

IMPROVEMENT OF THE DEHULLING EFFICIENCY OF SORGHUM AND MILLET

by

EZRA LYIMO LAZARO

B.Sc. Agriculture (Dar), M.Sc. Agric. Engineering (Cranfield)

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ABSTRACT

Methods for improvement of the dehulling efficiency of sorghum and millet were investigated. These included: studying the fundamental physical and mechanical properties of the grain and how these properties are influenced by different process variables, the use of different pre-treatment methods to loosen the grain seed coat and hence facilitate its removal during the dehulling process, the use of alkali dehulling as an alternative method to conventional abrasive and traditional dehulling methods, development of a numerical model which could be used as a tool for further study of the abrasive dehulling process and finally development of a prototype dehuller combining dehulling principles from both traditional and mechanical dehulling systems which could dehull tempered grain without problems experienced in current mechanical dehullers.

The effects of grain and process variables, such as moisture content, temperature and loading conditions on mechanical properties of grain were studied under uniaxial compression of individual whole grain kernels. Five temperature and moisture dependent parameters, which included modulus of deformability, ultimate strain, ultimate stress, energy to break point, force to break point and modulus of toughness were evaluated from force-deformation relations obtained. Each of these parameters except ultimate strain decreased with increase in kernel moisture content and temperature. Grain strength properties also depended heavily on the orientation of the grain during loading (flat loading vs. side loading), indicating that sorghum kernel was anisotropic with respect to mechanical properties.

Effect of different pre-treatments on dehulling efficiency was investigated using hydrothermal pre-treatments. These included, treating the grain with steam or tempering with distilled water for different durations followed by drying using either unheated ambient air at 20⁰C or heated air at 60⁰C to their initial moisture content (12%db). A tangential abrasive dehuller was used to dehull the pre-treated grain and the effect of different pre-treatments on dehulling efficiency of the pre-treated grain was evaluated based on the extent of seed coat removal and crude fibre reduction in the dehulled grain. Results indicated that hydrothermal pre-treatments improved the dehulling efficiency of sorghum and millet by an average of 8.5% and 20% respectively in terms of seed coat removal and by 16% and 13.7% respectively in terms of crude fibre reduction in the dehulled grain compared to untreated grain.

Tempering the grain for a short duration (<15 minutes) reduced the seed coat adhesion in sorghum and millet substantially without affecting the grain strength properties significantly. Seed coat adhesion strength at different tempering durations was quantified by measuring the tangential force required to remove a unit area of seed coat using a friction apparatus. Tempering for 15 minutes reduced the seed coat adhesion strength per unit area by 91.1% and

95.7% compared to untreated grain for sorghum and millet respectively. The effect of seed coat adhesion reduction due to tempering, however, was reversible as the grain kernel was dried.

Alkali dehulling of sorghum and millet was investigated using an aqueous solution of sodium hydroxide as a dehulling agent. Results indicated that alkali concentration, soaking time and temperature were significant factors during the dehulling process. Soaking the grain in 10% aqueous solution of sodium hydroxide for 10 minutes at 60°C was found to be the optimum alkali dehulling conditions for sorghum and millet. Under these conditions 90% yield of unbroken endosperm at 89% dehulling efficiency was achieved from a soft red sorghum variety, which is higher than can be achieved using any of the conventional dehulling systems.

Moisture absorption characteristics of sorghum and millet during tempering were studied at different temperatures, initial grain moisture contents, and endosperm textures. Temperature had a significant effect on moisture absorption characteristics of both sorghum and millet, moisture absorption increased with increase in temperature for both sorghum and millet. The moisture absorption characteristic was modelled using Fickian diffusion model and Peleg's model. Peleg's model was able to simulate the moisture absorption characteristics of both sorghum and millet at initial soaking stages more accurately than the Fickian diffusion model. A general model, based on Peleg's model and Arrhenius function, was developed for prediction of tempering duration at different temperatures within 20 – 50°C temperature range.

The abrasive dehulling process was successfully modelled using a three-dimensional discrete element model. The computer code was validated by experiment, and good correlation was obtained between simulation and experimental results. Several numerical experiments were also carried out using the developed computer code to investigate the influence of mill and grain parameters on dehulling of sorghum and millet. This model thus provides a tool which can be used to study the dehulling process in more detail than is currently possible using other methods.

Based on experimental results from the grain physical and mechanical property and pre-treatment tests, a prototype dehuller incorporating a dehulling surface, which enabled it to dehull moist grain without clogging, was designed and constructed. Grain-grain and grain-dehuller surface friction was the main dehulling principle. The dehuller was able to achieve higher yield, dehulling efficiency and colour reduction of the dehulled grain flour than a tangential abrasive dehulling device (TADD).

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NOTATION

Upper case letters:

A_c	Contact area (m^2)
C	Cohesion (N)
C_d	Coefficient of dehulling
C_w	Coefficient of wholeness
C_y	Yield factor
C_n	Normal damping constant
C_s	Shear or tangential damping constant
C^*	Coefficient of global damping
D	Diffusion coefficient ($m^2.h^{-1}$)
D_{AM}	Arithmetic mean diameter (m)
D_{eff}	Dehulling efficiency (%)
D_{GM}	Geometric mean diameter (m)
D_0	Arrhenius constant at reference temperature (Fickian model)
E	Modulus of elasticity (Pa)
E_a	Activation energy ($J.mol^{-1}$)
E_i	Decay modulus of elasticity (Pa)
$E(t)$	Relaxation modulus at time t (Pa)
E_0	Instantaneous modulus of elasticity at t=0 (Pa)
E_r	Retardation modulus of elasticity (Pa)
E_∞	Equilibrium modulus after infinite time (Pa)
E_{mod}	Modulus of deformability (Pa)
F_n	Normal force (N)
ΔF_n	Normal force increment (N)
ΔF_s	Shear force increment (N)
$F(t)$	Applied uniaxial compression force at time t (N)
G_s	Modulus of rigidity (Pa)
I	Moment of inertia ($kg.m^2$)
K_1, K_2	Peleg constants
K_0	Arrhenius constant at reference temperature (Peleg model)
L	Kernel length (m)
M_{ei}	Experimental moisture content (%db)
M_t	Metric ton (kg)
$M_{(t)}$	Mass of water absorbed at time t (kg)
MR	Moisture ratio
M_∞	Mass of water absorbed at saturation (kg)
M_0	Initial moisture content (%db)

$M(x)$	Moment about the centroid of the particle (N.m)
N	Normal Force (N)
P	Normal contact pressure (Pa)
P_{ri}	Predicted moisture content (%db)
R	Universal gas constant ($J.kg^{-1}.mol^{-1}.K^{-1}$), Particle radius (m)
R_2, R_2^*	Radii of curvature of spherical indenter (m)
R^2	Coefficient of determination
R_{max}	Maximum (major) radius of curvature of grain kernel (m)
R_{min}	Minimum (minor) radius of curvature of grain kernel (m)
RMSE	Root mean square error
S	Kernel surface area (m^2)
T	Absolute temperature (K)
V	Volume of the deformed area (m^3)
W	Kernel width (m)
W_{1000}	Thousand grain weight (kg)
\dot{X}	Particle velocity ($m.s^{-1}$)
\ddot{X}	Particle acceleration ($m.s^{-2}$)
Y_a	Actual yield obtained (%)
Y_e	Expected yield (%)

Lower case letters:

a	Radius of contact cycle (m)
db	Dry basis
d_2	Diameter of the spherical steel indenter (m)
e	Coefficient of restitution
f_R	Frequency of wave propagation (Hz)
frac	Fraction of the time step used in simulation
g	Acceleration due to gravity ($m.s^{-2}$)
h	Height of drop (m)
ha	Hectare (m^2)
\bar{i}	Unit vector in the x direction
\bar{j}	Unit vector in the y direction
\bar{k}	Unit vector in the Z direction
k	Contact stiffness
k_n	Normal stiffness
k_s	Tangential or shear stiffness
$\ln()$	Logarithm to base e (natural logarithm)
$\log()$	Logarithm to base ten

m	Mass of particles (kg)
m_c	Moisture content (%)
m_{cdb}	Moisture content dry basis (%)
n	Number of experimental points
Δn	Normal displacement increment (m)
r	Radial distance (m)
rad	Radians
Δs	Tangential displacement increment (m)
t	Soaking time (s)
Δt	Time step (s)
Δt_{crit}	Critical time step (s)

Greek letters:

β	Damping ratio
ε	Strain
$\varepsilon(t)$	Strain at time t
μ	Coefficient of friction
η_v	Viscosity (Pa.s)
ρ	Particle density (kg.m^{-3})
ρ_k	Kernel density (kg.m^{-3})
ρ_b	Bulk density (kg.m^{-3})
σ	Stress (Pa)
σ_0	Initial stress (Pa)
$\sigma(t)$	Stress at time t (Pa)
σ_e	Residual stress (Pa)
σ_d	Stress drop during stress decay (Pa)
τ	Relaxation time (s)
τ_{ret}	Time of retardation (s)
$\dot{\theta}$	Angular velocity (rad.s^{-1})
$\ddot{\theta}$	Angular acceleration (rad.s^{-2})
ϕ	Inter-particle friction angle
ω	Angular velocity (rad.s^{-1})
ν	Poisson ratio
α	Total deformation of particles in contact (m)

CHAPTER ONE

INTRODUCTION

1.1 Importance of sorghum and millet

Sorghum and millet are members of the Graminae family of grasses that are extensively grown in the arid and semi-arid tropics and sub tropical regions where they constitute a major source of protein and energy for population in these areas. In the arid and semi-arid parts of Africa and Asia, up to 70% of the daily dietary protein and energy intake is supplied by locally milled sorghum and millet products (Hulse *et al.*, 1980).

The genus sorghum includes at least four groups of cultivated annual plants which includes: Grain sorghum grown mainly for grain production, sweet sorghum or sorgo grown as forage and for animal feed and also for the sugary juice in their stems, sudan-grass also grown mainly for pasture, hay and silage, and broom corn grown, as the name suggests, for making brooms. There is some overlap in end use among groups, and some types may be grown for both forage and grain. The present study deals exclusively with the cultivated grain sorghum (*sorghum bicolor* (L) Moench) grown for production of grain for human consumption.

The most important millet species include pearl millet (*Penisetum tryphoides*), finger millet (*Eliusine coracona*), foxtail millet (*Setaria italica*) and proso millet (*Panicum miliaceum*). There are other minor millets of local significance, including teff, kodo, burn-yard, fonio and little millet. However, the species of interest in this work is pearl millet (*Penisetum tryphoides*)¹, which is the most important and most widely grown of all of the millets (Hulse *et al.*, 1980).

¹ Henceforth in the text the name "millet" will refer to this species unless otherwise stated.

In terms of production, sorghum and millet are ranked fifth and sixth respectively in importance among the world cereals, after wheat, rice, maize and barley (Dogget, 1988). Although they account for only 4.7 % of world grain production, which represents 4.4% of the world total starch staples on food energy basis (Dendy, 1995), they are extremely important in the arid and semi-arid zones where often little else can be grown. The main importance of sorghum and millet lies in their high tolerance to drought and their remarkable adaptation to dry tropical and sub-tropical ecosystems, where they are able to grow and produce well under a wide range of adverse environmental and soil conditions in which no other cereal grain can survive.

Sorghum and millet will assume even greater importance as food grains as we move towards the time when the global supply of grain is insufficient to meet needs of the population. This is coupled with the changing world climate with uncertain and lower rainfall, deteriorating soil fertility and a decline in the fallow periods as the increasing population pressure requires the less fertile, and agriculturally more difficult land be brought to cultivation will further signify the importance of these two grains in world food security, especially in developing countries. This situation already exists in many of developing countries such as India, China and many parts of the sub-Saharan Africa (Dogget, 1988).

Sorghum and millet are also grown in developed countries, mainly the United States (which is the largest producer of sorghum in the world), Argentina, Mexico, Brazil, some parts of Europe and Japan. In developed countries, however, sorghum and millet are grown mainly for livestock feed and to a minor extent for industrial production of starch, syrup and brooms. The food, fodder, feed and industrial uses of these grains make them important in both the developed countries and the agrarian economies of developing countries of Africa and Asia having low and unreliable rainfall and limited irrigation resources.

1.2 Problem definition

For many years sorghum and millet have been the traditional staples throughout the arid and semi-arid tropics of Africa and Asia. However, over the past two decades there has been a

dramatic shift in consumption patterns from these traditional coarse grains to non-traditional grains such as wheat, maize and rice (Kennedy and Reardon, 1994). This shift in consumption pattern is causing great concern because:

- (i) It is occurring in regions where production of wheat, rice or maize is not feasible or is very costly, which means the rising demand for these products must be met by commercial imports or food aid or both.
- (ii) It is occurring in some of the world's poorest countries, countries with severe foreign exchange constraints who can ill afford to increase food imports at the expense of other developmental issues such as health or education
- (iii) Farmers are abandoning production of these traditional staples and attempting to grow maize and rice on unsuitable soils and in uncertain climates leading to disastrous results, thus making these countries more and more prone to famine.

The lack of well developed mechanical processing technology and the high labour and time required for traditional home processing of these grains have been cited as the main reasons for this shift in consumption from sorghum and millet to non-traditional crops (Dendy, 1995; Laswai, 1992; Delgado and Reardon, 1987; Kennedy and Reardon, 1994). For human consumption, sorghum and millet need to be dehulled. The dehulling process is of paramount importance as it removes the seed coat, which is high in crude fibre and often contains pigments and anti-nutritional factors such as tannins and phytic acid. Fibre increases faecal loss of nutrients and minerals while tannins and phytic acid lowers the digestibility of proteins and absorption of some essential mineral elements in the body and are also potent carcinogens (Munck *et al.*, 1982). Dehulling of sorghum and millet is a difficult operation mainly due to the small size of the grains and because the seed coat is firmly attached to the endosperm making it difficult to separate during the dehulling process. In many developing countries where sorghum and millet are grown, more than 80% of the grain is still being dehulled by the traditional mortar and pestle method. This method can produce a good quality and highly acceptable end product, however, it is very laborious and time-consuming.

Compared to other cereal crops like maize, wheat and rice, where specialised and highly mechanised processing technologies have been developed to produce finished products of high quality and consumer acceptance, the mechanical processing technology for sorghum and millet and in particular the dehulling process has been very little developed. Flour from undehulled or poorly dehulled grain may contain relatively high levels of fibre, tannin and phytic acid. The flour is also highly speckled especially if from coloured varieties and often has an astringent taste and hence is unattractive to consumers. Thus, while high quality and acceptable maize and wheat flour are rapidly gaining a foothold in both rural and urban markets, sorghum and millet flour are not, and are viewed as low prestige coarse grains associated with the backwardness of rural areas. As a result, even in traditional sorghum and millet producing areas, they are increasingly regarded as inferior grains fit only for animal feed, brewing or consumption by the poorest section of society.

Rapid urbanisation, which has been taking place in most developing countries, has also had a profound influence on the utilisation of sorghum and millet. Urban dwellers do not have the time required and inclination to process these grains using the laborious traditional methods and therefore tend to opt for other more convenient foods which take less time and energy to process and prepare or which can be purchased already prepared. The result is that high quality maize and wheat products are readily available in the shops while sorghum and millet products are not.

Another factor related to the shift from sorghum and millet is the fact that dehulling of these grains is traditionally carried out exclusively by women. Urbanisation has resulted in a substantial increase in the number of women working outside of the home. This leaves less time available for women for manual processing of sorghum or millet and reinforces the preference for foods, which are more easily processed and prepared. The increase in family income also led to the diversification in the family diet and a shift from foods such as sorghum and millet products, which are perceived to be inferior to preferred or prestigious foods such as rice and wheat bread.

To address this problem and therefore restore consumer acceptance of sorghum and millet, new developments in sorghum and millet grain processing are required. To relieve the hard work of hand dehulling in rural areas, it is essential that suitable village scale dehullers be developed and introduced in areas where these grains are produced. However, for these dehullers to be accepted or adopted, in addition to reducing the drudgery involved in hand processing, they have to be more efficient than the traditional system and have to produce grain of an acceptable quality. Spare parts for these dehullers must also be easily available locally and at affordable prices. For sorghum and millet to be able to compete with wheat, rice and maize in urban areas, there is a need for development of efficient industrial or semi-industrial mills or other innovative processing techniques that can produce high quality and acceptable flour and other attractive products such as composite flour bread, snacks, break fast cereals and rice analogue from the available sorghum and millet varieties at an acceptable milling yield (>80%) and at a cheaper price than from maize and wheat.

The need for mechanical dehulling technology for sorghum and millet was recognised earlier by the United Nations Food and Agricultural Organisation (FAO) and the Canadian International Development Research Centre (IDRC). IDRC developed and introduced a number of small-scale dehullers (e.g. PRL dehuller) in sorghum and millet production areas in a number of developing countries in Africa including; Botswana, Zimbabwe, Zambia, Tanzania, Kenya, (Reichert, 1982; Munck *et al.*, 1982). Likewise, FAO initiated a program for sorghum milling in Sudan and Senegal (Perten, 1977). All of these were abrasive systems using carborundum stones. However despite being faster and less tedious than traditional dehulling method, these dehullers are highly inefficient and result in high losses of endosperm due to excessive breakage, especially for the soft varieties. Another problem is the lack of spare parts, especially the carborundum stones, which must be imported. These problems have resulted in low adoption of these mechanical dehullers in most areas where they have been introduced.

As far as efficiency is concerned, the main problem is the fact that most of these dehullers were originally developed for dehulling other grains, mainly, barley, rice and related grains and

were used to dehull sorghum and millet with minor or no modifications and with little consideration of the differences in physical and mechanical properties of the grains involved. The grain physical and mechanical properties play a major role in determining the efficiency of the processing machine and the quality of the final product (Reichert, 1987). This has been clearly demonstrated by the early attempts to use roller-milling technology for sorghum and millet, which resulted in poor end product due to poor separation of the grain constituents. The resulting flour was of poor quality and unattractive to consumers, and nothing developed from these early attempts. For efficient mechanical dehulling of sorghum and millet, the grain physical and mechanical properties and the manner in which these properties are affected by different conditions likely to be encountered during the dehulling process must be known and taken into consideration during the design and development of the dehulling equipment. At the moment very little is known about sorghum and millet grain physical and mechanical properties and how these properties are affected by different process conditions such as changes in moisture content, temperature or loading. The physical and mechanical properties of sorghum and millet grain important in the dehulling process therefore need to be studied and the relationship between these properties and different process conditions established.

Traditional experience in the sorghum and millet consuming areas has shown that both dehulling efficiency and the quality of the end product can be substantially improved by the use of cheap and simple yet effective grain pre-treatments. These include: soaking the grain in water (tempering), acid, or alkali solution, steaming, roasting and germinating, just to name a few. So far very few, if any, of these pre-treatments have been properly evaluated or successfully incorporated in the mechanical dehulling system despite their possible benefits. There is a need therefore to study the effect of some of these traditional pre-treatments on the dehulling efficiency of the current mechanical dehulling systems. Incorporation of some of these pre-treatments as they are, or with minor improvement into the current mechanical dehulling systems or into new dehuller designs could help to improve the dehulling efficiency and quality of products from sorghum and millet.

