipour, K. 2007. Some engineering properties of paddy (var. Sazandegi). *International Journal of Agriculture and Biology*, 9.5: 763-766

Wang, B., Dong, L., Wang, L., Huang, Z., Zhang, L., Chen, X. and Mao, Z. 2007. Effect of moisture content on the physical properties of fibered flaxseed. *International Journal of Food Engineering*. 3.5: 45-49

Wang, N. and Brennan, J. G. (1993). The influence of moisture content and temperature on the specific heat of potato measured by differential scanning calorimetry, DSC. *Journal of Food Engineering*, 19. 3: 303-310.

Yang, W., Sokhansanj, S., Tang, J. and Winter, P. 2002. Determination of thermal conductivity, specific heat and thermal diffusivity of Borage seeds. *Biosysytems Engineering* 82.2: 169-176

Zareiforoush, H., Komarizadeh, M.H. and Alizadeh, M.R. 2009. Effect of moisture content on some physical properties of paddy grains. *Research Journal of Applied Sciences, Engineering and Technology*. 1.3: 132-139

Zewdu, A. and Solomon, W. 2008. Moisture-dependent physical properties of Grass pea (*Lathyrus sativus* L.) seeds. *Agricultural Engineering International: the CIGR Ejournal*. 10: 1-14

APPENDIX

Appendix 1: Raw data on the size and shape parameters of locust bean as affected by seed moisture content.

MC %	REP	L mm	W mm	T mm	GMD mm	AMD mm	SPH	SA mm^2
5.9	1	11.18	8.14	5.9	8.12	8.4	0.68	207.13
,,	2	9.54	7.9	5.4	7.41	7.61	0.77	172.49
,,	3	10.34	8.62	4.96	7.61	7.97	0.73	181.93
,,	4	12.36	8.98	5.24	8.34	8.86	0.67	218.51
,,	5	10.12	8	5.76	7.75	7.96	0.76	188.69
,,	6	11.24	10.14	5.48	8.54	8.95	0.76	229.12
,,	7	11.06	9.02	6.28	8.55	8.78	0.77	229.65
,,	8	9.5	7.5	5.62	7.37	7.54	0.77	170.64
,,	9	9.18	8.44	5.58	7.56	7.73	0.82	179.55
,,	10	12.36	9.84	5.82	8.91	9.34	0.72	249.4
,,	11	9.62	8.44	4.92	7.36	7.66	0.76	170.17
,,	12	10.5	9.06	5.28	7.94	8.28	0.75	198.05
,,	13	9.36	7.8	6.14	7.65	7.76	0.81	183.85
,,	14	9.52	7.78	5.12	7.23	7.51	0.76	164.22
,,	15	11.58	8.16	4.86	7.71	8.2	0.66	186.74
,,	16	9.04	8.48	5.3	7.4	7.6	0.81	172.03
,,	17	9.12	7.16	6.18	7.38	7.48	0.81	171.1
,,	18	9.22	7.02	6.24	7.39	7.49	0.8	171.56
,,	19	10.6	10.04	5.6	8.41	8.74	0.79	222.19
,,	20	11.36	7.82	5.16	7.71	8.1	0.67	186.74
,,	21	11.38	10.04	5.2	8.4	8.87	0.73	221.67
,,	22	11.28	9.44	5.82	8.52	8.84	0.75	228.04
,,	23	9.82	8.24	5.16	7.47	7.74	0.76	175.3
,,	24	9.78	8.64	6.08	8	8.16	0.81	201.06
,,	25	9.34	8.5	5.16	7.42	7.66	0.79	172.96
,,	26	10.6	9.02	5.6	8.12	8.4	0.76	207.13
,,	27	9.64	7.56	5.7	7.46	7.63	0.77	174.83
,,	28	9.02	7.9	4.62	6.9	7.18	0.76	149.57
,,	29	8.74	8.3	5.42	7.32	7.48	0.83	168.33
,,	30	10.9	7.8	5.2	7.61	7.96	0.69	181.93
11.1	1	11.92	9.32	6.52	8.98	9.25	0.75	253.33
,,	2	10.36	8.34	5.5	7.8	8.06	0.75	191.13

MC=Moisture content, REP=Replicate, L=Length, W=Width, T=Thickness, GMD=Geometric mean diameter, AMD=Arithmetic mean diameter, SPH=Sphericity, SA=Surface area.