Dehulling is a complex process involving interaction between the grain kernels and the dehulling equipment or mill. The key to improvement of this process or development of a more efficient dehulling system lies in good understanding of what actually happens inside the dehuller of which very little is known at the moment. The lack of understanding is mainly due to the difficulty in measuring the behaviour of grains inside the dehuller and the lack of models that can quantify the dynamics of grain assembly and forces acting on individual grains. The use of computational methods to supplement the experimental studies of grain physical and mechanical properties could provide more insight on the mechanics of the dehulling process. An appropriate model could be used as the basis for guiding and optimising dehuller design and interpreting the results of laboratory experiments. There is a need, therefore for development of such a model which could be used as a new tool to study the mechanics of the dehulling process of sorghum and millet in more detail than is currently possible using the available experimental methods.

1.3 Objectives of the study

1.3.1 Main objective

The main objective of this research was to investigate how the dehulling efficiency of abrasive mechanical dehullers and the quality of the dehulled product of sorghum and millet can be improved.

1.3.2 Specific objectives

The specific objectives of this study were to:

- (1) Determine the physical, mechanical and structural properties of sorghum and millet grain.

- (2) Investigate the functional relationship between these properties and different process conditions likely to be encountered during the dehulling process notably, moisture content, temperature and loading condition.
- (3) Investigate how some of pre-treatment methodologies useful in traditional dehulling system can be improved and incorporated in the mechanical dehulling methods in order to improve their efficiency.
- (4) Develop a numerical model which can be used to study the mechanics of the dehulling process of sorghum and millet in more detail than is currently possible using the available experimental methods.
- (5) Design and develop an experimental prototype dehuller on the basis of the results of the experimental work.

1.4 Organisation of the thesis

This thesis consists of seven chapters; Chapter One presents the introduction, background to the problem under investigation and the objectives of the study. Chapter Two presents the general literature review on historical development and distribution of sorghum and millet, and the attempts made so far to improve the quality of products from these grains for human food through different processing methods. Chapter Three presents the results and methods used in determination of physical and mechanical properties of sorghum and millet and the relationship between these properties and different process conditions. Chapter Four examines the effect of different pre-treatments commonly used in traditional dehulling systems on the dehulling efficiency of current abrasive dehulling methods. Also the use of alkali as a dehulling agent in production of dehulled sorghum and millet grain for food use is investigated. The moisture absorption characteristics of sorghum and millet are investigated and an analytical model for determination of tempering duration at different temperatures is developed. The development of a mechanical model for the abrasive dehulling process is presented in Chapter Five and the design and development of a prototype dehuller for tempered sorghum and

millet grain is presented in Chapter Six. Finally Chapter Seven presents the general conclusions drawn from this study and recommendations for future study.

CHAPTER TWO

LITERATURE REVIEW

2.1 Historical background

A detailed account of the history and origin of sorghum and millet was presented by Dogget (1988). Briefly it would appear that sorghum and millet had their origin in the region of Africa currently known as Ethiopia, from where they spread westwards to West Africa across the Sahara and southwards to Eastern and Southern Africa. Historical records suggested that sorghum and millet reached India from East Africa soon after 2000 BC. They may have been carried from East Africa to Arabia and from Arabia with the dow traffic, spread to the Persian Gulf and into the Near East. The spread along the coast of Southeast Asia and around to China may have taken place about the beginning of the Christian era or possibly earlier via silk trade routes (Hulse *et al.*, 1980). Grain sorghum arrived in America as guinea corn from West Africa with the slave trade. Sorghum spread to Central and South America from North America, where its importance in semi-arid areas is increasing but mostly as feed grain and fodder (Dogget, 1988).

2.2 Geographical distribution

The sorghum and millet production zone almost encircles the earth beginning in China through India and extending to most of Africa, the southern United States, Central America and Latin America. Though the area covered by sorghum and millet is comparable or greater than most other internationally important cereals, sorghum and millet have received scanty attention when compared with grains prominent in international trade such as wheat, rice and maize (IDRC, 1977). Tables 2.1 and 2.2 show the area harvested and grain production for sorghum and millet respectively for the years 1989 to 1996.

**Table 2.1 Area harvested ('000 ha), and production ('000 Mt) of sorghum for the period
1989 to 1996**

Region	Area harvested (1000 ha)				Production (1000 Mt.)			
	1989-91	1994	1995	1996	1989-91	1994	1995	1996
Africa	18492	23070	21529	24212	13905	18242	17608	20852
N&C. America	6108	5281	5132	6808	20651	20677	16352	25774
S. America	1415	1262	1091	1160	3635	3679	3086	3508
Asia	16614	14754	13882	14141	17080	17787	15556	16679
Europe	163	161	140	182	651	641	553	632
Oceania	461	494	687	653	981	932	1273	1556
World Total	43365	45021	42461	47155	57027	61957	54427	69000

Source: FAO production yearbook vol. 50 (1996)

**Table 2.2 Area harvested ('000 ha), and production ('000 Mt) of millet for the period 1989
to 1996**

Region	Area harvested (1000 ha)				Production (1000 Mt)			
	1989-91	1994	1995	1996	1989-91	1994	1995	1996
Africa	15824	20155	19075	19067	10402	12243	11800	12881
N&C America	124	120	120	120	187	180	180	180
S. America	72	36	48	43	99	53	65	45
Asia	18499	17091	16101	16414	14453	15123	14136	15795
Europe	11	15	12	14	21	23	18	19
Oceania	31	37	44	44	27	37	44	27
World Total	37462	38636	36256	36259	28047	28298	27000	29563

Source: FAO production yearbook vol. 50 (1996)

2.2.1 Sorghum and millet in the semi-arid tropics

Probably the most important character of sorghum and millets is their ability to tolerate and survive under conditions of continuous or intermittent droughts that result from low and unreliable rainfall. Their principal homes are found in the semi-arid tropics (SAT) of Africa and Asia. The term 'semi-arid' cannot be precisely defined, but in general it describes those regions in which evapo-transpiration exceeds rainfall for more than half the year (Hulse *et al.*, 1980). In Africa, a major sorghum growing area runs across West Africa south of the Sahara almost to the Atlantic coast and eastwards to Sudan, Ethiopia, and Somalia. It is grown in Upper Egypt but it is minor along the North African coast. Southwards, it is commonly grown in Kenya, Tanzania, Uganda, Rwanda and Burundi, Zambia, Malawi, Botswana, Lesotho, Mozambique and the drier parts of South Africa and Namibia.

In Asia, sorghum is an important cereal grain in India, Pakistan, Thailand and central and Northern China. Sorghum is also important in the many states of the former Soviet Union and Australia. In America, sorghum is an important crop in the south-western United States and north into Nebraska. In South America, sorghum is particularly important in the drier areas of Argentina, the Sao Paulo and North-eastern areas of Brazil, and the drier areas of Venezuela, Columbia and Mexico. In Europe, sorghum is grown in France and Italy.

Pearl millet is common in much of semi-arid tropical and sub-tropical region, where it is cultivated on poor soils and in areas of low or inconsistent rainfall. It is the most drought tolerant of all cereal grains. With a strong and deep rooting system and efficient use of available moisture, pearl millet can survive in areas with as little as 300 mm or less of seasonal rainfall. This compares with a minimum of 400 mm for sorghum and 500-600 for maize (Dogget, 1988; Dendy, 1995; Hulse *et al.*, 1980). Most important countries growing pearl millet are India, Nigeria, Niger, Chad, Mali, Tanzania, Ethiopia, China and the drier parts of the former USSR (Ukraine and Kazakhstan). Small-scale producers include Uganda, Burkina-Faso, Senegal and Sudan. India is the largest producer of millet in the world with pearl

millet making up 60% of the total millet production. Production of millet in Americas, Australia and Europe is low, although it is sometimes grown for grazing or fodder and for game birds (Dogget, 1988).

2.3 Grain structure and composition

2.3.1 Grain structure

The structure of grain has an important bearing on various processing and food quality traits. The structure of sorghum and millet grain has much in common. The unique kernel structure of these two cereal grains offers several advantages over other cereals, however, the grains contain specific constituents that create problems for the millers, feed processors and consumers. Research on the components of sorghum and millet grain is therefore an important factor in the development and production of refined and improved products from these grains. Also the knowledge of the kernel structure and its relation to grain quality can be utilised on a practical basis in selection and development of the best processing method for the separation of the component parts (Rooney and Miller, 1981).

2.3.1.1 Sorghum grain structure

The structure of the sorghum kernel varies significantly due to environmental and genetic factors and plays an important role in determining the processing properties of the grain and food quality traits. The shape, size, proportion and nature of the endosperm, germ and pericarp, the presence or absence of sub-coat (testa) and colour of the pericarp are all genetically controlled. Several researchers (Rooney, 1973; York, 1976; Rooney and Clark, 1968; Sullins and Rooney, 1975; Rooney and Miller, 1981) have studied the structure of the sorghum grain. There appears to be a general agreement that the sorghum kernel or caryopsis is roughly spherical in shape and composed of three major structural parts; the seed coat, the

embryo or germ, and the endosperm (see figure 2.1). Each component part is distinct, and there are no cell walls common to any two of them.

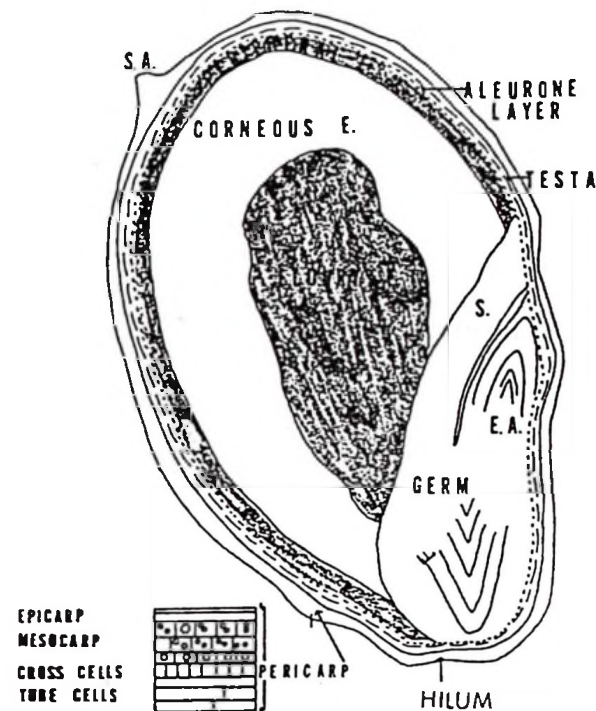


Figure 2.1 Sorghum kernel showing component parts
(From Rooney and Miller, 1981)

2.3.1.1.1 The seed coat

The seed coat consists of fused pericarp and testa. The pericarp is the extreme outer layer of the grain the original ovary wall, which is surrounded by a waxy cuticle and is composed of three different layers; the epicarp or epidermis (frequently pigmented), the mesocarp and the endocarp which is the innermost layer of the pericarp. The endocarp cells are located at the point of breakage where the pericarp or seed coat is removed during mechanical dehulling (Sullins and Rooney, 1975).

The testa (also known as the sub coat, hyaline layer, nucellus or integument) is the layer immediately below the endocarp and surrounding the endosperm. According to Wall and Ross (1970) the testa is always present in the ovary as an inner integument with a definite structure. However, as the kernel matures and the endosperm expands, the cellular configuration of the testa may give way to a continuous layer or in some instances it may totally or partially disappear. The presence or absence of the testa is also genetically controlled. Consequently, some sorghum lines contain a complete testa, for some the testa seems to be absent, and some contain partial testa. The partial testa occurs sporadically around the kernel and may or may not contain spots of pigment. Where a complete testa exists, it may vary in thickness among different sorghum lines and from one area to another. The testa may or may not be pigmented, a feature which also appears to be genetically controlled (Hulse *et al.*, 1980; Ayyagan and Krishnaswani, 1941).

The pigmentation of both the pericarp and the testa is sometimes attributed to the presence of high concentrations of polyphenols or tannins (Hulse *et al.*, 1980). The pericarp or seed coat is the part of the kernel which is responsible for the coarseness, and colour of sorghum and millet products, and it is the layer which is usually removed during the dehulling process.

2.3.1.1.2 The embryo (germ)

The embryo appears as the lower portion on one side of the seed and consists of a large scutellum, an embryonic axis, a plumule and a primary root. The scutellum is the flattened portion that serves as an absorptive organ. There is a cementing layer between the scutellum and the endosperm with glands protruding from the scutellum into the endosperm. The embryo is relatively firmly embedded and difficult to remove by dry milling (Rooney, 1973). However, adding water to the grain causes the germ to swell and to pull away from the cementing layer (Wall and Ross, 1970).

2.3.1.1.3 The endosperm

The endosperm represents the largest portion of the kernel and consists of an aleurone layer (a single continuous layer of cells around the extreme edge of the endosperm peripheral), corneous and flourey zones. The peripheral layer of the endosperm is made up of cells containing a high proportion of protein. The corneous layer beneath the peripheral layer, contains less protein and higher proportion of starch than the peripheral. The corneous layer is also termed, the flinty, hard or horny endosperm. Inside the corneous layer is found the flourey or soft endosperm, which is lowest in protein (Rooney, 1973; Hulse *et al.*, 1980). The texture of the endosperm varies within a sample and is influenced by heredity and environment (Rooney, 1973). Whether a sorghum grain is described as 'flourey' or 'corneous' depends on the ratio of flourey (soft) to corneous (hard) endosperm components within the kernel. Often the 'flourey' sorghums contain brown pericarp and pigmented thick testa (Rooney, 1973). The relative proportion of the corneous to flourey endosperm is termed the kernel texture or endosperm texture. Endosperm texture plays a major role in determining the sorghum grain quality and is also used in classification of the grain.

Hubbard *et al.* (1950) described the proportions of component parts of the sorghum kernel obtained by hand dissection after soaking the grain in distilled water. The endosperm ranged from 81.1 to 84.6%, the germ from 7.8 to 12.1% and bran (pericarp and testa) from 7.3 to 9.3%. These results agree in general with the findings of Bidwell (1918) and Bidwell *et al.* (1922). However, these results were disputed by Rooney (1973) who thought that the results reported by Hubbard *et al.* (1950) might have underestimated the proportion of pericarp and overestimated the endosperm content since the pericarp fraction appear to have been separated at the mesocarp layer. Also Dogget (1988) agreed with Rooney (1973) and commented that, while Hubbard's data may be typical of USA grain sorghum, the range of proportion variation would be much greater amongst the international sorghum collection.



2.3.1.2 Millet grain structure

The structure of millet grain is similar to that of sorghum with a few but important differences. The pearl millet kernels are about one-third the size of sorghum kernels. The average weight of each kernel is about 9 mg compared to 20-30 mg for sorghum. Sorghum kernels are generally spherical in shape whereas pearl millet kernels are generally 'tear' shaped. The germ of pearl millet is much larger as the percentage of the total kernel than is the case in sorghum (17.4% compared to 9.8% in sorghum). This explains in part the higher protein and oil contents of pearl millet as compared to sorghum (Klopfenstein and Hosenev, 1995). The pericarp of pearl millet is similar to that of sorghum except that no starch granules are found in millet mesocarp. The corneous endosperm of millet consists of tightly packed starch granules and protein bodies with no air spaces, and the flourey and corneous endosperm areas of millet are also not as distinct as they are for sorghum kernels (Sergio and Rooney, 1995).

2.3.2 Grain composition

Knowledge of the composition of the component parts of the grain is important because it is then possible to predict the effect of processing by various methods on the composition of the final product. Hubbard *et al.* (1950) dissected five USA sorghum varieties and analysed for protein, fats, ash and starch. Their results are presented in Table 2.3.

The composition of sorghum grain is generally similar to that of maize except for a lower oil content (Hubbard *et al.*, 1950). The whole grain contains 8 to 12% proteins and 72 to 76% starch. The pericarp is rich in fibre and sometimes pigments and anti-nutritional factors. The germ, a rich source of oil (28% of the germ), also has high levels of protein (19%) and ash (10%). However, the proximate composition of sorghum from different sources may vary widely because of many factors, including genetic factors, soil and climatic conditions, and manner of crop management (Wall and Blessin, 1969).

Table 2.3 Component parts of sorghum kernel and their proximate composition

Component	% by wt.	Starch (%)	Protein (%)	Fat (%)	Ash (%)
Endosperm	82.3	82.5	12.3	0.6	0.37
Pericarp	7.9	34.6	6.7	4.9	2.02
Germ	9.8	13.4	18.9	28.1	10.36
Whole grain	100	73.8	12.3	3.6	1.65

Source: Reichert (1977).

2.3.2.1 Nutritional quality of sorghum and millet products

Sorghum is a nutritious starch rich cereal, high in available energy content comparable to wheat, rice or maize (Table 2.4). However, the lysine content of the protein, which is a nutritionally limiting amino acid, is the lowest of all cereals, especially in milled flour where the lysine rich germ has been removed. Protein quality is critically important in developing countries where human diets consist mainly of cereals. Supplementation of sorghum and millet based diets with legumes, vegetables, and animal proteins is thus crucial if the protein is to be utilised nutritionally (Munck *et al.*, 1982).

The content of digestible nutrient in low-tannin sorghum products is very high compared to other cereals (Eggum *et al.*, 1982). The true digestibility of protein and energy in dehulled grain is 100% and 96% respectively. When sorghum is cooked to make thick porridge (*ugali*) these values are decreased by 8% and 2% respectively (Munck *et al.*, 1982). Although the digestibility of sorghum decreases through cooking, the values before and after cooking are comparable with the best values for other cereals such as wheat, maize, and rice. The storage proteins of sorghum are highly cross-linked and hydrophobic which affect water absorption, processing conditions and digestibility of sorghum products. These problems are exaggerated in high tannin varieties containing polyphenols, which in large quantities are toxic and impair digestibility (Sergio and Rooney, 1995).

Pearl millet in general has a higher protein content and a much more nutritionally favourable amino-acid composition than sorghum, including a relatively high level of lysine. Protein content of pearl millet ranges from 8-19%. The higher germ to endosperm ratio is responsible for the higher protein content and improved amino acid composition (Sergio and Rooney, 1995). Starch represents about 56-65% of the kernel. Ether extractable lipids range from 3.0 - 7.4%, they are mostly in the germ and similar in composition to sorghum lipids.

Table 2.4 Comparison of nutrients in 100 gm edible portions of various cereals at 12%mc.

Cereal grain	protein (g)	Fat (g)	CHO (g)	Fibre (g)	Ash (g)	Energy (kcal)	Ca (mg)	Fe (mg)	Thiamine (mg)	Niacin (mg)
Wheat	11.6	2.0	71	2.0	1.6	348	30	3.5	0.405	5.05
Rice	7.9	2.7	76	1.0	1.3	362	33	1.8	0.413	4.31
Maize	9.25	4.6	73	2.8	1.2	329	26	2.7	0.378	3.57
Sorghum	10.9	3.2	73	2.3	1.6	363	27	4.3	0.300	2.83
Pearl Millet	11.0	5.0	69	2.2	1.9	351	25	3.0	0.300	2.0

Source: Hulse *et al.* (1980)

2.3.2.2 Sorghum and millet anti-nutritional factors

2.3.2.2.1 Sorghum

Sorghum is unique among major cereals because some cultivars produce highly condensed polymeric polyphenols in their seed coats. The most important are tannins and phytic acid. All sorghums contain phenols and most contain flavanoids, however, only cultivars with pigmented testa produce these condensed tannins.

2.3.2.2.1.1 Tannins

Many coloured grain sorghum genotypes contain high levels of polyphenolic compounds commonly referred to as tannins. These occur mainly in the pericarp and testa layers of the grain (Glennie, 1983; Earp *et al.*, 1983). Tannins have been observed to possess some agronomic advantages such as resistance to bird predation (Butler, 1982; Bullard and Elias, 1980; Subramanian *et al.*, 1983), pre-harvest germination (Harris and Burns, 1970), protection from insect pests (Woodhead *et al.*, 1980) and protection from moulding (Harris and Burns, 1970). High tannin sorghum cultivars, however, have also been found to be nutritionally inferior when compared with low tannin types of otherwise similar chemical composition. This is mainly due to the ability of the tannins to bind dietary proteins by interacting with the proteins by multiple irreversible hydrogen bonding of phenolic groups to peptide or amide bonds making them indigestible hence unavailable to the body (Synge, 1975; Salunkhe *et al.*, 1982). Tannins have also been associated with reduction in dry matter digestibility (McGinty, 1969) and growth retardation in chicken and pigs (Jambunathan and Mertz, 1973; Muind and Thomke, 1981; Maxom *et al.*, 1973; Schaffert *et al.*, 1974;). Tannins impart astringency to sorghum products, which tend to reduce animal feed intake. The reduced weight gain in animals fed sorghum has been attributed to the reduced feed intake (Buttler, 1990).

It is essential, however, especially in the developing countries and in areas like the southern United States where bird (quelea) predation is a big problem to retain the agronomic advantages associated with the high tannin content and at the same time devise means of overcoming their deleterious effects. Various methods have been developed to deactivate the tannins (Salunkhe *et al.*, 1982). These include treatment or extraction of the grain with water, alkali, acid and formaldehyde (Featherstone and Rogler, 1975; Reichert *et al.*, 1980; Prince *et al.*, 1979; Armstrong *et al.*, 1974). Another approach to improve nutritional quality of the high tannin sorghum is the removal of the tannin containing layers by mechanical abrasion i.e. dehulling using grinding wheels in horizontal or vertical type dehullers or traditional method using pestle and mortar (Cross, 1985; Reichert, 1982; Eastman, 1980). However, the yield of

grain also contains oxalic acid, which forms an insoluble complex with calcium thereby reducing bio-availability of the mineral (Whitney *et al.*, 1987).

2.4 Sorghum and millet processing

2.4.1 Research on sorghum and millet processing

Although sorghum and millet are among the most abundant coarse cereals throughout the world, it is only recently that cereal grain researchers have begun to pay them the attention they really deserve (Kapasi-Kakama, 1977; IDRC, 1977; Dendy, 1995). The scant attention paid to these cereals by researchers resulted from the obvious fact that, for the countries with more advanced scientific and technological know-how, sorghum and millets were neither cereal staples for their people nor a source of feed for their livestock. For their cereal staples they had crops such as wheat, rice, barley and oats while their livestock requirements was taken care of by barley, oats and maize. So their scientists concentrated their efforts on these crops. The realisation, especially in the USA, that sorghum grain could supplement maize in animal feed preparations was responsible for attracting attention to sorghum and later millet by cereal grain researchers in the 1970's (Kapasi- Kakama, 1977; Hulse *et al.*, 1980).

In the years following this realisation, breeders, agronomists, and entomologists have done substantial work on the production of improved high yielding varieties and hybrids of sorghum and millet. Most of this work has been successfully directed at maximising grain yields through breeding (Wall and Ross, 1979). While it may suffice to concentrate on quantitative aspects of sorghum production for animal feeds, quality aspects must be taken into consideration when the end product is to be used for human consumption. Thus researchers all over the world who are concerned about the increase in food use of sorghum and millets are now engaged in the improvement of these crops through breeding and processing programmes. Attempts have been made at developing suitable processing equipment for sorghum and millet though most

of these are still at laboratory testing stage and include minor modification of existing machinery for either wheat, barley or rice milling (Reichert, 1982; Hulse *et al.*, 1980).

2.4.2 Sorghum and millet milling

The single term "milling" when applied in the context of cereal grain covers a wide range of processes. In general, the purpose of milling is first to condition the grain in a dry or semi-wet state in such a way that the different components can be separated as cleanly as possible. The separated fractions can then be finely milled in a simple processing step without the need for a subsequent sophisticated separation process. Milling embraces a wide range of technologies, from simple grinding of the whole grain between stones or pounding in a wooden mortar with a pestle, to the complex continuous systems of precision rolls, sifters and classifiers found in modern wheat roller mills.

Modern milling systems seek to separate the grain kernel into three fractions; bran, germ, and the endosperm. Bran is an industrial term, it does not refer to a specific anatomical part of the kernel, the grain miller strives to include the pericarp (seed coat), and aleurone layer in the bran. The removal of bran lowers fibre content, anti-nutritional factors and decreases the pigmentation of the meal or flour. Elimination of the germ and aleurone layer reduces oil content and thus ensures longer stability of the milled endosperm. Since there is no milling process that is ideal, there is always some overlap of fractions in the products (Kent and Evers, 1994). The milling properties of the grain, and consequently flour quality are affected by the structure and moisture content of grain as well as the milling equipment and the grinding technique.

2.4.3 Dehulling of sorghum and millet

The purpose of the dehulling process, even in the simple traditional household method, is to bring about efficient and complete removal of the outer layers (seed coat) from the kernel

leaving a seed coat free endosperm. This is due to the presence of high fibre content and anti-nutritional factors on the grain seed coat. Dehulling considerably improves the nutritional quality, digestibility and consumer acceptability of sorghum and millet products by reducing the fibre content, pigments and getting rid of the anti-nutritional factors present in the seed coat. For sorghum and millets, dehulling is therefore an important and essential part of the milling process for the production of refined and high quality end product for human consumption.

2.4.4 Sorghum and millet dehulling methods

2.4.4.1 Traditional dehulling methods

Traditional methods of dehulling sorghum and millet have been in use from time immemorial. The process is very simple but is able to produce a good product and, with care and experience, it is possible to achieve high extraction rates and a high quality end product. Apart from the bran, nothing is wasted, and even at the end, the bran is used in feed stuffs. However, considerable amount of time and energy is involved in producing products of quality suitable for human consumption.

1

The traditional dehulling equipment is the mortar and pestle (figure 2.2). Both the pestle and mortar are carved from wood. The mortar is about 60-70 cm high with a diameter of about 30 cm. The pestle is about 1.2 m long, 6 cm in diameter with bulbous ends and weighs about 3 kg. During the dehulling process approximately 2-3 kg of clean grain is placed in the mortar and at least 20-25% water (by weight) is added to the grain (Carr, 1961; Reichert *et al.*, 1981; Egum *et al.*, 1982). The grain is mixed with the water and allowed to rest between 10 and 15 minutes to allow the tempering water to soak in. The moist grain is then pounded. One, two or three women can pound the grain simultaneously; each working at about 40-60 strokes a minute (figure 2.3).



Figure 2.2 Traditional dehulling equipment – mortar and pestle



Figure 2.3 Traditional dehulling of sorghum and millet using mortar and pestle

The abrasive action generated due to strong interaction between the grains and between grain and the equipment frees the seed coat from the endosperm, normally at the interface between the endocarp and the endosperm. Addition of water or tempering causes the bran layers to swell and become partially detached from the endosperm, which facilitates its peeling and removal from the endosperm during pounding. The moisture does not normally penetrate deep into the endosperm since the grain is pounded only a few minutes after water is added.

The dehulled grain is removed from the mortar, sun dried for few minutes and winnowed to separate the bran. Normally two to three decortications are required to obtain a satisfactory product from local hard cultivars with recovery from 72-85% of the raw material (Carr, 1961; Muller, 1970). After winnowing to separate the bran, the dehulled grain is washed in excess water and sun dried. After drying the grain can be pounded or ground into flour by using a grinding stone or small diesel driven mechanical mills that are available in most villages. Care is taken to prepare the milling products and cook them within few days, because keeping quality of flour is low in tropical hot climate (Vogel and Graham, 1978). Figure 2.4 depicts the flow chart of the traditional dehulling process.

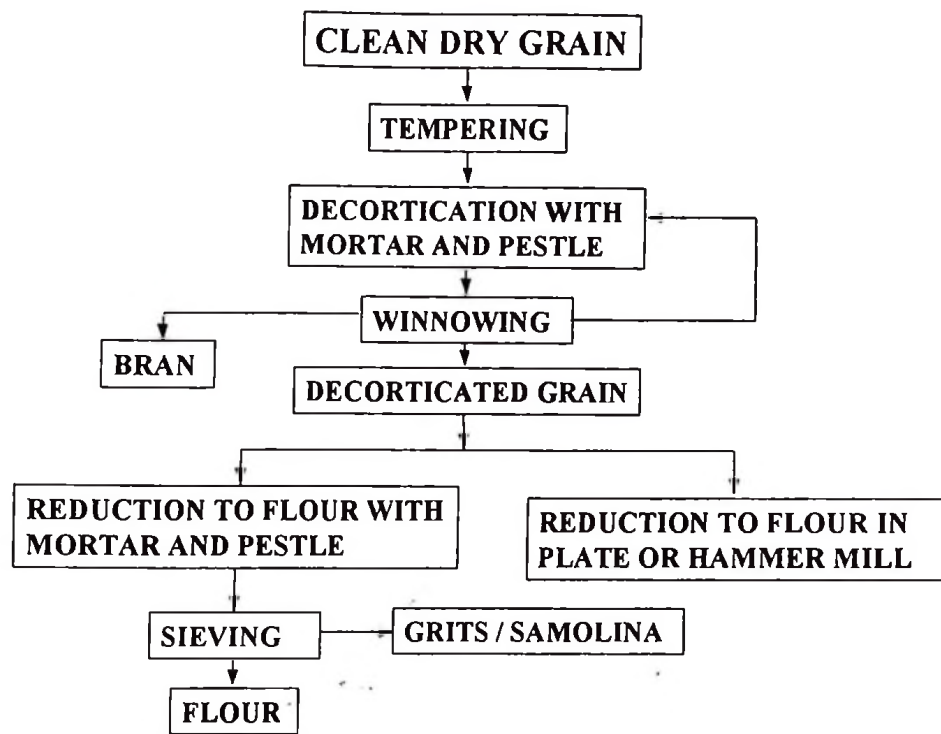


Figure 2.4 Flow chart of traditional mortar and pestle dehulling method

Carr (1961) noted that when high tannin red sorghum was traditionally dehulled, original grain produced 66% meal, 29% offals and 5% waste. Favier *et al.* (1972) recorded endosperm recovery of 76.8% and 73.9% in two villages in Cameroon after traditional dehulling of red soft sorghum. They also estimated that 11 to 21 minutes are required to dehull 3kg of grain.

Consumers prefer high endosperm recovery with minimal breakage of the endosperm and complete removal of the pericarp. Striking differences between genotypes for dehulling quality evaluated by traditional methods have been reported (Murty and House, 1980). The physical and structural properties of the grain such as shape, pericarp thickness and endosperm hardness affect the traditional dehulling efficiency. Scheuring *et al.* (1982) found that those grains possessing a thick pericarp and highly corneous endosperm produced the maximum quantity of dehulled grain with minimal breakage and with minimum effort and time required

for pounding. In pearl millet, they observed that grain with thick pericarp and globular shape, were relatively easier to dehull with less endosperm loss and yielded cleaner endosperm.

Eggum *et al.* (1982) investigated traditional dehulling of sorghum in Tanzania and compared the results with mechanical dehulling. They found that in most cases traditional dehulling was able to produce better and more refined products compared to mechanical dehulling. Nutrient loss was greater in mechanical dehulling than in the traditional method because mechanical dehulling removed more germ and endosperm than the traditional method. Also Reichert and Young (1976,1977) found that traditional dehulled sorghum and millet contain higher oil, protein and ash than mechanically dehulled grain. This was due to the fact that the germ is firmly embedded in the sorghum endosperm and is not readily removed during traditional dehulling. He also found that traditional and mechanically dehulled grain did not differ as markedly in protein content as they do in ash and oil content.

2.4.4.2 Mechanical dehulling methods

The different mechanical dehulling technologies which have so far been used to dehull sorghum and millet or which could potentially be used can be categorised into four main categories and include:

- (i) Roller milling equipment
- (ii) Rice-dehulling equipment
- (iii) Abrasive type dehullers and
- (iv) Attrition dehullers

Many of the machines in the last two categories have been developed specifically for sorghum and millet and similar grains. As in milling of other cereals, maximum endosperm recovery as grits, meal, or flour is desired.

2.4.4.2.1 Methods adapted from wheat and other cereals

Since the original interest in mechanical milling of sorghum occurred in wheat growing areas in the USA, and involved people familiar with wheat milling, the first attempts to dry mill sorghum were made on wheat roller mills. A number of researchers have used roller mills such as; Buhler mill (Badi *et al.*, 1976), conventional roller milling equipment (Hahn, 1970; Shoup *et al.*, 1970) and Brabender Quadrumat mills (Rooney and Sullins, 1969; Maxom *et al.*, 1971; Badi *et al.*, 1976) to mill sorghum and millet. The general consensus, however, appears to be that roller milling is not appropriate for sorghum and millet because the product does not have consumer acceptability as tested in Senegal, Chad and Sudan (Perten, 1977). The reasons for this were mainly because of its poor quality and relatively high production costs due to low extraction rate. The poor colour and specks of bran in the flour also limit the usefulness of roller milling for sorghum and millet. The main reason for the poor quality was the fact that the physical properties of wheat germ and seed coat are different from those of sorghum and millet. Whereas in wheat, the seed coat through its toughness, resists crushing and allows itself to be separated by sieving as coarse particles, the germ and seed coat of sorghum and millets easily pulverises into fine powder which is difficult to separate from the fine flour (Hahn, 1970). Recent studies at the Natural Resource Institute (NRI), however, showed that roller-milling results could be improved by prolonged steeping at high moisture content under semi-wet conditions (Cecil, 1986).

2.4.4.2.2 Application of rice and barley milling equipment

In applying the dehulling principle to sorghum and millet, rice and barley dehullers and polishers were a major source of inspiration to be used as such or as the basis for further optimised development to serve for grain sorghum and millets (Hulse *et al.*, 1980; Reichert, 1982). Polishing in a rice dehuller is a method of dehulling sorghum and millets especially favoured in the Orient. In this machine, a vaned rotor drives the grain around inside the machine. The seed coat is removed by the rubbing of the grain against itself and the machine

walls. The degree of hull removal and yield of the product depends on the extent of tempering and on the rates of throughput. Minimum nutrient loss results in a degree of bran removal of between 7.8 and 12% (Wall, 1967; Raghavendra Rao and Desikachar, 1964). Viraktamath *et al.* (1971) tested three types of rice milling equipment; a rice huller (a horizontal ribbed rotor), a Gota machine (a horizontal truncated cone) and a Dandekar-type rice mill (a vertical truncated cone rice polisher). Only the latter produced satisfactory dehulled sorghum from tempered grain.

Engleberg rice dehullers or similar dehullers have also been tested on sorghum and millet (Raghavendra Rao and Desikachar, 1964) and are used in several West African countries. The machine consists of a ribbed rotor rotating within a slotted screen. In general, however, many of the rice dehullers particularly those like Engleberg type do not work well with sorghum or millet mainly due to the fact this machine result into high breakage of the endosperm (Reichert *et al.*, 1981). For barley milling equipment, the horizontal (Buhler Miag Uzvil, Switzerland) and the vertical (Decomatic, Benhard Keller AG, Zurich) machines have been thoroughly studied by Perten (1977) on dehulling of sorghum and millet.

2.4.4.2.3 Abrasive type dehullers for sorghum and millet

Abrasive dehulling, as the name implies, employs a rough surface such as carborundum or abrasive resinoid disks or hard stone in form of discs, rolls or cones to rub off progressively the outer layers of the grain. The objective of abrasive dehulling is to remove the outer layers (bran) of the grain sequentially thereby removing the seed coat together with the fibre and anti-nutritional factors associated with it (Despande *et al.*, 1982). Abrasive dehullers equipped with carborundum stone or emery coated abrasive discs appear to be most commonly used (Reichert *et al.*, 1981). Abrasion systems for sorghum and millets have been extensively reviewed (Reichert, 1977; Normand *et al.*, 1965; Rooney *et al.*, 1972; Anderson, 1969; Shoup *et al.*, 1970; Viraktamath *et al.*, 1971). Normand *et al.* (1965) used a tangential abrasive mill to remove successive peripheral layers from sorghum, barley, wheat and rice. They found that

the protein content of the peripheral successive layers in the four cereals differed according to depth of abrasion, and in the majority of cases the highest protein concentration was found in the layers near the periphery.

2.4.4.2.4 Attrition type dehullers

The term attrition dehulling is generally applied to a mill in which the dehulling takes place between two steel or stone disks rotating in a horizontal or vertical plane. One of the disks may be stationary and either of the disks may be modified with a variety of impact or cutting surfaces. The Palyi Compact mill is one type of attrition mill. Two attrition plates, one stationary and one rotating provide the dehulling action in this mill. The distance between the plates is adjustable providing variable extraction rates. de-Man *et al.* (1973) tested the machine and modifications of it and obtained good results on sorghum and millet. However, Reichert and Young (1976) found that the throughput was relatively low (70 and 140 kg per hour at extraction rates of 68 and 83 respectively) and the dehulling efficiency poor.

2.4.4.2.5 Comparative studies

Perten *et al.* (1974) reported on a collaborative study on dehulling and grinding equipment for sorghum and millet which was carried out between 12 laboratories and manufacturers of milling machines in 10 countries. Participants were sent up to 50 kg of grain and asked to (a) dehull the grain to extraction between 75 and 80%, (b) report methods and equipment used, and (c) submit samples of dehulled grain. The criteria for choosing the best dehuller included throughput and equipment considerations such as, power consumption, cost, kernel cracking, and purity of the dehulled grain judged by ash, fat, crude fibre content, and colour. The best results with respect to purity were obtained from abrasive dehulling machines.