Size and shape parameters cont’d

MC %	REP	L mm	W mm	T mm	GMD mm	AMD mm	SPH	SA mm^2
11.1	3	10.34	9.34	4.92	7.8	8.2	0.75	191.13
,,	4	10.32	8.34	5.64	7.85	8.1	0.76	193.59
,,	5	10.4	8.5	5.72	7.67	8	0.73	184.81
,,	6	11.38	9.02	5.02	8.01	8.47	0.7	201.56
,,	7	11.38	9.04	5.04	8.03	8.48	0.7	202.57
,,	8	10.36	9.42	5.12	7.93	8.3	0.76	197.55
,,	9	10.22	9.02	5.52	7.98	8.25	0.78	200.05
,,	10	10.14	9.22	5.04	7.78	8.13	0.76	190.15
,,	11	10.54	7.98	5.14	7.56	7.88	0.71	179.55
,,	12	11.64	9.86	4.56	8.05	8.68	0.69	203.58
,,	13	10.18	8.22	4.84	7.39	7.74	0.72	171.56
,,	14	10.52	8.34	4.84	7.51	7.9	0.71	177.18
,,	15	9.14	8.68	5.5	7.58	7.77	0.82	180.5
,,	16	10.46	8.14	5.14	7.59	7.91	0.72	180.98
,,	17	10.52	7.98	4.74	7.35	7.74	0.69	169.71
,,	18	9.62	7.82	4.52	6.97	7.32	0.72	152.62
,,	19	10.46	8.02	5.86	7.89	8.11	0.75	195.57
,,	20	11.58	6.28	5.74	7.47	7.86	0.64	175.3
,,	21	9.02	7.46	4.52	6.72	7	0.74	141.86
,,	22	9.74	7.66	4.08	6.72	7.16	0.69	141.86
,,	23	11.58	8.44	5.32	8.04	8.44	0.69	203.07
,,	24	10.04	6.72	4.96	6.94	7.24	0.69	151.31
,,	25	10.02	7.84	4.82	7.23	7.56	0.72	164.22
,,	26	10.58	8.74	4.88	7.67	8.06	0.72	184.81
,,	27	10.36	8.32	4.46	7.27	7.71	0.7	166.04
,,	28	11.74	7.44	5.42	7.79	8.2	0.66	190.64
,,	29	10.34	8.42	5.5	7.82	8.08	0.75	192.11
,,	30	9.86	8.02	4.64	7.15	7.5	0.72	160.6
16.6	1	10.4	8.3	5.66	7.87	8.12	0.75	194.58
,,	2	10.9	8.8	5.08	7.86	8.26	0.72	194.08
,,	3	10.68	10.12	4.3	7.74	8.36	0.72	188.2
,,	4	12	9	5.1	8.19	8.7	0.68	210.72
,,	5	10.74	9.24	4.68	7.74	8.22	0.72	188.2
,,	6	9.92	7.92	5.5	7.56	7.78	0.76	179.55
,,	7	9.62	8.9	4.84	7.45	7.78	0.77	174.36
,,	8	9.94	8.04	6.56	8.06	8.18	0.81	204.08
,,	9	9.32	8.06	5.58	7.48	7.65	0.8	175.77
,,	10	9.76	8.36	5	7.41	7.7	0.75	172.49
,,	11	10.66	8	5.14	7.59	7.93	0.71	180.98
,,	12	10.14	8.52	4.4	7.24	7.68	0.71	164.67
,,	13	11.12	7.74	4.62	7.35	7.82	0.66	169.71

MC=Moisture content, REP=Replicate, L=Length, W=Width, T=Thickness, GMD=Geometric mean diameter, AMD=Arithmetic mean diameter, SPH=Sphericity, SA=Surface area.