Reichert and Young (1976) compared the efficiency of different mills which included the Paly compact mill (attrition mill) with two abrasion mills, a laboratory scale Strong Scott barley

pearler and Hill grain thresher, the last modified to provide an abrasive action. Efficiency was measured by flour colour (using Hitachi Perkin Elmer Spectrophotometer) against material removed, kernel breakage, and throughput. According to their results, the laboratory pearler and the Hill grain thresher mill were similar in removing most of the colour with least loss of material. The Palyi compact mill was in this respect least efficient.

To put the results into perspective, the product from the three methods were compared with an acceptable sample of flour produced by traditional pestle and mortar method. The percentage of sorghum kernel required to be removed by each milling method to produce reflectance at 450 nm equivalent to acceptable hand processed sample was 21% for the barley pearler, 23% for abrasion mill and 44% for the Palyi attrition mill. The percentage of pearl millet to be removed by each decorticating method to achieve equivalent reflectance was closely similar to those quoted for sorghum. An excessive amount of kernel breakage in the attrition-type dehuller was one explanation for the low efficiency. Another was that the sharp saw-tooth blades of the latter dug deeper into the grain and removed relatively more endosperm resulting into high losses.

2.4.4.2.6 Laboratory equipment for assessing dehulling quality

To screen for dehulling quality in sorghum and millet, a wide range of laboratory equipment has been developed which in small-scale (samples from 0.5 g to 2000 g) aim at simulating the dehulling action of larger commercial mills. Plant breeders and grain processing laboratories often use these laboratory mills to evaluate milling quality. Occasionally commercial millers also use laboratory mills to assess suitability of a particular grain lot or variety for processing.

Rooney and Sullins (1969) used a Scott barley pearler and adapted it with wire brushes instead of the disks to dehull 100-200 g samples batch-wise. The bran and flour was separated from the decorticated grain by sieving. A Satake grain-testing mill based on the

same principle as barley pearler was used by Rooney *et al.* (1972) for sorghum. Maleshi and Desikachar (1985) used a combination of a Satake sheller for dehusking and a McGill rice polisher for dehulling millet, reaching a yield of 69-77%. Shepherd (1979) modified the Udy cyclone mill, which is based on abrasion, to provide a gentle abrasive action and combine it with a straining procedure specific for pericarp, testa, and aleurone to study dehulling on small sorghum and pearl millet samples. Normand *et al.* (1965) used a laboratory tangential abrasion mill, originally developed for rice by Hogan *et al.* (1964), to remove successive peripheral layers from sorghum. The machine consists of a single abrasive disk rotating horizontally with a sample cup held in position over its surface.

Oomah *et al.* (1981) and Reichert *et al.* (1986) developed an abrasion technique to remove successive layers from sorghum and other grains by a multisample tangential abrasive dehulling device (TADD). In this device, a carborundum stone, mounted horizontally directly beneath the sample cups, provide the abrasive action. The dehulling head plate is exchangeable, allowing up to 12 samples to be dehulled at one time. Results are presented as percent kernel removed and are related to retention time and flour colour after milling. The reproducibility of this device is very high, and about 40 test samples can be dehulled per hour.

2.3.5 Chemical dehulling of sorghum and millet

A number of chemical-dehulling methods have been proposed and used for a number of cereal grains. Pomeranz (1961) reviewed methods as applied to wheat, it was thought that these methods would also be effective with grain sorghum (Wall and Ross, 1970). Alkali debranning has been used for a number of cereal grains, including maize, barley, rye and oats to improve yield and provide attractive ready-to-eat products (Barta *et al.*, 1966). Alkali treatment under controlled conditions of temperature, alkali concentration and soaking duration has been shown to loosen and separate the seed coat from a number of grains including maize, and sorghum in wet milling for starch production purposes (Blessin *et al.*,

1970, 71; Mistry and Eckhoff, 1992). The loosened bran was then removed by vigorous washing with water followed by a warm dilute acid wash to restore surface whiteness. Enzymatic removal of the aleurone and bran layers has also been accomplished by treating cracked grains with 0.5% cellulase for two hours. An 80% yield of endosperm was obtained (Simon, 1962).

Several traditional methods in Africa are used to reduce the harmful effects of polyphenols in sorghum and millet. These include, soaking the grain in sour milk or in water with tamarind seeds in which case lactic acid or tartaric acids respectively bleach the seed coat pigments and polyphenols. Other communities germinate the grain in wet wood ash, under which conditions the alkali hydrolyses the tannins present in the grain.

2.4.6. Grain factors affecting dehulling quality of sorghum and millets

The key raw material characters for grain milling quality are the size, shape, and the structure of the seed, including the development of its outer (bran) layers and the endosperm hardness. Also of great importance for quality is the distribution of anti-nutritional factors such as tannin and phytic acid as well as other pigments among the botanical tissue components that are removed in milling and separation process (Munck, 1995). The dehulling quality attributes of sorghum and millets are intrinsically related to the grain physical and mechanical properties, the most important being the strength properties of the grain, which determines whether the grain is going to withstand the rigorous mechanical action exerted by the dehulling disk during the dehulling process. Soft grains tend to crack easily under the pressure of the abrasive surface resulting in the removal of fine material from all parts of the grain kernel rather than from the periphery regions only. Therefore hard grains are desirable for both mechanical and traditional dehulling methods (Reichert *et al.*, 1981).

Kernel texture, which is the proportion of corneous to floury endosperm within the kernel, is another property that affects the dehulling quality of sorghum and millet. Corneous

endosperm is harder and produces higher yields of grits with lower ash and fat content. Floury endosperm on the other hand tends to chip and shatter during abrasion. Thus in kernels with a higher percentage of corneous endosperm, the seed coat is more readily separated from the intact endosperm, giving a higher yield compared to kernels with high percentage of floury endosperm (Rooney and Miller, 1981; Maxson *et al.*, 1971).

Pericarp thickness is another factor which influences the performance of sorghum and millet grain in mechanical dehulling. All other parameters being equal, kernels with thin seed coats stand a better chance of giving a more satisfactory performance than those with thick seed coats in mechanical dehulling (Kapasi-Kakama, 1977). Endosperm recovery in mechanical dehulling is positively correlated to grain with both thin pericarp and corneous endosperm (Maxon *et al.*, 1971; Shephard, 1981; and Reichert *et al.*, 1982).

Pericarp colour is another kernel characteristic that is correlated to the dehulling performance of sorghum and millet. Grains with coloured pericarp have been found to give lower yields of dehulled products than grains possessing similar other characteristics but with white or light tan seed coat (Kapasi-Kakama, 1977). Seed coat adhesion strength is another important grain factor which affects the dehulling quality of sorghum and millet. Seed coat adhesion determines the amount of force required to remove the seed coat from the endosperm, therefore the lower the adhesion strength the less the force required and the less the likelihood of kernel breakage. Kernel size and shape have also been found to affect the dehulling performance. Plump, spherical kernels have been found to give better results than small oblong or flattened types. (Munck *et al.*, 1982).

2.5. Factors influencing acceptance of sorghum and millet

For consumer acceptance, prestige of the food is one of the most important characteristics. Though food is a physiological requirement, people often select a particular food for social reasons. In general sorghum and millet, like barley, carry among sophisticated people the

stigma of being considered coarse grain intended for animal feed, hence are not considered as socially acceptable as wheat, rice or maize. Sorghum and millet products have a low status as food not only because they are available at a cheaper price compared to other staples but because of certain poor food quality attributes of these grains (Desikachar, 1981). The dark colour, high fibre content, pronounced flavour and grittiness of their products are some of the disadvantages in using sorghum or millets in producing high status foods like bread, biscuits and pastries (Pushpamma and Vogel, 1981). In addition, sorghum and millet foods prepared from whole grain are low in digestibility compared to other cereals, especially those varieties with high tannin content (Hulse *et al.*, 1980).

The third factor, which is attributed to the low status of sorghum and millets foods, is the poor nutritive image, which is held not only by consumers but also by a number of sorghum and millet scientists. However, the adequacy of sorghum and millet based diets when consumed in a proper combination with other foods, has been tested in a longitudinal study with pre-school children (Pushpamma *et al.*, 1979) and proved to be adequately capable of supporting desirable growth.

Other factors, which appear to constrain a more widespread acceptance and use of sorghum and millet, include the lack of commercial mills specifically designed for sorghum and millet, which dehulls and grind the grains into flour. The lack of commercially processed sorghum and millet food products, which could be sold as snacks especially in urban centres, is another important factor (Perten, 1977).

2.5.1 Methods for improving the acceptability of sorghum and millet food products

Several approaches are being concurrently investigated to attempt to improve the acceptability of sorghum and millet products throughout the regions where sorghum and millet are consumed. The most efficient way of improving sorghum and millet utilisation is the

combination of better processing techniques with better varieties of sorghum. Breeding is a long-term approach whereas improved processing techniques are significant in both the long term and the short term (Rooney *et al.*, 1972).

The importance of improving the dehulling process for sorghum and millets so as to improve the quality of the final product and hence its acceptability has been reported by several workers (Desikachar, 1981; Badi and Hosney, 1976; Vogel and Graham, 1979; Hulse *et al.*, 1980). What remains now is the development of dehullers, which are efficient in dehulling of these grains. The following have been identified as some of methods that could improve consumer acceptability of sorghum and millet.

- (i) Refining and processing: The use of refined flours with pre-treatments like malting, pre-cooking, flaking, and puffing of sorghum grain or grits has been recommended for improving acceptability of sorghum products and for diversified food use (Raghavendra-Rao *et al.*, 1975).
- (ii) The use of composite flour: Several research studies have indicated the possibility of improving the utilisation of sorghum and millet flours by combining at various levels with wheat flour to form composite flours (Hart *et al.*, 1970; Narasinha *et al.*, 1974; Hulse *et al.*, 1980 and Dendy and Trotter, 1988). Such composite flours can be used for producing high status foods like bread, biscuits, and other snacks.
- (iii) Conversion of sorghum and millet products into high status foods. The possibility of feeding sorghum based diets in schools and pre-school centres has been tested and results were very encouraging (Pushpamma and Vogel, 1981). However, both the children and the parents accepted only when the sorghum and millet were processed and converted into high status foods similar to those prepared from wheat and rice.

2.6 Summary

Despite the delayed interest in research on sorghum and millets, this review revealed that substantial effort has been made by researchers to develop different milling methods and dehulling devices for sorghum and millets. The methods and devices have attracted a lot of research interest, to test and further improve the technology in different locations throughout the world. Both dry and wet processing methods have been used; each method may have a certain advantage over the other with regard to certain aspects, however, so far there is no single method that can claim to have been able to produce a product at both acceptable extraction rate (>80%) and refinement comparable to that of other cereal grains like maize or wheat (Munck *et al.*, 1982). It has also been difficult to compare results from different researchers because so far there is no any standardised grading system for sorghum or millets products comparable to that of wheat. Consequently, most of the results reported on sorghum and millets are empirical, highly variable and only indicative of the efficiency of the particular milling process used (Hulse *et al.*, 1980).

The need for more research to improve the existing milling devices and methods especially the dehulling stage is a challenge still facing researchers interested in the improvement of sorghum and millet products for human consumption. Of the many different methods of dehulling sorghum and millets, abrasive dehulling seems to have a big potential for more rapid and successful results (Reichert and Young, 1976; Hulse *et al.*, 1980). However, abrasive dehulling still needs further research and improvement in order to ascertain its suitability for grain with different characteristics especially the soft endosperm varieties. The rest of this thesis investigates ways by which the dehulling efficiency of sorghum and millet could be improved either using the existing dehulling equipment or in development of new designs in combination with different pre-treatments.

CHAPTER THREE

DETERMINATION OF PHYSICAL AND MECHANICAL PROPERTIES OF SORGHUM AND MILLET

3.1 Introduction

Physical and mechanical properties of agricultural materials are essential engineering data in design of machines, structures, processes and controls used in production, handling and processing. These material properties strongly influence the performance and efficiency of processing machines and equipment. In some machines this influence can be compensated for to some extent by use of simple setting devices. However, for most machines, raw material properties have a great influence on capacity and efficiency even if the machine settings are optimal. Knowledge of the physical and mechanical properties of agricultural materials is therefore essential if maximum efficiency and high quality end product is to be realised.

Many processing operations for agricultural materials are intended to alter the shape of the material by straining the material beyond its elastic limit through application of mechanical forces. Crushing of grain during milling is an example. In other operations, however, permanent deformation or crushing is a detrimental side effect of forces applied to achieve other results. In these instances, such as breakage of grain during dehulling, it is desirable to minimise or limit these resultant deformations, in which case the knowledge of the strength properties of the grain and how the grain behaves under different loading conditions is essential.

3.1.1 Physical properties

The basic physical properties of grain such as shape, size, volume, density, porosity and colour are important in the design of processing machines and in analysing their behaviour during actual processing situations. Shape and size influence stress distribution patterns in a material under the action of applied forces or system of forces, therefore shape and size of grain affect its damage resistance against applied loads. The size of the grain can be expressed in terms of kernel weight, arithmetic mean diameter, geometric mean diameter, or kernel volume. The shape of the grain kernel may be classified as flat or round depending upon its width and thickness criteria. The term 'sphericity', which is defined as the ratio of the volume of the grain to the volume of a circumscribed sphere, is commonly used to characterise grain shape.

Bulk density and kernel density are used as a measure of grain quality and in grading systems. Besides other factors both bulk density and kernel density greatly depend on the cellular structure of the grain. The cellular structure of a biological material has a great influence on its mechanical behaviour under load e.g. during mechanical processing (Singh, 1985). Hence the kernel density or bulk density may affect its fracture resistance due to different types of loading. The influence of physical properties of sorghum and millet kernels on their strength properties and behaviour during processing is relatively unknown, hence the need to study these properties and how they are affected by different process conditions.

3.1.2 Mechanical and viscoelastic properties

Mechanical properties of a material are those properties, which describe the behaviour of the material under the action of applied force (Mohsenin, 1986). The basic mechanical properties are strength, elasticity, ductility, resilience and toughness. Mechanical properties of biological materials are usually quantified in terms of force-deformation tests. By means of force-deformation diagrams or curves obtained from such tests, the mechanical properties can be

evaluated in a manner suitable for engineering purposes. The force-deformation curve defines how a material behaves under applied load and provides such data as force at yield and failure point, deformation at yield and failure, work or energy to yield and failure, and modulus of elasticity. These basic mechanical properties are important in understanding the response of a material to external forces such as those encountered during mechanical processing of grain.

It has long been recognised that biological materials display characteristics of both elastic bodies and viscous fluids when mechanically stressed (Mohsenin, 1986; Hemmerle and Mohsenin, 1970; Floyd *et al.*, 1979) and are therefore described as visco-elastic. Within the elastic deformation range, mechanical properties are a function of force and deformation, independent of time effects. Beyond this range mechanical properties are time dependent and are referred to as rheological properties (Mohsenin, 1986; Zoerb and Hall, 1960).

The study of this complex force-deformation-time behaviour (i.e. time dependent stress-strain relationships) fall under the general concept of rheology, which implies a combination of liquid-like and solid-like characteristics governed by the fundamental properties of elasticity, plasticity and viscosity. When the ratio of stress to strain involved is a function of time alone and not of stress magnitude, the material is said to be linear viscoelastic. However, if the viscoelastic behaviour is not only time but also stress magnitude dependent such that some of the resulting strain is non-recoverable upon unloading, the material is said to be non-linear viscoelastic (Mohsenin, 1986). On the basis of experimental evidence from different researchers (Mohsenin, 1963; Zoerb and Hall, 1960; Timbers *et al.*, 1965), the viscoelastic behaviour of agricultural materials under large strain is usually non-linear. However, from the practical engineering point of view and for small levels of strain, it is a usual practice to make simplifying assumptions and apply the theories of linear viscoelasticity to biological materials as in the case of engineering materials.

3.1.3 Importance of physical and mechanical properties of grain on dehulling of sorghum and millets

Dehulling of sorghum and millet involves mechanical manipulation of the grain. During this process, individual kernels are subjected to complex forms of forces that may include a combination of compressive, impact and abrasive forces. The resulting forces may cause physical damage to the kernels if the level of these forces is higher than the kernel's ultimate strength. Physical damage to the kernels often results in breakage and is manifested in the form of fine and broken materials which are removed with the hulls during aspiration or winnowing resulting in loss of endosperm.

The dehulling equipment and the practices associated with the dehulling process are primarily responsible for high losses and poor quality end product. Quality of the final product could be improved and losses minimised by making appropriate improvements in the equipment and practices employed in the present dehulling systems. For this to be possible, the interaction between the machine and grain properties must be clearly understood. Fracture caused by forces exerted on sorghum and millet kernels can be analysed with knowledge of the mechanical properties of the grain. Also knowledge of the grain's basic mechanical properties is a requirement for simulations and calculations to predict the behaviour of sorghum and millet under different types of loading.

3.1.4 Factors influencing physical and mechanical properties of agricultural materials

As already explained in previous sections, agricultural materials display characteristics of both elastic bodies and viscous fluids when mechanically stressed. Thus, improvements in processing operations which result in residual deformation of these materials, whether beneficial or detrimental, depend upon good understanding of the principles of rheology, the

study of deformation and flow. The inter-relationships between the three parameters of force, deformation, and time depend upon both the intrinsic and controllable properties of the material. The two principal controllable properties of a material during processing operations are moisture content and temperature.

The aim of the work in this section was, therefore, to determine the physical and mechanical properties of whole kernels of sorghum and millet and to study how these properties are affected by changes in grain moisture content and temperature, and hence establish a functional relationship between these variables and grain properties. Information on changes in physical and mechanical properties of individual kernels of sorghum or millets as their moisture content is increased e.g. during tempering, which is a usual practice in traditional dehulling and some of the mechanical dehulling systems, will be useful in future design of improved sorghum and millet processing equipment and improvement of the efficiency of current systems.

3.2 Review of related literature

A review of pertinent literature produced no evidence of previous work on the physical or mechanical properties of sorghum and millets. However, the response of other cereal grains and grain legumes to mechanical loading has been a subject of numerous research investigations. Studies of the responses of cereal grains to mechanical stresses have progressed from analyses as simple Hookian models to the generalised Kelvin and Maxwell models used singly or jointly. Moisture content, which is considered to be of greater importance than temperature in influencing mechanical properties of grain, was first studied in detail by Barkas (1953), who concluded that water held by molecular forces, rather than capillary water affected visco-elastic responses. This implies a greater effect of moisture content at the lower moisture levels. Shpolyanskaya (1952) studied the structural and mechanical properties of wheat grain. Upon repeated uniaxial loading it was found that the load-deformation behaviour of wheat kernels approached that of an elastic body and by

applying the Hertz theory of contact stresses, a modulus of elasticity for wheat was evaluated. The effect of moisture content on mechanical properties of wheat was also investigated and it was found that wheat grain underwent a plastifying effect upon absorbing moisture, which became evident at lower values of the limiting stress under uniaxial compression.

Zoerb and Hall (1960), in their study of core samples of wheat grain, noted the same strain hardening tendencies but concluded that plastic rather than elastic behaviour characterised the mechanical properties of wheat. Shelef and Mohsenin (1967) applied the Hertz theory for compression of convex bodies and Boussinesq's solution for semi-infinite bodies to maize and wheat kernels and determined modulus of elasticity of maize and wheat at different moisture contents. Their results supported the findings of earlier studies on wheat by Zoerb and Hall (1960) that elastic properties were evident at lower moisture levels and plastic properties prevailed at higher moisture levels. Mohsenin *et al.* (1971) used a spherical indenter to determine the shear and creep compliance of a slab of maize horny endosperm at different moisture contents. Their analysis demonstrated the utility of the creep test to determine the visco-elastic parameters.

Stewart (1964) using tri-axial tests reported the dependence of bulk mechanical properties of grain upon moisture content. Hoki and Tomita (1976) also evaluated moisture effects on mechanical properties of soybeans using rectangular parallel piped specimen in compression as well as tension. Hoag (1972), also working on soybean, showed that the energy absorption of soybean pods due to shatter was proportional to moisture content. Paulsen (1978) studied the effect of moisture on fracture resistance of intact soybean in terms of compressive force, deformation and toughness at seed coat rupture. In all these investigations it was found that all the strength parameters of the grain decreased as the moisture content increased.

3.3 Theoretical background

3.3.1 Rheological models

When a material is subjected to varying conditions of stress or strain, two extremes in behaviour may occur. The material may undergo a pure viscous flow of a Newtonian fluid (represented by a dashpot) or pure elastic deformation of a Hookean solid (represented by a spring). In reality, however, as it has already been noted from previous sections, biological materials exhibit both viscous and elastic behaviour (Mohsennin, 1986; Hammerle and Mohsennin, 1970; Pappas *et al.*, 1988). In rheology, phenomenological models consisting of a suitable combination of springs (obeying Hooke's law) and dashpots (obeying Newton's law) are normally used to explain and interpret the mechanical and rheological behaviour of a material when subjected to external forces. The models are supposed to behave qualitatively to some degree of approximation in a manner similar to that of the actual material. If the mechanical behaviour can be expressed in terms of force, deformation and time, the result can lead to a rheological equation. Such an equation can be used to explain, and in certain cases predict the behaviour of the material under various loading conditions.

The two basic units in these mechanical models are the Kelvin (or Voigt) and Maxwell models, which are illustrated in figure 3.1(a) and 3.1(b) respectively. The Kelvin model consists of a spring and dashpot in parallel; when subjected to a constant strain both the spring and the dashpot are required to move together at a constant rate. The Maxwell model consists of a spring and dashpot in series. When subjected to a constant strain, initially all the energy goes into stretching the spring; however, with time the dashpot gradually dissipates energy by its constant rate movement resulting in an exponential decay of stress in the system. The stress decay equation for a Maxwell model subject to a constant strain can be written as (Rao *et al.*, 1975):

$$\sigma_{(t)} = \sigma_0 \exp\left(-\frac{t}{\tau}\right) \quad (3.1)$$

where σ_0 is the initial stress (MPa) and $\sigma_{(t)}$ is stress at time t (MPa) and τ is the relaxation time (s) which determines the rate of stress decay.

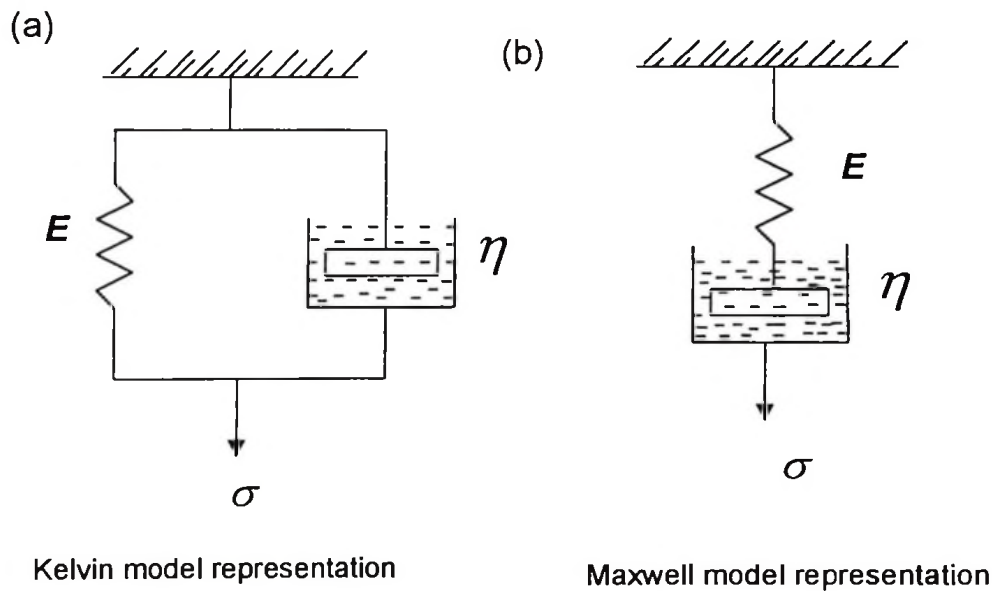


Figure 3.1 Kelvin and Maxwell models

(From Mohsenin, 1986)

Due to the complexity of the mechanical behaviour of most agricultural materials, single element models are often inadequate to describe or represent their visco-elastic behaviour, in which case, the models may require in theory an infinite number of basic units. The specific number and combination of individual elements required to represent a material depends on the structure and physical characteristics of the material together with the behaviour of the material under varying physical loading conditions. Therefore, a generalised Maxwell model consisting of several Maxwell elements with a spring in parallel with the n^{th} element (if the stress does not decay to a zero value after very long time) as illustrated in figure 3.2 is

usually preferred to describe the behaviour of agricultural materials realistically. Upon the application of constant strain or deformation, the visco-elastic function exhibited by the model is of the form:

$$E_{(t)} = E_{\infty} + \sum_{i=1}^n \left[E_i \exp\left(-\frac{t}{\tau}\right) \right] \quad (3.2)$$

where: $E_{(t)}$ is the relaxation modulus at time t (MPa), n is an integer constant, E_i is the decay modulus of the i^{th} Maxwell element (MPa), T_i is the time of relaxation of the i^{th} Maxwell element given as $\left(T_i = \frac{\eta_i}{E_i}\right)$, E_{∞} is the equilibrium modulus after infinite time (MPa) and η_i is the viscosity of the i^{th} viscous element. If no residual stress remains the E_{∞} term is omitted.

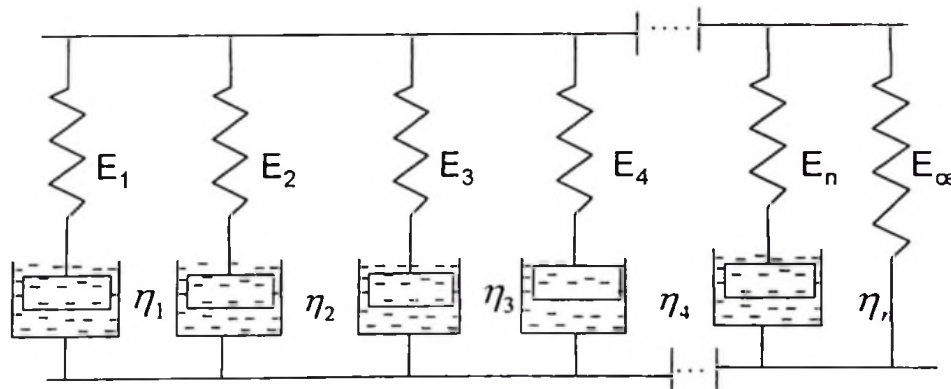


Figure 3.2 Generalised Maxwell model representation
(From Mohsenin, 1986)

Experimental evidence has also shown that biological materials exhibit more than one relaxation or retardation time (Mohsenin, 1986). For these materials a single Kelvin model is inadequate to represent their visco-elastic behaviour. To represent the visco-elastic behaviour of such materials realistically, a chain of Kelvin models each with its own time of retardation is usually used. The model is known as a generalised Kelvin model and it consist of n Kelvin elements connected in series with an initial spring and a final viscous element as shown in figure 3.3. The creep behaviour for this model can be expressed by the following equation:

$$\varepsilon_{(t)} = \frac{\sigma_0}{E_r} \left(1 - e^{-\frac{t}{\tau_{ret}}} \right) \quad (3.3)$$

where $\varepsilon_{(t)}$ is strain at time t , σ_0 is the initial stress (MPa), E_r is retardation modulus of elasticity (MPa), τ_{ret} is time of retardation (s).

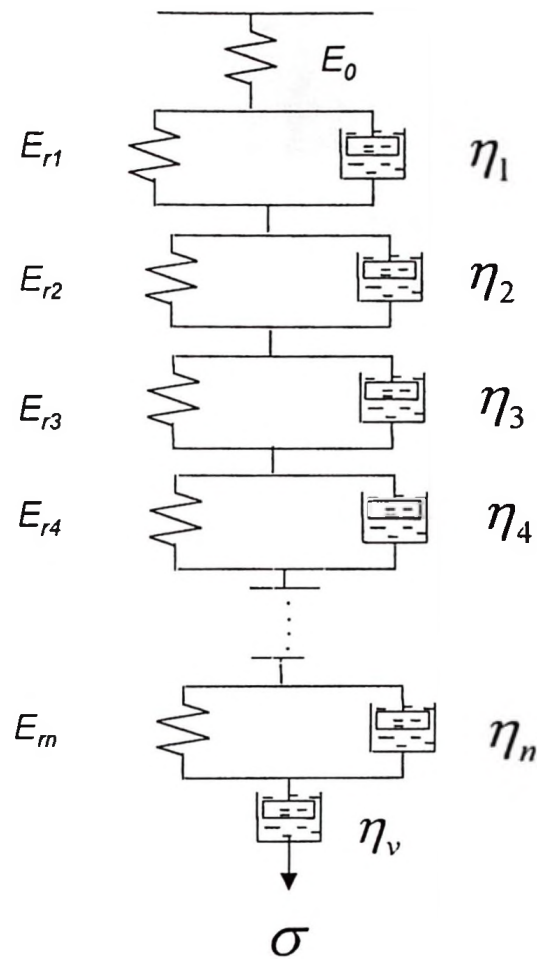


Figure 3.3 Generalised Kelvin model

(From Mohsenin, 1986)

3.3.2 Rheological tests

There are a number of test procedures which may be used to study viscoelastic materials such as biological materials in order to determine the relationship between stress, strain, and time for a given type of deformation and a given type of loading pattern. The most important tests include creep-recovery, stress relaxation and stress-strain (compression) tests.

3.3.2.1 Creep - recovery test

In this test, the load is suddenly applied and held constant. The deformation of the material is then measured as a function of time. The rheological model usually used to represent the creep behaviour is a combination of Maxwell and Kelvin models in series known as the four-element Burgers model (figure 3.4). The rheological equation for this model was given by Morrow (1965) in the following form:

$$\varepsilon_{(t)} = \sigma_0 \left[\frac{1}{E_0} + \sum_{i=1}^n \frac{1}{E_n} \left(1 - e^{-\frac{t}{T_n}} \right) + \frac{t}{\eta_v} \right] \quad (3.4)$$

where $\varepsilon_{(t)}$ is the strain at time t , σ_0 is constant applied stress (MPa), E_0 is the instantaneous modulus or modulus at zero time (MPa), E_n is the retarded modulus of elasticity of the i th Kelvin element (MPa), T_n is the retardation time of the i th Kelvin element (s) given as

$\left(T_n = \frac{\eta_v}{E_n} \right)$, η_v is the viscosity of the i th Kelvin element, and n is an integer constant.

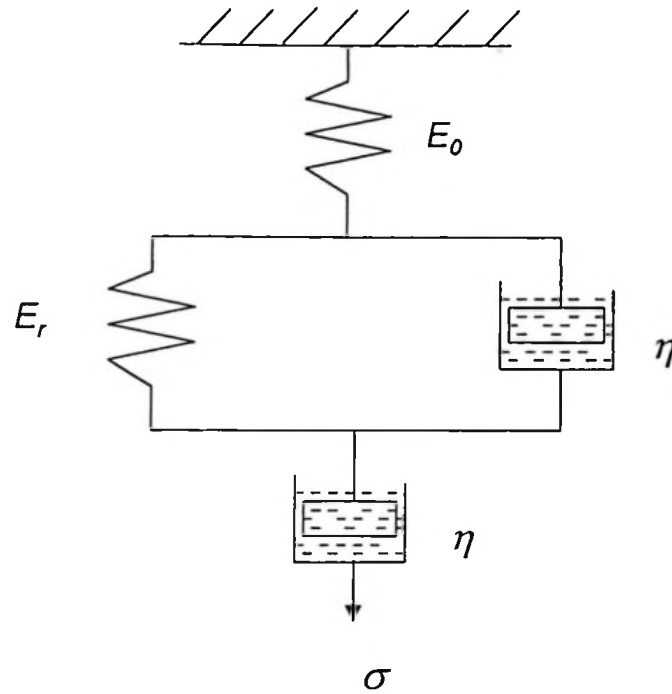


Figure 3.4 Four-element Burgers model
(From Mohsenin, 1986)

3.3.2.2 Stress-relaxation test

Stress-relaxation is the reduction in stress with time in a material subjected to a constant strain. This occurs when the test specimen is rapidly brought to a given deformation (strain) and the force (stress) required to hold the initial deformation constant is measured as a function of time. A series of one or more Maxwell bodies (a spring and a dashpot in series) are usually used to represent biological materials under conditions of stress-relaxation (figure 3.2). The general differential equation for Maxwell model (spring and dashpot in series) representing stress-relaxation behaviour is given as:

$$\frac{d\sigma}{dt} = E \frac{d\varepsilon}{dt} - \frac{\sigma}{\tau} \quad (3.5)$$

If the material is subjected to an instantaneous strain which is then kept constant over time

then, since deformation rate is zero, the term $E \frac{d\varepsilon}{dt} = 0$

By integration equation (3.5) becomes:

$$\sigma = \sigma_0 \exp\left(-\frac{t}{\tau}\right) \quad (3.6)$$

where σ_0 is the initial stress when $t=0$

If there is residual stress in the material after a very long time, then there is need to add a constant σ_e to represent this residual stress.

The variation of stress with time is then described by the equation

$$\sigma_{(t)} = \sigma_d \exp\left(-\frac{t}{\tau}\right) + \sigma_e \quad (3.7)$$

where σ_d is the stress drop during stress decay (MPa) and σ_e is the residual stress (MPa) when equilibrium has been attained.

This shows that stress decays exponentially with time and one would expect a linear relationship between stress and time on a semi-log scale. The relaxation time is the time for the initial stress to relax to its original value and is a measure of how fast a material can dissipate stress after receiving a sudden deformation. It is therefore considered an important rheological property of a material during processing.

3.3.2.3 Stress-strain or compression test

Four methods are commonly used for determination of mechanical properties of grain under compression. These include; (i) loading the grain by a spherical indenter, (ii) loading the grain by a cylindrical rigid die, (iii) cutting the grain ends off and loading between parallel plates and (iv) loading the whole grain kernel between parallel plates.

3.3.2.3.1 Compression by means of parallel plates

The application of normal stress and strain equations for uniaxial compression tests on convex sections of biological materials is not possible due to the irregular shape and size of most agricultural materials. An alternative method for determining the response of such materials to mechanical loading is by the use of Hertz's theory by replacing the force F with time dependent force $[F(t)]$. This substitution transforms Hertz's equation into the following for compression between parallel flat plates (Mohsenin, 1986; Pappas *et al.*, 1988).

$$E(t) = \frac{0.338k^{3/2}F(t)(1-\nu^2)}{D^{3/2}} \left(\frac{1}{R_{\min}} + \frac{1}{R_{\max}} \right)^{1/2} \quad (3.8)$$

where $E(t)$ is the modulus of elasticity at time t (MPa), k is a factor, which depends on the geometric property of the contacting bodies, $F(t)$ is the applied uniaxial compression load (N) at any time t , ν is the Poisson ratio of the body (dimensionless), D is the combined deformation of contacting bodies (mm), and R_{\max} and R_{\min} are maximum and minimum radii of curvature of the body.

In the case of parallel plate loading, the radii of curvature of the steel plates are considered to be infinite so;

$$\frac{1}{R_2} = \frac{1}{R_2} = 0 \quad (3.9)$$

The use of equation (3.8), however, requires that certain fundamental assumptions be satisfied. Kozma and Cunningham (1962) discussed these assumptions in detail. They include: the radii of curvature of the contacting bodies are assumed to be large when compared with the dimensions of the contacting area, the material is both homogeneous and isotropic, Hooke's law holds and the loads applied are static. Morrow (1965) discussed these

assumptions as applied to agricultural materials and products, and an example for satisfying the assumptions of a semi-infinite body has been given by Morrow and Mohsenin (1966).

3.3.2.3.2 Compression by means of a smooth spherical indenter

Hertz solution for contact stress between two elastic convex bodies can be applied to yield the following equation for calculation of the apparent modulus of elasticity for a grain kernel loaded by means of a smooth spherical indenter;

$$E(t) = \frac{0.338k^{\frac{3}{2}}F(t)(1-\nu^2)}{D^{\frac{3}{2}}} \left(\frac{1}{R_{\min}} + \frac{1}{R_{\max}} + \frac{4}{d_2} \right)^{\frac{1}{2}} \quad (3.10)$$

Under these conditions,

$$\frac{1}{R_2} = \frac{1}{R_2'} = \frac{2}{d_2} \quad (3.11)$$

where d_2 is the diameter of the spherical steel indenter, R_2 and R_2' are the major and minor radii of curvature of the spherical indenter respectively.

3.3.2.3.3 Compression by means of a cylindrical indenter

Bousinesq (1885) first proposed the original solution for evaluation of stress-strain relations for semi-infinite bodies loaded by cylindrical rigid indenter. Later this solution was expanded by Timoshenko and Goodier (1951). According to this solution, when a rigid indenter in the form of a circular cylinder is pressed against the plane boundary of a semi-infinite elastic solid, while the displacement D is constant over the circular base of the indenter, the distribution of pressure q is given by the following equation:

$$q = \frac{P}{2\pi a(a^2 - r^2)^{\frac{1}{2}}} \quad (3.12)$$

where P is the load on the indenter, a is the radius of the indenter, and r is the distance from the centre of the circle on which the pressure acts. Equation (3.12) indicate that, the pressure is smallest at the centre where $r = 0$ and it becomes infinite at the boundary of the same area where $r = a$. The modulus of elasticity of the compressed material E is given by the following equation (Arnold and Roberts, 1969);

$$E(t) = \frac{P(1 - \nu^2)}{2aD} \quad (3.13)$$

where D is the displacement of the indenter and ν is Poisson's ratio. As in the case of Hertz's solution, the use of equation (3.13) requires that the fundamental assumptions of elasticity, homogeneity, semi-infinite body etc. be valid.