Size and shape parameters cont’d

MC %	REP	L mm	W mm	T mm	GDM mm	ADM mm	SPH	SA mm^2
16.6	14	10.54	8.64	5.38	7.88	8.18	0.74	195.07
,,	15	9.96	7.84	5.44	7.51	7.74	0.75	177.18
,,	16	10.28	7.72	4.42	7.05	7.47	0.7	156.14
,,	17	9.58	8.38	5.38	7.55	7.78	0.78	179.07
,,	18	11	8.24	5.86	8.09	8.36	0.73	205.61
,,	19	9	7.86	5.76	7.41	7.54	0.82	172.49
,,	20	10.64	8.52	4.96	7.66	8.04	0.71	184.33
,,	21	11.28	9.04	5.06	8.02	8.46	0.71	202.06
,,	22	10.58	8.58	4.52	7.42	7.88	0.7	172.96
,,	23	11.18	8.8	4.26	7.45	8.08	0.66	175.77
,,	24	10.18	7.28	6.16	7.69	7.87	0.75	185.78
,,	25	11	7.66	4.82	7.4	7.82	0.67	172.03
,,	26	10.86	8.1	5	7.6	7.98	0.69	181.45
,,	27	10.88	8.04	5.02	7.6	7.98	0.69	181.45
,,	28	11.06	7.44	4.7	7.3	7.74	0.66	167.41
,,	29	11.58	9.04	4.94	8.02	8.52	0.69	202.06
,,	30	13.38	11.2	6.26	9.78	10.28	0.73	300.48
22	1	10.48	8.72	5.2	7.8	8.13	0.74	191.13
,,	2	10	9.86	4.34	7.53	8.06	0.75	178.13
,,	3	11.12	9.68	5.38	8.33	8.72	0.74	217.99
,,	4	11.78	9.22	5.18	8.25	8.72	0.7	213.82
,,	5	11.6	9	5	8.05	8.53	0.69	203.58
,,	6	10.64	8.18	5	7.57	7.94	0.71	180.02
,,	7	10.86	8.22	4.92	7.6	8	0.69	181.45
,,	8	11.26	6.6	5.48	7.41	7.78	0.65	172.49
,,	9	10.46	9	4.58	7.55	8.01	0.72	179.07
,,	10	10	9.82	4.88	7.82	8.23	0.78	192.11
,,	11	10.58	9	5	7.8	8.19	0.73	191.13
,,	12	9.46	8.38	5.12	7.4	7.65	0.78	172.03
,,	13	9.94	7.8	4.9	7.24	7.54	0.72	164.67
,,	14	12.06	9.84	6.44	7.14	9.44	0.75	262.44
,,	15	11.28	7.94	5.9	8.08	8.37	0.71	205.1
,,	16	10.86	8.14	6.7	8.39	8.56	0.77	221.14
,,	17	11.52	9.16	6.58	8.85	9.08	0.76	246.05
,,	18	10.7	8.3	5.82	8.02	8.27	0.76	202.06
,,	19	9.9	8.14	6	7.84	8.01	0.79	193.09
,,	20	10.54	7.52	4.92	7.3	7.66	0.69	167.41
,,	21	10.44	9.22	4.52	7.57	8.06	0.72	180.02
,,	22	9.48	8.74	4.84	7.37	7.68	0.7	170.64
,,	23	10.26	7.4	5.64	7.53	7.76	0.73	178.13

MC=Moisture content, REP=Replicate, L=Length, W=Width, T=Thickness, GMD=Geometric mean diameter, AMD=Arithmetic mean diameter, SPH=Sphericity, SA=Surface area.

Size and shape parameters cont’d

MC %	REP	L mm	W mm	T mm	GDM mm	ADM mm	SPH	SA mm^2
22	24	11.24	7.8	4.5	7.33	7.84	0.65	168.79
,,	25	10.34	7.94	5.5	7.72	7.92	0.74	187.23
,,	26	10.72	8.76	4.4	7.44	7.96	0.69	173.89
,,	27	11.32	9.48	4.92	7.78	8.57	0.68	190.15
,,	28	11.18	7.9	5.88	8.03	8.32	0.71	202.57
,,	29	10.44	8.18	5.38	7.71	8	0.73	186.74
,,	30	10.38	8.68	5	7.66	8.02	0.73	184.33
28.2	1	12.18	9.64	7.36	9.52	9.72	0.78	284.72
,,	2	11.4	8.66	5.64	8.22	8.56	0.72	212.27
,,	3	10.92	8.7	5.1	7.85	8.24	0.71	193.59
,,	4	10.74	9.84	5.36	8.27	8.64	0.77	214.86
,,	5	11.52	8.7	5.06	7.97	8.42	0.69	199.55
,,	6	11.92	9.3	5.5	8.47	8.9	0.73	225.38
,,	7	11.38	10.16	4.82	8.22	8.78	0.72	212.27
,,	8	11.18	9.6	5.08	8.18	8.62	0.73	210.21
,,	9	12.16	8.96	5	8.16	8.7	0.67	209.18
,,	10	10.92	9.36	5	7.99	8.42	0.73	200.55
,,	11	11.52	8.64	5.2	8.02	8.45	0.69	202.06
,,	12	11.08	8.74	4.92	7.81	8.24	0.7	191.62
,,	13	11.24	9	5.1	8.02	8.44	0.71	202.06
,,	14	11.18	9.4	5.26	8.2	8.61	0.73	211.24
,,	15	11.34	8.78	4.48	7.64	8.2	0.67	183.37
,,	16	10.08	8.64	4.92	7.53	7.88	0.74	178.13
,,	17	10.72	8.64	5.4	7.95	8.26	0.74	198.55
,,	18	11	8.84	5.08	7.9	8.3	0.71	196.06
,,	19	9.94	8.44	5.26	7.61	7.88	0.76	181.93
,,	20	12.14	9.32	6.66	9.09	9.37	0.74	259.58
,,	21	13.12	9.12	6.3	9.1	9.51	0.69	260.15
,,	22	13.86	9.78	5.58	9.11	9.74	0.65	260.72
,,	23	11.38	9	4.3	7.6	8.22	0.66	181.45
,,	24	10.84	8.8	5.4	8.01	8.34	0.73	201.56
,,	25	11.26	8.24	4.54	7.49	8.01	0.66	176.24
,,	26	12	9.3	4.76	8.09	8.68	0.67	205.61
,,	27	10	9.62	5.44	8.05	8.35	0.8	203.58
,,	28	11	9.4	5.38	8.22	8.59	0.74	212.27
,,	29	10.34	7.74	5.46	7.58	7.84	0.73	180.5
,,	30	10.54	10.24	4.7	7.97	8.49	0.75	199.55

*MC=Moisture content, REP=Replicate, L=Length, W=Width, T=Thickness, GMD=Geometric mean diameter, AMD=Arithmetic mean diameter, SPH=Sphericity, SA=Surface area.

Appendix 2: Raw data of gravimetric parameters influenced by seed moisture content.

MC %	REP	TGW g	SW g	SV mm^3	BD kgm^{-3}	TD kgm^{-3}	POR %
5.9	1	245	0.25	186	641.3	1250	48.69
,,	2	251	0.25	202	635.3	1176.5	46
,,	3	262	0.25	200	651	1250	47.92
,,	4	245	0.25	205	655	1250	47.6
,,	5	235	0.24	185	642.3	1333.3	51.82
11.1	1	265	0.26	216.2	674	1250	46.08
,,	2	266	0.26	223.7	680	1176.5	42.2
,,	3	276	0.27	220.8	674.7	1176.5	42.65
,,	4	257	0.25	205.1	669.3	1250	46.45
,,	5	254	0.25	210.5	694.7	1250	44.42
16.6	1	271	0.26	216.2	699	1250	44.08
,,	2	275	0.24	200	698.3	1250	44.13
,,	3	267	0.27	207.3	689.7	1176.5	41.37
,,	4	302	0.26	223.6	700.7	1176.5	40.44
,,	5	262	0.26	207.7	713.7	1250	42.9
22	1	283	0.27	223.6	685.7	1176.5	41.71
,,	2	269	0.27	192.3	709.7	1333.3	46.77
,,	3	282	0.25	192.3	701.3	1333.3	47.4
,,	4	272	0.25	220.8	707	1176.5	39.9
,,	5	281	0.27	209.9	708.7	1176.5	39.76
28.2	1	287	0.26	216.2	723.3	1250	42.13
,,	2	288	0.28	202.5	702.3	1250	43.81
,,	3	288	0.26	197.5	698.3	1250	44.13
,,	4	279	0.26	214.3	718.7	1111	35.31
,,	5	279	0.26	200	697.7	1250	44.18