3.4 Experimental procedures

3.4.1 Determination of physical properties of sorghum and millet

3.4.1.1 Materials

3.4.1.1.1 Grain samples

Seven sorghum varieties (Dionje, Pato, Tegemeo, Mbagala, WS, RS and Jumbo) and four varieties of pearl millet (Okoa, Uwele, IM and ILM) were used in this study. The grain samples were obtained from Ilonga Agricultural Research Station, Tanzania and International Crop

Research Institute for the Semi-Arid Tropics (ICRISAT), India. The initial moisture content of the grain was determined by oven drying of representative samples according to ASAE standards S 352.2 (ASAE, 1991). Prior to performing any test the grain was cleaned and graded using a round-hole sieve to remove the undersize and oversize grain and any foreign matter present. For sorghum, kernels passing through 5 mm but retained on 3-mm sieve were used in the tests while for millet, grain passing through 4 mm and retained on 2 mm sieve except for uwele was used for the tests.

3.4.1.1.2 Equipment

The following equipment were used: a micrometer screw gauge for kernel dimension determination, a pycnometer bottle for specific gravity determination, a hot air oven for moisture content determination and a round hole sieve for cleaning and grading the grain.

3.4.1.2 Methods

The following grain physical properties were determined: kernel principal dimensions, shape, weight, volume, bulk density, kernel density and porosity. All these properties were determined at four different moisture levels ranging from 12 to 25% db. for twenty replications at each moisture level. All the experiments were carried out at room ambient conditions of temperature and relative humidity (20^oC and 70% RH). To determine the grain principal dimensions, approximately 100 grains were taken randomly from the main sample and from these sub-samples 20-grains were randomly picked and each labelled for easy identification. For each grain kernel the three principal dimensions, i.e. length (L), width (W), and thickness (T) were measured as accurately as possible using a micrometer screw gauge reading to 0.01 mm. These principal dimensions were later used to calculate other geometrical parameters of the grain. These follow.

3.4.1.2.1 The geometrical mean diameter (D_{GM})

The geometric mean diameter of individual grain kernel was calculated as (Mohsenin, 1986):

$$D_{GM} = (LWT)^{\frac{1}{3}} \quad (3.14)$$

where L is the length of the grain, W is the width of the grain and T is the grain thickness

3.4.1.2.2 Sphericity

The grain sphericity, which is the grain roundness index, was calculated as (Mohsenin, 1986);

$$\text{Sphericity} = \left(\frac{\text{Volume of grain kernel}}{\text{Volume of circumscribed sphere}} \right)^{\frac{1}{3}} \quad (3.15)$$

or

$$\text{Sphericity} = \frac{\text{Geometric mean diameter}}{\text{Major diameter}} = \frac{(LWT)^{\frac{1}{3}}}{L} \quad (3.16)$$

3.4.1.2.3 Surface area (S)

The grain kernel surface area was calculated as (Deshpande *et al.*, 1993);

$$S = \pi D_{GM}^2 \quad (3.17)$$

3.4.1.2.4 Thousand grain weight (W_{1000})

Thousand-grain weight was determined by weighing 100 randomly selected grain kernels on a chemical balance accurate to 0.001 g. and multiplying the result by 10.

3.4.1.2.5 Grain volume, Density and specific gravity

The grain kernel volume and density was determined by the liquid displacement method using toluene. A fifty-kernel sample displacement was measured with aid of toluene and a measuring cylinder. The kernel volume was determined by dividing the displaced toluene volume by the number of kernels used in the sample. The grain density and specific gravity was determined by pycnometer method. Since the density of water is approximately equal to one, the density of the grain sample was equal to the specific gravity of the sample.

3.4.1.2.6 Porosity

The porosity of the grain sample, which is the percentage of volume of voids in the grain sample at given moisture content, was calculated from the following relationship;

$$Porosity = \left(1 - \frac{\rho_b}{\rho_k}\right) 100 \quad (3.18)$$

where ρ_b is the bulk density and ρ_k is the kernel density

3.4.2 Mechanical property tests

Mechanical properties of sorghum and millet were studied using quasi-static compression tests. As discussed in section 3.3.2.3, four main methods are commonly used for the determination of the mechanical properties of grain. The conventional parallel plate compression of whole grain kernel duplicates more closely the actual conditions likely to be encountered during abrasive dehulling process, and was therefore selected as the most suitable technique for determining the mechanical behaviour of the grains under quasi-static (low speed) compression. The compressive mode of loading was adopted because during

abrasive mechanical dehulling, the grains are more likely to be subjected to compressive loads than tensile or impact loads.

3.4.2.1 Equipment and instrumentation

Quasi-static compression tests were performed using a J.J. universal tensile testing machine (Model T20K, J.J. Lloyd Instruments Ltd.) operated in compression mode and equipped with a 500-N load cell and parallel plates. A deformation rate of 1.25 mm/min was used in all compression tests as recommended by the ASAE standards S.368.3 for compression of food materials of convex shape (ASAE, 1995). The data obtained was fed directly into a computer from which force deformation curves were drawn and analysed.

3.4.2.2 Grain samples

The same grain varieties used in determination of physical properties were used in mechanical property tests. Before the tests, all grain kernels to be tested were examined for cracks using a magnifying glass. Kernels with cracks were discarded.

3.4.2.2.1 Conditioning of grain samples

The grain samples were conditioned to four different moisture levels ranging from 12% to 25% db (i.e. 12, 15, 20 and 25%) by adding calculated amounts of distilled water to pre-weighed grain samples. The grain samples were then thoroughly mixed, sealed in air tight glass bottles and stored in a cold room at 5⁰C for 14 days to allow the moisture to be evenly distributed throughout the sample and within individual grain kernels. Just before performing the tests, the required quantity of grain was taken out of the cold room and allowed to warm up to room temperature (20⁰C). The moisture content of the grain was determined again to establish the actual grain moisture content during the tests.

3.4.2.2.2 Tempering of grain samples

Grain samples at 12% mc db were removed from the cold room and allowed to equilibrate to room temperature, after which the samples were tempered by addition of 20% by weight distilled water and mixed thoroughly. Each sample was then divided into four sub-samples, sealed in air-tight glass bottles and allowed to rest for three different durations i.e. 15, 30, and 60 minutes before compression test were performed. The addition of 20% by weight of water was used here because this is the average amount of water usually added to the grain in the traditional dehulling method (Egum *et al.*, 1982).

3.4.2.3 Experimental procedure

3.4.2.3.1 Mechanical properties tests

Quasi-static compression tests were performed on individual grain kernels conditioned to four moisture levels as explained above. In all compression tests, twenty kernels were selected randomly from the conditioned grain sample and slowly loaded to their break point. Break point in this case was defined as the point on the force-deformation curve where there was an increase in strain with no accompanying increase in stress i.e. the point on the force deformation curve where the force decreased or remain constant as strain continued to increase.

The simulation of the type of loading conditions on sorghum grain which are likely to be encountered in practice during processing required consideration of three different kernel configurations. These could be classified in decreasing order of stability as, lying flat (hilum facing down), lying on the side (hilum on the side) or standing on the end. In this study, the effect of kernel loading orientation or position was investigated by loading the grain in either flat loading position (i.e. with the hilum side flat on the metal plate) or side loading position

(with the hilum on the side). Millet was loaded on one side only (with the hilum side lying flat on the plate). Prior to loading, the thickness of each kernel was measured with a micrometer screw gauge and then individual kernels were cemented on a flat plate using a quick setting glue. This was done to prevent the kernel from rolling or slipping during loading and also to prevent kernel deformation on the lower side.

Force-deformation curves obtained at different moisture levels were analysed to evaluate the different mechanical properties of the grain. These included maximum force or load at break point of the grain kernel, deformation at break point, ultimate stress (stress at break point), ultimate strain (strain at break point), and modulus of deformability (i.e. modulus based on the first loading cycle). ASAE standard 368.3 (ASAE, 1995) specifies that the modulus of elasticity is calculated using only elastic deformations, and modulus of deformability is determined as the sum of both elastic and plastic deformations. To separate elastic and plastic deformations, an unloading force-deformation curve is required. No unloading force-deformation curve is required to calculate the modulus of deformability. Shpolyanskaya (1952) suggested that the modulus of deformability is of practical significance in processing because it reflects the mechanical properties of the grain in the form in which it arrives at the mill. Shelef and Mohsenin (1967) agreed with this suggestion. Therefore in this study modulus of deformability of the grain was considered of more importance than modulus of elasticity. Other properties determined from the force-deformation curves included energy required to deform the grain kernel to its break point and modulus of toughness, which is defined as the energy per unit volume required to rupture the grain kernel.

The modulus of deformability was calculated from the following equation (Mohsenin, 1986), assuming all the assumptions listed by Kozma and Cunningham (1962) hold for sorghum and millet.

$$E(t) = 0.531 \frac{(1 - \nu^3)}{D^{\frac{3}{2}}} F(t) \left(\frac{1}{R_1} + \frac{1}{R_1'} \right)^{\frac{1}{2}} \quad (3.19)$$

where ν is the Poisson ratio, F is the force producing deformation midway between the origin and the linear limit, D is the deformation, R_1, R_1^* are radii of curvature of the grain kernel. The radii of curvature were determined according to ASAE standard S368.3 for compression of agricultural materials (ASAE, 1995).

Other parameters such as ultimate strain, the maximum load and deformation at kernel break point were determined directly from the force-deformation curve as the strain, load and deformation at the break or rupture point. The modulus of toughness was determined by computing the area under the force deformation curve up to the kernel rupture point and dividing this area by the kernel volume. The rupture point in this case referred to the point on the force deformation curve characterised by a sudden drop in applied force as deformation increased. Energy at the break point was also determined by calculating the area under the force-deformation curve to the break point.

3.4.2.3.2 Effect of tempering on mechanical properties of the grain

To investigate the effect of tempering duration on the mechanical properties of sorghum and millet, grain kernels tempered for three different durations, (15, 30, and 60 minutes) were quasi-statically compressed. The same procedure was followed as in the case of mechanical property tests. All experiments were carried at ambient laboratory conditions.

3.4.2.3.3 Effect of temperature on mechanical properties of sorghum and millet

The effect of temperature on the mechanical properties of sorghum and millet was investigated at three temperatures i.e. 20, 30, and 50°C. The grain samples were equilibrated at the required temperature by placing the grain samples in an air tight bottles in a water bath

maintained at the required temperature $\pm 0.1^{\circ}\text{C}$ for one hour before tests were carried out. The compression machine was also enclosed in a plywood chamber maintained at $30\text{-}40^{\circ}\text{C}$ to prevent rapid fall in sample temperature during compression at 40 and 50°C temperatures. Compression tests were repeated as outlined in section 3.4.2.3.1 to obtain force-deformation curves for individual kernels at each temperature level from which the grain mechanical properties at different temperatures were evaluated. Twenty replications were carried out at each temperature for each grain variety.

3.4.2.3.4 Rheological tests

Rheological tests were confined to the determination of stress-relaxation behaviour of sorghum and millet kernels under compression. Grain from the same batch as that used for mechanical compression tests was used.

Two varieties of sorghum (Dionje and RS) and two millet varieties (Oka and IM) were used in these tests. Individual kernels glued to metal plates were subjected to compression to a given load (50 N) at a fixed rate of deformation (1.25 mm/min), the deformation was then held constant and the decay of force as a function of time was recorded. The tests were repeated at four different moisture levels i.e. 12, 15, 20, 25% (db) and replicated 10 times. The resulting data were analysed by plotting the logarithm of the relaxation force against time from which the number of Maxwell elements and relaxation time for each sample at each moisture level was evaluated.

There are different ways by which the force-time curves can be analysed to determine the number of Maxwell units needed to represent the stress-relaxation behaviour of the material under test. One of the widely used methods is the method of 'successive residuals' described by Mohsennin (1986) and used by Zoerb and Hall (1960). The method involves plotting the difference between the log values of the original curve and the extrapolated straight line from the original curve on the same axis. Typical results of such plots are shown on figures 3.24

and 3.25. It can be seen that after about 10 minutes relaxation the force-time curve became a straight line; if this straight line is extrapolated to the ordinate it can be represented by an equation of the form

$$Y_1 = A_1 \exp\left(-\frac{t}{\tau_1}\right) \quad (3.20)$$

where Y_1 is log (force), A_1 is a constant.

If the difference between this line and original curve is plotted on the same axis a second curve is obtained which can be represented by the equation

$$Y_2 = A_2 \exp\left(-\frac{t}{\tau_2}\right) \quad (3.21)$$

The original curve can now be represented by a two term exponential equation of the form:

$$Y = A_1 \exp\left(-\frac{t}{\tau_1}\right) + A_2 \exp\left(-\frac{t}{\tau_2}\right) \quad (3.22)$$

This process was repeated until an approximately straight line was obtained. Three residuals were sufficient to represent the rheological behaviour of sorghum and millet. The constants A_1 , A_2 , and A_3 were evaluated for each term by setting $t = 0$ to obtain the y-intercepts. The time constants, which also represent the relaxation time, were evaluated from the slopes of the extrapolated straight lines as (Mohsenin, 1986);

$$\tau = \frac{t_2 - t_1}{\log(F_1) - \log(F_2)} \quad (3.23)$$

Since the deformation of the grain kernels under load was held constant, it was assumed that the loaded area of contact remained constant during the relaxation tests and the recorded

force-time curve was representative of stress-time curve. Since stress is force divided by the area (which was assumed constant) the shape and the time constants of the curves were unaltered by plotting force instead of stress against time (Zoerb and Hall, 1960; Mohsenin, 1986).

3.5 Determination of endosperm texture

The endosperm texture which is the proportion of the corneous (hard) to floury (soft) endosperm present in the kernel was evaluated by sectioning twenty kernels randomly picked from each sample and visually assess the proportion of the two types of endosperm as shown in Table 3.1. The mean values from the twenty-grain kernels from each sample was calculated and used to classify the sample as either corneous (hard), intermediate, or floury (soft). The floury type was given a score less than 2.5, the intermediate type a score between 2.5 and 3.9, and the corneous type a score greater than 4.

Table 3.1 Classification of the sorghum and millet endosperm texture

Floury proportion (%)	Corneous proportion (%)	Score
100	0	1
75	25	2
50	50	3
25	75	4
0	100	5

Source: Kapasi-Kakama (1977)

3.6 Results and discussion

3.6.1 Grain physical properties

3.6.1.1 Grain dimensions and shape

The average values of the three principal dimensions of the grain kernels (length, width and thickness) determined in this study are presented in Table 3.2 for both sorghum and millet. The results showed that for sorghum, the grain thickness (T) was the smallest grain dimension and the difference between kernel length (L) and width (W) was much smaller compared to the difference between these two dimensions and grain thickness (T), thus resulting in a flattened sphere shape. For millet, however, the difference between kernel width and thickness were smaller compared to the difference between these two dimensions and kernel length (L), thus forming a cono-spherical shape (i.e. tear or liquid drop shape). In this shape, the second largest and smallest principal dimensions form a spherical base.

Kernel shape was expressed in terms of sphericity or degree of roundness, which expressed how close the grain kernel shape, approached a sphere. The results are also summarised in Table 3.2. Average sphericity for sorghum was 75% while for millet it was 71%, which shows that, on average sorghum kernels for the varieties used in this study were more spherical compared to millet kernels as indicated by their higher sphericity. There was no significant difference ($P < 0.05$) in kernel shape between different varieties for both sorghum and millet.

3.6.1.2 Grain colour

All sorghum varieties used in this investigation were white in colour except RS and Jumbo, which were red. All millet varieties were grey in colour. Grain colour is an important factor in the milling of these two grains because consumer preference of products made from these

grains may be influenced by the colour of the products. Most consumers prefer white flour, for production of speck-less white products. Grain with coloured pericarp have been found to give lower yield of dehulled products than grains possessing similar other characteristics but with a white or light tan seed coat (Kapasi-kakama, 1977).

Table 3.2 Sorghum and millet kernel physical dimensions and shape

Grain variety	L (mm)	W (mm)	T (mm)	D _{AM} (mm)	D _{GM} (mm)	S (mm ²)	Sphericity (%)
1. Sorghum							
Dionje	4.96	3.87	2.23	3.68	3.49	38.3	71
Mbagala	4.83	3.92	2.29	3.68	3.51	38.7	73
Pato	4.75	4.10	2.78	3.87	3.78	44.9	80
Tegemeo	4.37	3.91	2.57	3.62	3.53	39.2	81
RS	4.33	3.47	2.51	3.43	3.35	35.3	77
WS	3.94	2.84	2.05	2.95	2.85	25.4	72
2. Millet							
Okoa	3.83	2.60	2.60	3.01	2.83	25.2	75
Uwele	3.41	1.84	1.84	2.36	2.26	16.0	66
IM	3.56	2.47	2.47	2.85	2.79	24.6	77
ILM	3.55	2.00	2.00	2.51	2.42	18.3	68

* L is the major diameter (length), W is the intermediate diameter (width), T is the minor diameter (thickness), D_{AM} = Arithmetic mean diameter, D_{GM} = Geometric mean diameter.

3.6.1.3 Grain weight

Grain weight was expressed in terms of a thousand-grain weight. The one thousand-grain weight for sorghum ranged from 40.6 g to 21.2 g while for millet the range was between 17.1 g and 8.2 g per 1000 kernels (Table 3.3), which is similar to values reported in literature (Sergio

and Rooney, 1995). There was a significant difference ($P < 0.05$) in thousand kernel weight between varieties for both sorghum and millet. Among the sorghum varieties WS had the smallest thousand-grain weight and also the smallest kernel size, while for millet, Uwele had the smallest grain weight and smallest grain size.

Table 3.3 Grain weight, kernel volume, kernel specific gravity and density

Grain variety	W_{1000} (g)	kernel volume (mm^3)	kernel density (g/mm^3)	Specific gravity
(1) Sorghum:				
Dionje	32.6	0.026	1.32	1.32
Mbagala	30.8	0.023	1.35	1.35
Pato	40.6	0.030	1.33	1.33
Tegemeo	33.9	0.027	1.30	1.30
RS	25.9	0.020	1.29	1.29
WS	21.2	0.016	1.37	1.37
Jumbo	33.5	0.028	1.28	1.28
(2) Millet:				
Okoa	17.1	0.014	1.30	1.30
Uwele	8.2	0.007	1.30	1.30
IM	15.0	0.012	1.30	1.30
ILM	9.0	0.008	1.32	1.32

W_{1000} – Thousand grain weight

3.6.1.4 Kernel density and specific gravity

The results for kernel density and specific gravity are summarised in Table 3.3. Since the density of water is $1.0 \text{ g}/\text{mm}^3$ the kernel density was equal to specific gravity. For sorghum,

kernel density varied from 1.35 g/mm³ to 1.28 g/mm³, whereas for millet the kernel density varied from 1.32 g/mm³ to 1.30 g/mm³.