MC=Moisture content, REP=Replicate, TGW=Thousand grain weight, SW=Seed weight, SV=Seed volume, BD=Bulk density, TD=True density, POR=Porosity.

Appendix 3: Raw data on friction properties of Locust bean seeds as affected by seed moisture content.

MC	REP	STATIC COEFFICIENT OF FRICTION (Degrees)							SAR	DAR	AIF	CIF
%		GLVI	RUB	ALM	STST	PLY	GLS	MDS	(deg.)	(deg.)	(deg.)	
5.9	1	0.466	0.363	0.531	0.531	0.466	0.466	0.466	47	25.85	22.24	0.409
,,	2	0.531	0.383	0.577	0.531	0.466	0.363	0.509	48	23.57	19.13	0.347
,,	3	0.531	0.404	0.554	0.577	0.487	0.445	0.577	49	24.56	13.6	0.242
,,	4	0.466	0.466	0.531	0.577	0.509	0.363	0.577	49	27.55	15.74	0.282
,,	5	0.577	0.466	0.531	0.577	0.509	0.466	0.509	49	24.95	14.25	0.254
11.1	1	0.509	0.509	0.509	0.487	0.487	0.466	0.531	50	26.73	30.49	0.589
,,	2	0.466	0.531	0.531	0.577	0.509	0.509	0.487	52	26.38	27.87	0.529
,,	3	0.509	0.531	0.6	0.466	0.577	0.466	0.424	50	26.21	40.46	0.853
,,	4	0.424	0.466	0.466	0.577	0.466	0.509	0.363	49	24.66	32	0.625
,,	5	0.466	0.466	0.509	0.577	0.487	0.577	0.531	51	25.07	26.38	0.496
16.6	1	0.466	0.624	0.531	0.531	0.509	0.577	0.531	50	26.56	27.47	0.52
,,	2	0.509	0.577	0.531	0.531	0.577	0.531	0.554	50	27.84	28.72	0.548
,,	3	0.531	0.554	0.624	0.531	0.577	0.577	0.577	50	29.11	28.01	0.532
,,	4	0.531	0.531	0.6	0.577	0.509	0.509	0.577	53	27.47	29.11	0.557
,,	5	0.531	0.531	0.554	0.624	0.509	0.531	0.531	51	28.89	31.38	0.61
22	1	0.531	0.531	0.509	0.577	0.554	0.487	0.531	53	27.47	29.37	0.543
,,	2	0.577	0.446	0.509	0.577	0.554	0.649	0.531	53	25.93	27.92	0.511
,,	3	0.509	0.531	0.509	0.554	0.577	0.509	0.531	54	27.05	24.93	0.448
,,	4	0.509	0.554	0.649	0.6	0.509	0.624	0.509	52	25.2	23.84	0.426
,,	5	0.445	0.509	0.509	0.531	0.509	0.487	0.531	56	25.26	26.24	0.493
28.2	1	0.554	0.649	0.577	0.466	0.624	0.554	0.554	58	28.72	26.97	0.509
,,	2	0.509	0.531	0.487	0.577	0.6	0.554	0.531	55	30.96	28.14	0.535
,,	3	0.509	0.6	0.487	0.531	0.624	0.531	0.531	55	32	28.59	0.545
,,	4	0.487	0.577	0.509	0.466	0.6	0.531	0.577	55	30.79	27.87	0.529
,,	5	0.554	0.649	0.577	0.487	0.6	0.531	0.531	57	30.96	29.63	0.569

MC=Moisture content, REP=Replicate, GLVI=Galvanized Iron, RUB=Rubber, ALM=Aluminium, STST=Stainless Steel, PLY=Plywood, GLS=Glass, MDS=Mild Steel, SAR= Static angle of repose, DAR=Dynamic angle of repose, AIF=Angle of internal friction, CIF=Coefficient of internal friction.

Appendix 4: Raw data on Coefficient of mobility and Hopper wall angle of locust bean.

MC %	REP	COM	HWA (deg.)
5.9	1	0.45	56.12
,,	2	0.506	54.56
,,	3	0.619	51.8
,,	4	0.573	52.87
,,	5	0.604	52.12
11.1	1	0.326	60.24
,,	2	0.362	59.43
,,	3	0.212	65.23
,,	4	0.307	61
,,	5	0.384	58.19
16.6	1	0.368	58.73
,,	2	0.35	59.36
,,	3	0.36	59
,,	4	0.345	59.55
,,	5	0.315	60.69
22	1	0.353	59.68
,,	2	0.374	58.96
,,	3	0.419	57.46
,,	4	0.436	56.92
,,	5	0.386	58.12
28.2	1	0.375	58.48
,,	2	0.358	59.07
,,	3	0.352	59.29
,,	4	0.362	58.93
,,	5	0.338	59.81

MC=Moisture content, REP=Replicates, COM=Coefficient of mobility, HWA=Hopper wall angle.

Appendix 5: Shear stress and normal stress values under different loads and varying seed moisture levels.

LOAD	REP	SHEAR AND NORMAL STRESS VALUES (g cm^{-2}) AT DIFFERENT SEED MOISTURE LEVELS									
g		5.9 %		11.1 %		16.6 %		22 %		28.2 %	
		SS	NS	SS	NS	SS	NS	SS	NS	SS	NS
200	1	0.509	8.384	0.881	8.554	1.014	8.659	0.7	8.674	0.755	8.699
,,	2	0.639		1.038		0.946		0.689		0.85	
,,	3	0.619		0.943		1.109		0.699		0.931	
300	1	0.774	9.394	1.247	9.564	1.083	9.669	1.144	9.684	0.967	9.709
,,	2	0.601		1.287		1.31		0.934		1.063	
,,	3	0.69		1.126		1.106		1.032		0.964	
400	1	0.611	10.404	1.191	10.574	1.317	10.679	1.097	10.694	1.179	10.719
,,	2	0.628		1.139		1.064		1.09		1.392	
,,	3	0.677		1.365		1.304		1.072		1.069	
500	1	0.724	11.414	1.603	11.584	1.501	11.689	1.394	11.704	1.33	11.729
,,	2	0.589		1.521		1.344		1.511		1.362	
,,	3	0.686		1.513		1.495		1.464		1.387	

REP=Replicate, SS=Shear stress, NS=Normal stress. Normal stress is constant for each load at each seed moisture level.

Appendix 6: Raw data on rupture force, deformation and rupture energy under seed moisture effect.

MC %	REP	RF N	DEF mm	RE Nmm
5.9	1	347.3	1.2	208.38
,,	2	241.6	1	120.8
,,	3	166.1	0.8	66.44
,,	4	166.1	0.9	74.74
,,	5	151	1	75.5
11.1	1	317.1	1.3	206.11
,,	2	90.6	0.8	36.24
,,	3	256.7	1	128.35
,,	4	75.5	0.55	20.76
,,	5	256.7	1.2	154.02
16.6	1	173.65	1.25	108.53
,,	2	105.7	1.3	68.7
,,	3	166.1	1	83
,,	4	226.5	1.5	169.87
,,	5	226.5	1	113.25
22	1	166.1	0.95	78.89
,,	2	196.3	1.2	117.78
,,	3	120.8	1.5	90.6
,,	4	151	2.4	181.2
,,	5	90.6	2	90.6
28.2	1	211.4	0.9	95.13
,,	2	105.7	0.75	39.63
,,	3	90.6	0.8	36.24
,,	4	151	1.7	128.35
,,	5	90.6	1.5	67.95

MC=Moisture content, REP=Replicate, RF=Rupture force, DEF=Deformation, RE=Rupture energy.