3.6.1.5 Endosperm texture classification

The results for endosperm texture classification are summarised in Table 3.4. Among the seven sorghum varieties evaluated, two varieties (Dionje and WS) were classified as Corneous (or hard), three varieties (Mbagala, Pato and Tegemeo) as intermediate and two (RS and Jumbo) as floury (or soft). For millet, two varieties (Uwele and ILM) were classified as Corneous and two varieties (Okoa and IM) as intermediate.

Table 3.4 Endosperm texture classification for sorghum and millet varieties

Grain variety	Texture rating	Texture class
(1.) Sorghum		
Dionje	4.5	Corneous
Tegemeo	3.0	Intermediate
Pato	3.0	Intermediate
Mbagala	3.0	Intermediate
W.S	4.8	Corneous
R.S	1.5	Floury
Jumbo	1.5	Floury
(2) Millet		
Okoa	3.0	Intermediate
Uwele	4.0	Corneous
IM	3.0	Intermediate
ILM	4.0	Corneous

*4.0 - 5.0 Corneous (hard), 2.5 – 3.9 intermediate, 0 - 2.5. floury (soft)

3.6.2 Effect of moisture content on the physical properties of sorghum and millet

Two varieties of sorghum, Dionje (hard Corneous variety) and Jumbo (soft floury variety) and one variety of millet (IM) were used to investigate the effect of moisture content on the physical properties of sorghum and millet. The results are presented in Appendix A1. The relationship between the grain physical property (Y) and moisture content (M) was found to be linear, which could be expressed by the following equation:

$$Y = a + b M \quad (3.24)$$

where Y is the grain physical property, a and b are constants and M is the moisture content of the grain (%db). The values of constants a and b for each grain physical property along with corresponding coefficients of determination (R^2) are presented in Appendix A2.

3.6.2.1 Grain dimensions

All the principal dimensions of the grain kernel increased with increase in moisture content indicating that upon moisture absorption the grain kernel expand in length, width and thickness within the moisture range covered in this study. It was also observed that the kernels expanded more along their thickness in comparison with the other two principal axes.

3.6.2.2 Geometrical mean diameter, sphericity and surface area

The average values for geometric mean diameter, sphericity and surface area of individual grain kernels at different moisture contents are given in Appendix A1. All these parameters increased linearly as the moisture content increased from 12% to 25% (db). The relationship

between these grain parameters and moisture content is shown in figure 3.5 and values for the constant for the fitted lines for individual grain varieties together with corresponding R^2 values are given in Appendix A3.

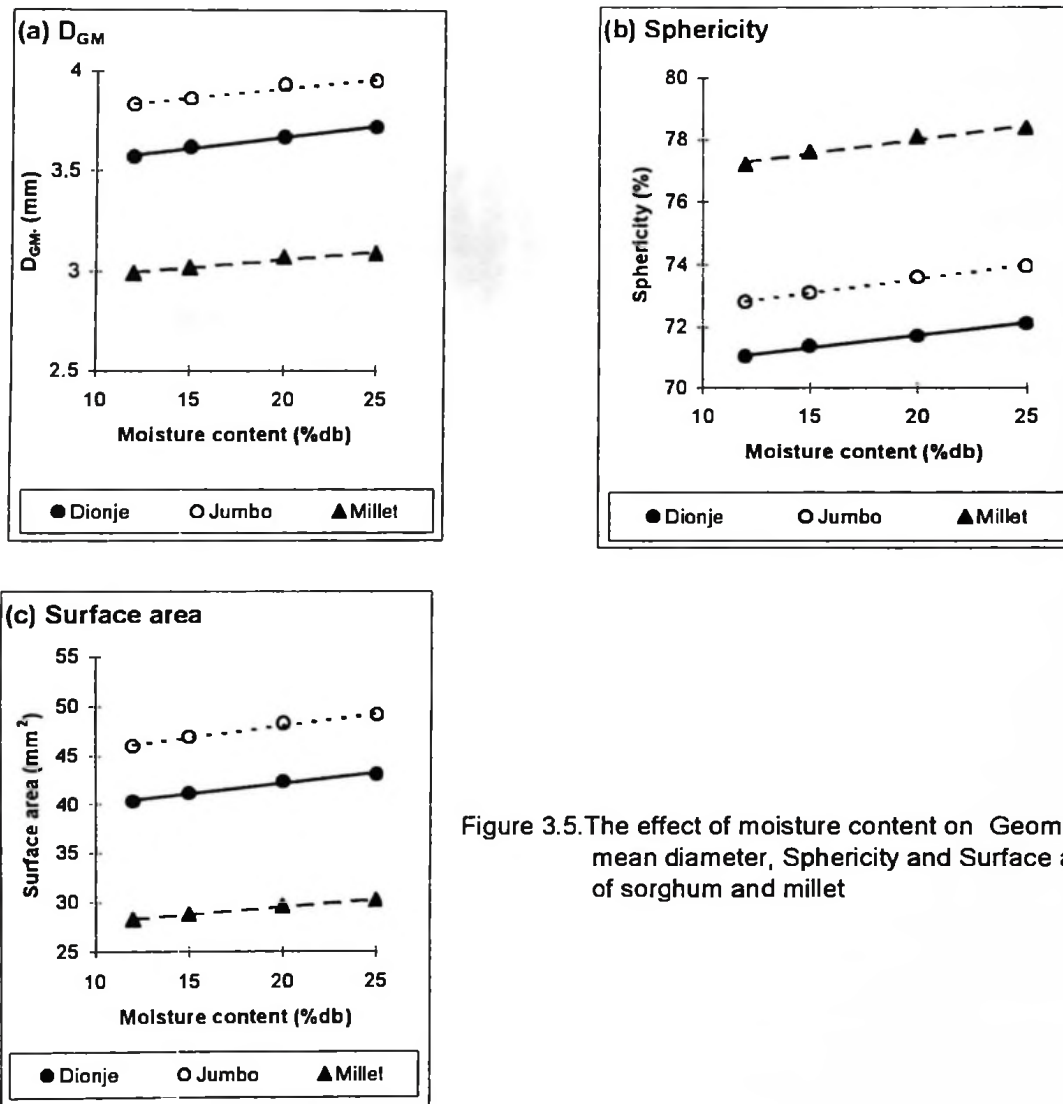


Figure 3.5. The effect of moisture content on Geometric mean diameter, Sphericity and Surface area of sorghum and millet

3.6.2.3 Thousand-grain weight (W_{1000})

Thousand-grain weight increased with increase in moisture content for both sorghum and millet. The relationship between thousand-grain weight and moisture content is shown in figure. 3.6(a) while the values of the constants for the linear equation representing the fitted lines are given in Appendix A3.

3.6.2.4 Kernel density (ρ)

The results of the variation of kernel density with moisture content are summarised in figure 3.6(b). Kernel density increased linearly with increase in moisture content for both sorghum and millet. Kernel density for Dionje increased from 1240 to 1370 kg/m³ (10.5% increase), Jumbo from 1070 to 1220 kg/m³ (14% increase) and millet from 1110 to 1230 kg/m³ (10.8% increase). These results agreed well with previous observations in other grains such as Maize, wheat, pigeon-pea and sunflower (Gupta and Das, 1997). The values of the coefficients for the fitted lines representing the relationship between kernel density and moisture content are given in Appendix A3.

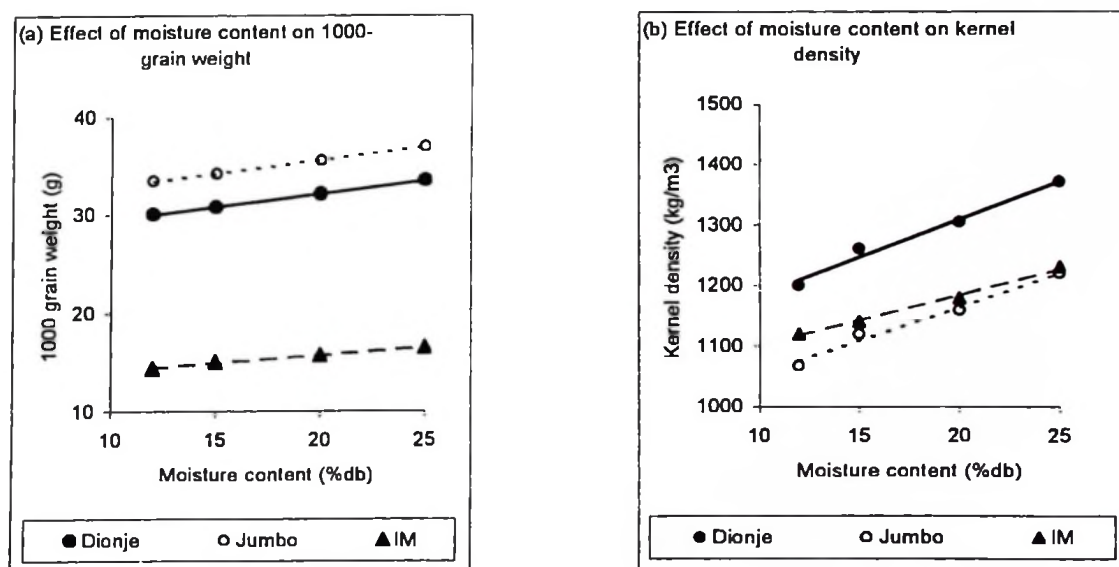


Figure 3.6. Variation of 1000-grain weight and kernel density of sorghum and millet with moisture content

3.6.2.5 Bulk density (ρ_B)

Results of the effect of moisture content on the grain bulk density are summarised in figure 3.7(a). Bulk density decreased with increase in moisture content for all grain varieties investigated. The bulk density of Dionje decreased from 684.7 kg/m³ to 661.4 kg/m³, while for Jumbo, bulk density decreased from 619.7 kg/m³ to 601.2 kg/m³ and for IM millet, bulk density decreased from 688.1 kg/m³ to 636.0 kg/m³. Carman (1996) and Gupta & Das (1997) also observed a negative linear correlation between bulk density and moisture content in lentil and sunflower seeds. Of the three grain varieties studied the decrease in bulk density with increase in moisture content was higher in millet than in sorghum as evidenced by the much steeper slope of the millet curve. The value of the coefficients of the fitted lines together with corresponding R² values for each variety are given in Appendix A3.

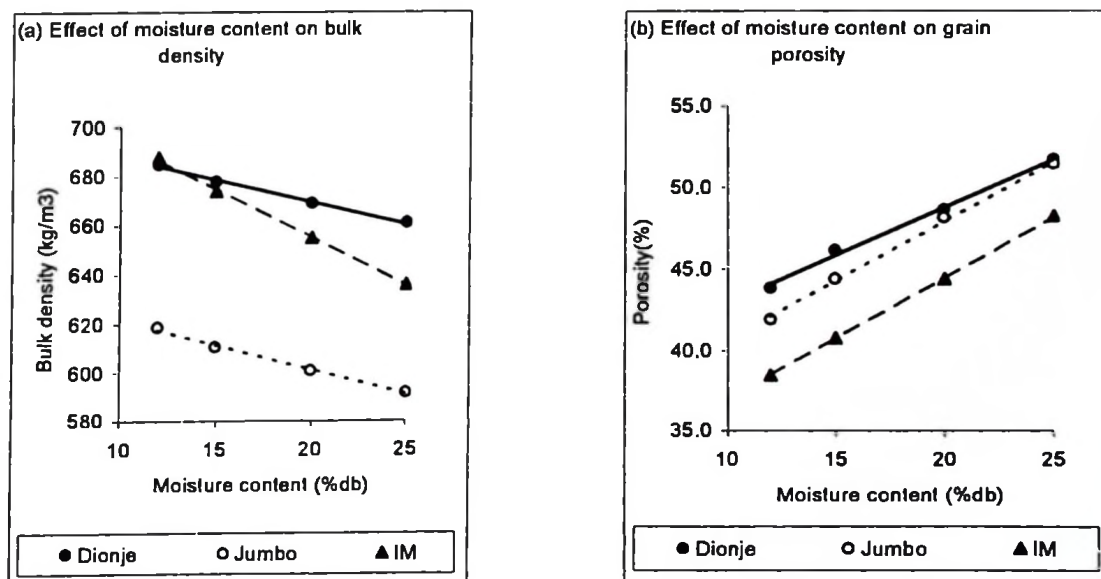


Figure 3.7 Effect of moisture content on bulk density and porosity of sorghum and millet.

3.6.2.6 Porosity

The effect of moisture content on porosity of the grain sample is shown in figure 3.7(b). The porosity of sorghum and millet increased linearly with increase in moisture content. For Dionje porosity increased from 44.8% to 52.9% (an increase of 18%), Jumbo from 41.9% to 51.4% (22% increase) and millet from 34.5% to 48.3% (40% increase). Carman (1996) and Shepherd Bhardway (1996) observed a similar trend in lentils and pigeon pea respectively. The values of the constant of the linear equation representing the relationship between porosity and moisture content are given in Appendix A3.

The bulk density of the grain varieties investigated here decreased with increase in moisture content despite an increase in the kernel density, due to the fact that within the same moisture range the porosity of the grain sample increased by a higher percentage than the kernel density.

3.6.3 Mechanical properties of sorghum and millet

3.6.3.1 Quasi-static compression tests

Typical force-deformation curves obtained during compression tests are shown in figures 3.8(a) and 3.8(b) for sorghum and millet respectively. Considerable variation was observed in the results of compression of individual kernels for both sorghum and millet. This was probably due to the non-homogeneous nature of the grain kernels and stress concentrations set up by the irregular bearing surface of the grain kernels. However, from the force-deformation curves obtained, the elastic properties of the grain kernels during the initial period of deformation were apparent. In most cases the initial part of the curve was linear up to the elastic limit, beyond which it became non-linear until rupture occurred. Most force-deformation curves displayed clear yield and rupture points at low moisture content range (12-15% db), however, this became less and less obvious as moisture content increased (20-25% db).

The results of the effect of moisture content and loading position on mechanical properties of sorghum and millet are given in Appendix A4 and A5 respectively.

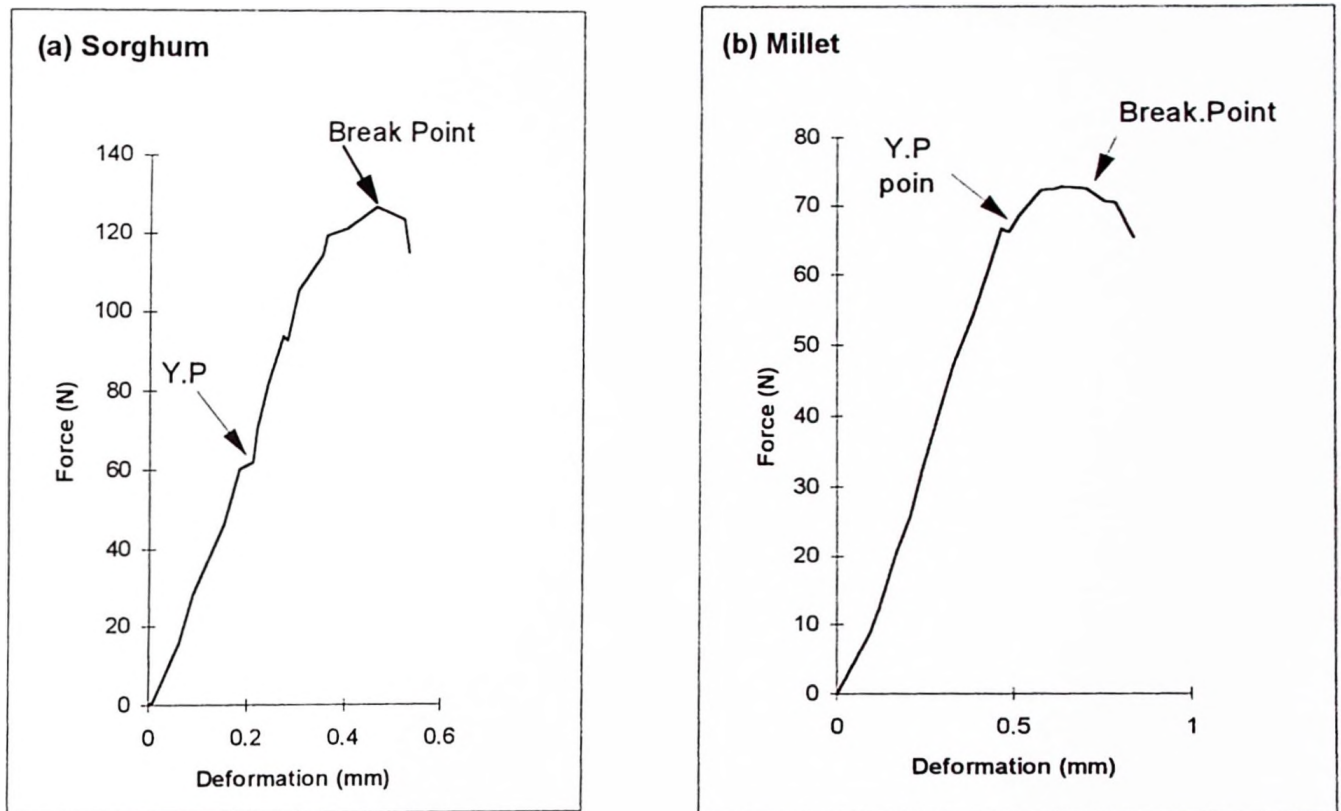


Figure 3.8 Typical F-D curves for (a) sorghum (Dionje) and (b) Millet (IM) at 15% (mcdB)
(Y.P. is the yield point)

3.6.3.2 The effect of moisture content on the mechanical properties of sorghum and millet

Two varieties of sorghum (Dionje and Jumbo) and one variety of millet (IM) were used to study the effect of moisture content on the mechanical properties of the grains. Typical results for the effect of moisture content on the force-deformation characteristics of sorghum is shown in figure 3.9 for Dionje. The results showed that the force required to cause a similar amount of deformation in the grain kernel decreased with increase in moisture content of the grain, thus

giving an indication that the grain kernels were becoming softer as moisture content increased. Similar behaviour has been observed in wheat and Maize (Zoerb and Hall, 1960), in Maize endosperm (Shelef and Mohsenin, 1969), in soybeans (Misra and Young, 1981), in rice (Hoki and Tomita, 1976), in wood (Meredith, 1956) and in wheat (Praveen *et al.*, 1995). Also the analysis of force-deformation curves obtained at different moisture contents indicated that the linear elastic range decreased with an increase in grain moisture content.