Appendix 7: Raw data on thermal properties of locust bean seeds as affected by seed moisture content.

MC %	REP	TC W m^{-1} ^{0}C	SHC kJ kg^{-1} ^{0}C	TD m^{2}s^{-1}
5.9	1	0.05	2.76	2.83
,,	2	0.059	2.77	3.26
,,	3	0.047	2.69	2.72
11.1	1	0.055	3.16	2.57
,,	2	0.069	4.11	2.49
,,	3	0.109	3.59	4.37
16.6	1	0.095	4.62	2.94
,,	2	0.093	5.38	2.48
,,	3	0.124	4.01	4.33
22	1	0.089	4.87	2.61
,,	2	0.144	5.08	4.02
,,	3	0.107	4.37	3.45
28.2	1	0.134	4.76	3.94
,,	2	0.098	3.99	3.46
,,	3	0.122	4.4	3.97

MC=Moisture content, REP=Replicate, TC=Thermal conductivity, SHC=Specific heat capacity, TD=Thermal diffusivity.

Appendix 8: ANOVA results for size and shape parameters.

Squares		Sum of	df	Mean Square	F	Sig.
LENGTH	Between Groups	18.333	4	4.583	6.607	.000
	Within Groups	100.583	145	.694		
	Total	118.916	149			
WIDTH	Between Groups	10.549	4	2.637	4.536	.002
	Within Groups	84.310	145	.581		
	Total	94.859	149			
THICKNESS	Between Groups	2.631	4	.658	2.088	.085
	Within Groups	45.679	145	.315		
	Total	48.310	149			
GMDIAM	Between Groups	4.646	4	1.162	5.357	.000
	Within Groups	31.442	145	.217		
	Total	36.088	149			
SPH	Between Groups	3.066E-02	4	7.664E-03	4.756	.001
	Within Groups	.234	145	1.611E-03		
	Total	.264	149			
SRFC-AREA	Between Groups	11188.282	4	2797.070	4.741	.001
	Within Groups	85539.527	145	589.928		
	Total	96727.809	149			
ARTHDIAM	Between Groups	6.134	4	1.533	6.201	.000
	Within Groups	35.860	145	.247		
	Total	41.994	149			

GMDIAM=Geometric mean diameter, SPH=Sphericity, SRFC-AREA=Surface area, ARTHDIAM= Arithmetic mean diameter.

Appendix 9: Gravimetric parameters (ANOVA results cont'd)

		Sum of Squares	df	Mean Square	F	Sig.
TGW	Between Groups	4138.160	4	1034.540	10.767	.000
	Within Groups	1921.600	20	96.080		
	Total	6059.760	24			
SW	Between Groups	.001	4	.000	2.317	.092
	Within Groups	.002	20	.000		
	Total	.002	24			
SV	Between Groups	1075.948	4	268.987	2.549	.071
	Within Groups	2110.192	20	105.510		
	Total	3186.140	24			
BD	Between Groups	13483.386	4	3370.847	35.328	.000
	Within Groups	1908.288	20	95.414		
	Total	15391.674	24			
TD	Between Groups	4003.074	4	1000.768	.285	.884
	Within Groups	70247.620	20	3512.381		
	Total	74250.694	24			
POR	Between Groups	133.378	4	33.344	4.255	.012
	Within Groups	156.715	20	7.836		
	Total	290.093	24			

TGW=Thousand grain weight, SW=Seed weight, SV=Seed volume, BD=Bulk density, TD=True density, POR=Porosity

Appendix 10: ANOVA results on friction properties

10.1 Coefficient of static friction on material surfaces

		Sum of Squares	df	Mean Square	F	Sig.
GLVI	Between Groups	.007	4	.002	1.182	.349
	Within Groups	.030	20	.002		
	Total	.037	24			
RUB	Between Groups	.098	4	.025	13.506	.000
	Within Groups	.036	20	.002		
	Total	.134	24			
ALM	Between Groups	.006	4	.002	.741	.575
	Within Groups	.043	20	.002		
	Total	.049	24			
STST	Between Groups	.013	4	.003	1.873	.155
	Within Groups	.034	20	.002		
	Total	.046	24			
PLY	Between Groups	.044	4	.011	11.428	.000
	Within Groups	.019	20	.001		
	Total	.063	24			
GLS	Between Groups	.059	4	.015	6.045	.002
	Within Groups	.049	20	.002		
	Total	.108	24			
MDS	Between Groups	.023	4	.006	3.287	.032
	Within Groups	.035	20	.002		
	Total	.058	24			

GLVI=Galvanized iron, RUB=Rubber, ALM=Aluminium, STST=Stainless steel, PLY=Plywood, GLS=Glass, MDS=Mild steel.

10.2 Other friction parameters (ANOVA results)

		Sum of Squares	df	Mean Square	F	Sig.
SAR	Between Groups	176.960	4	44.240	27.309	.000
	Within Groups	32.400	20	1.620		
	Total	209.360	24			
DAR	Between Groups	96.722	4	24.180	18.131	.000
	Within Groups	26.673	20	1.334		
	Total	123.395	24			
AIF	Between Groups	618.709	4	154.677	14.991	.000
	Within Groups	206.354	20	10.318		
	Total	825.062	24			
CIF	Between Groups	.279	4	.070	12.215	.000
	Within Groups	.114	20	.006		
	Total	.394	24			

SAR=Static angle of repose, DAR=Dynamic angle of repose, AIF=Angle of internal friction, CIF=Coefficient of internal friction.

10.3 Coefficient of mobility and Hopper wall angle (ANOVA results cont'd)

		Sum of Squares	df	Mean Square	F	Sig.
COM	Between Groups	.169	4	.042	18.834	.000
	Within Groups	.045	20	.002		
	Total	.213	24			
HWA	Between Groups	157.200	4	39.300	15.711	.000
	Within Groups	50.030	20	2.501		
	Total	207.230	24			

COM=Coefficient of mobility, HWA=Hopper wall angle.

Appendix 11: ANOVA results for mechanical properties

11.1. Shear stress

		Sum of Squares	df	Mean Square	F	Sig.
SHSTR-200g	Between Groups	.386	4	9.640E-02	18.789	.000
	Within Groups	5.131E-02	10	5.131E-03		
	Total	.437	14			
SHSTR-300g	Between Groups	.516	4	.129	14.562	.000
	Within Groups	8.867E-02	10	8.867E-03		
	Total	.605	14			
SHSTR-400g	Between Groups	.773	4	.193	15.428	.000
	Within Groups	.125	10	1.252E-02		
	Total	.898	14			
SHSTR-500g	Between Groups	1.534	4	.383	98.197	.000
	Within Groups	3.905E-02	10	3.905E-03		
	Total	1.573	14			

SHSTR=Shear stress.

11.2. Rupture force, Deformation and Rupture energy

		Sum of Squares	df	Mean Square	F	Sig.
RF	Between Groups	25491.518	4	6372.879	1.247	.323
	Within Groups	102194.082	20	5109.704		
	Total	127685.600	24			
DEF	Between Groups	1.362	4	.341	2.434	.081
	Within Groups	2.798	20	.140		
	Total	4.160	24			
RE	Between Groups	5280.737	4	1320.184	.456	.767
	Within Groups	57934.384	20	2896.719		
	Total	63215.120	24			

RF=Rupture force, DEF=Deformation, RE=Rupture energy

Appendix 12: ANOVA results for thermal properties

		Sum of Squares	df	Mean Square	F	Sig.
TCND	Between Groups	.009	4	.002	5.131	.016
	Within Groups	.004	10	.000		
	Total	.014	14			
SHCAP	Between Groups	8.757	4	2.189	11.161	.001
	Within Groups	1.962	10	.196		
	Total	10.718	14			
TDIF	Between Groups	1.208	4	.302	.554	.701
	Within Groups	5.449	10	.545		
	Total	6.657	14			

TCND=Thermal conductivity, SHCAP=Specific heat capacity, TDIF=Thermal diffusivity.