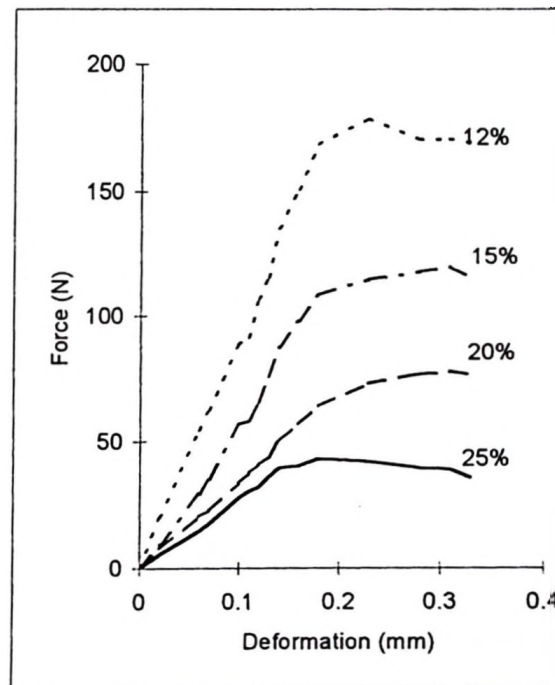


Figure 3.9 Effect of moisture content on force-deformation behaviour of sorghum (Dionje)

The softening of the grain kernel and the decrease in compressive strength of the kernel with increase in moisture content may have been caused by the disruption of the endosperm matrix due to absorption of moisture. Sullins and Rooney (1974) working on reconstituted sorghum found that there was disruption of the endosperm matrix at high moisture content caused by the swelling of starch granules as they absorb moisture. The same trend was also observed in millet.

The plot of the log values of the grain mechanical property against moisture content indicated a linear relationship, which could be represented by the following general equation:

$$\ln(Y) = a + bM \quad (3.23).$$

where Y is the grain mechanical property, a and b are constants and M is moisture content (% db). The values of the constants for the fitted lines and corresponding R^2 values for different mechanical properties investigated are given in Appendix A6.

3.6.3.2.1 Effect of moisture content on modulus of deformability (E_{mod})

Modulus of deformability of both sorghum and millet grain decreased with increase in moisture content [figure 3.10(a)]. The average modulus of deformability decreased from 1150 MPa to 274 MPa, 1016 MPa to 158 MPa and from 1225 MPa to 288 MPa for Dionje; Jumbo and IM millet respectively as the grain moisture content increased from 12% - 25% (db). The decrease in E_{mod} with increase in moisture content was found to be statistically significant in both grains ($P < 0.001$). The relationship between kernel moisture content and E_{mod} is shown in figure 3.10(b) for both sorghum and millet. The values of the constants and corresponding R^2 values for the fitted lines are given in Appendix A6. There was a high correlation between the log of E_{mod} and moisture content as indicated by the high R^2 -values. Loading position also had significant effect on the values of E_{mod} obtained. The E_{mod} of Dionje obtained for side loading orientation was approximately 50% lower than that obtained for flat loading orientation (746 MPa vs. 1554 MPa) The same trend was observed for Jumbo variety where for flat loading E_{mod} was 1018 MPa and side loading was 519 MPa.

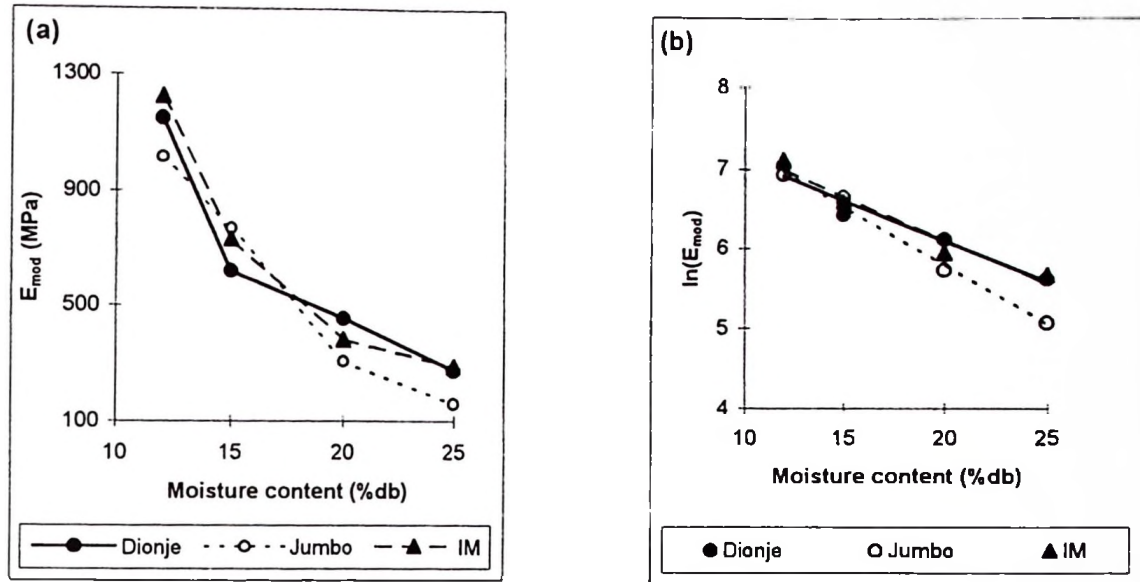


Figure 3.10 (a) Modulus of deformability of sorghum and millet as a function of moisture content and (b) a log-linear plot of E_{mod} against moisture content with fitted lines

3.6.3.2.2 The effect of moisture content on ultimate strain

Ultimate strain increased with increase in grain moisture content for both sorghum and millet [Figure 3.11(a)]. This could be explained by the fact that at high moisture content the grain became less elastic and more viscous in nature therefore enabling it to sustain larger deformation before reaching the breaking point. The same behaviour was observed by Singh (1985) working on different varieties of maize within 10 to 25% (db) moisture range. The relationship between the log of ultimate strain and moisture content for sorghum and millet is shown in figure 3.11(b). The values for the constants for the fitted lines, representing this relationship are given in Appendix A6.

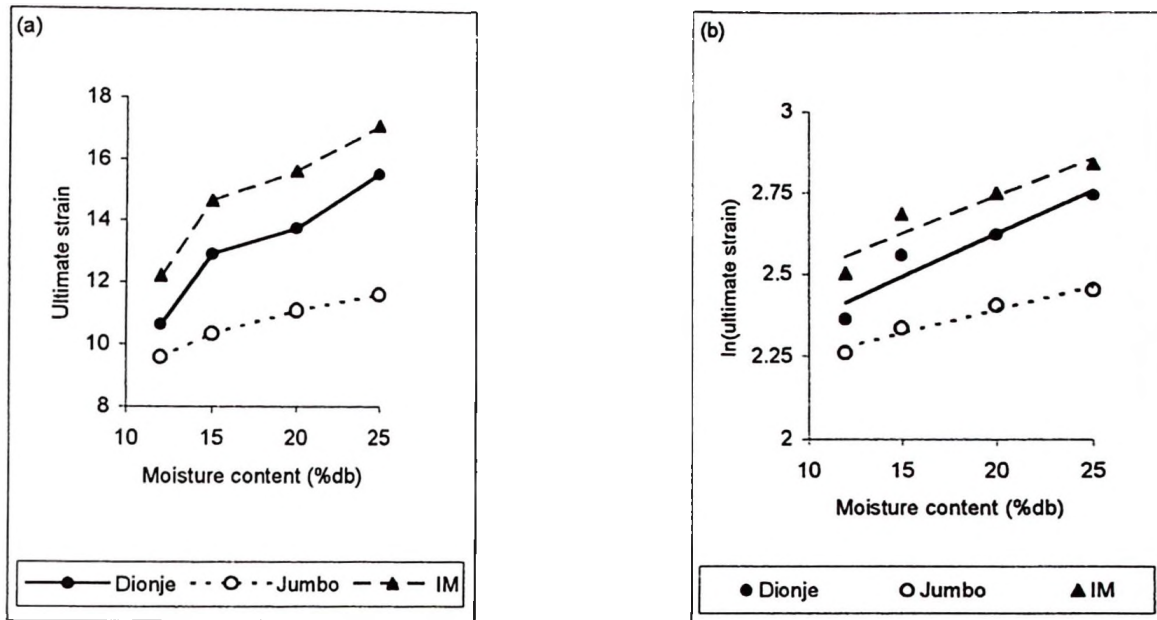


Fig. 3.11 (a) Ultimate strain of sorghum and millet kernels as a function of moisture content and (b) log-linear plot of ultimate strain against moisture content with fitted lines.

3.6.3.2.3 The effect of moisture content on the ultimate stress

Ultimate stress for both sorghum and millet decreased with increase in moisture content [figure 3.12(a)]. The ultimate stress decreased by approximately 80%, 79% and 76% for Dionje, Jumbo and IM millet respectively as the grain moisture increased from 12% to 25% db. The relationship between moisture content and the log of ultimate stress is shown in figure 3.12(b). There was a linear relationship between the log of ultimate stress and grain moisture content. The values of the constant for the linear model representing this relationship are given in Appendix A6.

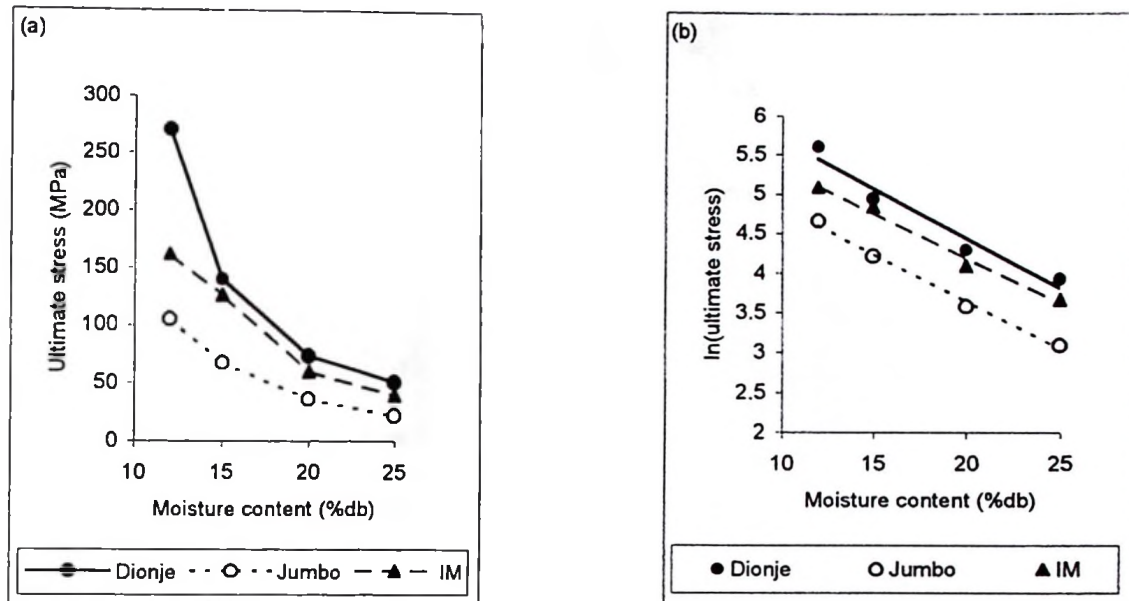


Figure 3.12 (a) Ultimate stress of sorghum and millet grain as a function of moisture content and (b) a log-linear plot of ultimate stress against moisture content with fitted lines.

3.6.3.2.4 Effect of moisture content on energy requirement to break point

The energy required to deform the grain kernel to the break point decreased with increase in grain moisture content for both sorghum and millet as shown in figure 3.13(a). For Dionje energy required to break the grain kernel decreased from an average of 52.47 mJ at 12% to 17.12 mJ at 25% (mcdB), (66 % decrease), and for Jumbo the energy absorbed decreased from 17.72 mJ at 12% to 6.9 mJ at 25% (mcdB) (61% decrease), while for millet the energy absorbed to break point decreased from 10.25 mJ to 5.78 mJ within the same moisture content range. The relationship between moisture content and the energy absorbed up to kernel break point is shown in figure 3.13(b) and the constants for the fitted lines with respective R^2 values are given in Appendix A6.

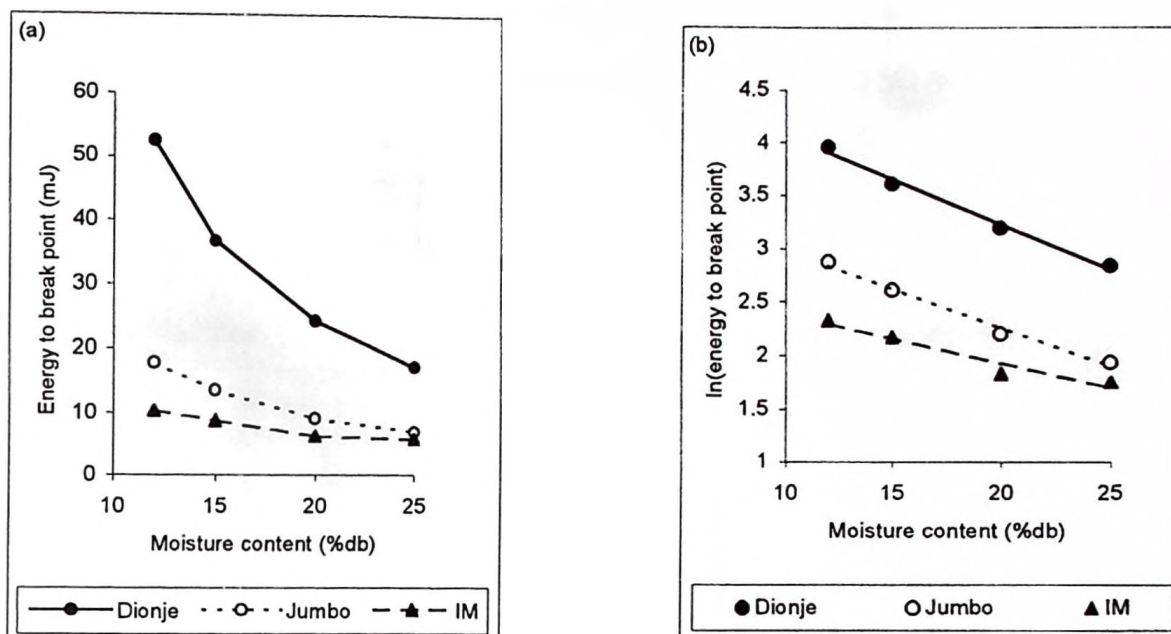


Figure 3.13 (a) Energy at kernel break point as a function of moisture content in sorghum and millet and (b) a log-linear plot of energy at break point against moisture content with fitted lines

3.6.3.2.5 The effect of moisture content on modulus of toughness (G_t) of sorghum and millet

Modulus of toughness of the grain decreased as moisture content increased from 12% to 25% (mcdB) for all varieties tested [figure 3.14 (a)]. The modulus of toughness decreased from 2018 MJ/m³ at 12% (mcdB) to 590 MJ/m³ at 25% (mcdB) for Dionje, from 797 to 271 MJ/m³ for Jumbo, and from 921 MJ/m³ to 413 MJ/m³ for millet within the same moisture range. The relationship between moisture content and kernel toughness (G_t) is illustrated in figure 3.14 (b) and the values for the constants for the fitted lines representing the relationship are given in Appendix A6.

Loading position also had a significant effect on the grain toughness, with kernels loaded in flat position showing much higher toughness than those loaded on the side loading position. The

modulus of toughness of Dionje for flat loading position was 3151 MJ/m³ at 12% mc and 855 MJ/m³ at 25% mc.db, while for side loading position was only 1266 MJ /m³ at 12 % mc. and 573 MJ/m³ at 25 % (mcdb).

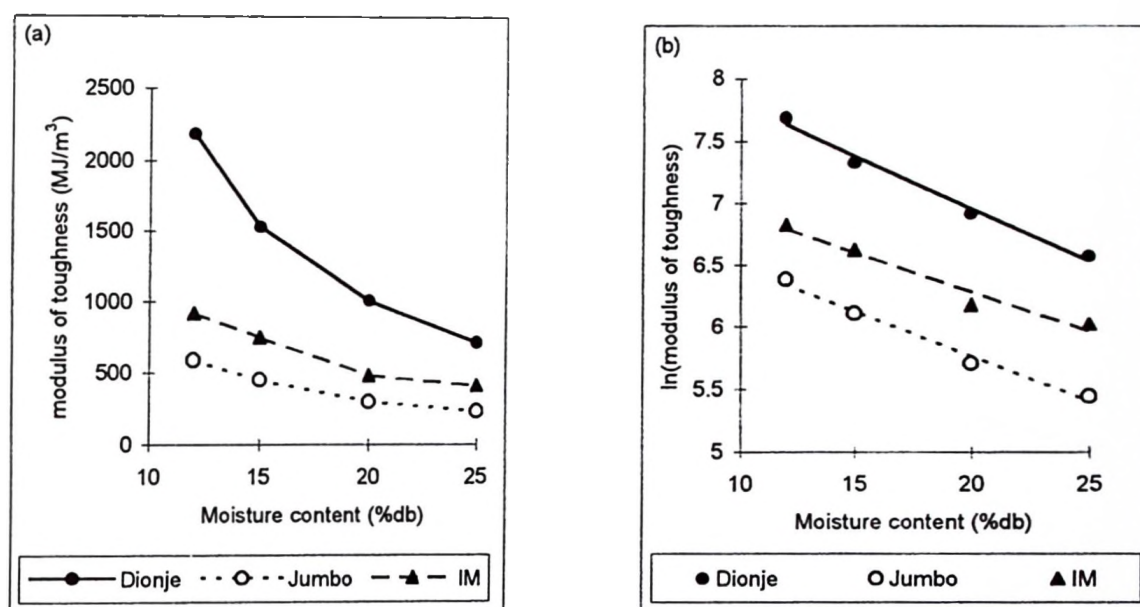


Figure 3.14 (a) Modulus of toughness as a function of moisture content in sorghum and millet and (b) a log-linear plot of modulus of toughness against moisture content with fitted lines

3.6.3.2.6 The effect of moisture content on force required to break the grain kernel for sorghum and millet.

The results of the effect of moisture content on the force required to break the grain kernel are given in figure. 3.15 (a). There was a significant ($P < 0.01$) decrease in the amount of force required to break the grain kernel as moisture content increased from 12% to 25% (db). Dionje required an average of 148 N at 12% (mcdb) and only 82 N at 25% (mcdb) to break the grain kernel, (a decrease of about 45%.) Jumbo required an average of 86.3 N at 12% mc and 35 N at 25% mc (a decrease of 59%), and millet required 37 N at 12% (mcdb) and only 23 N at 25%

(mcdb) (a decrease of 38%). The decrease in force could be attributed to a decrease in the strength of the grain kernel at high moisture content, a trend, which was also observed by Paulsen (1978) for soybeans and Zoerb and Hall (1960) for maize and wheat. The relationship between force to break point and moisture content is shown in figure 3.15(b) and the values of the constants for the log-linear model representing this relationship together with R^2 values are given in Appendix A6.

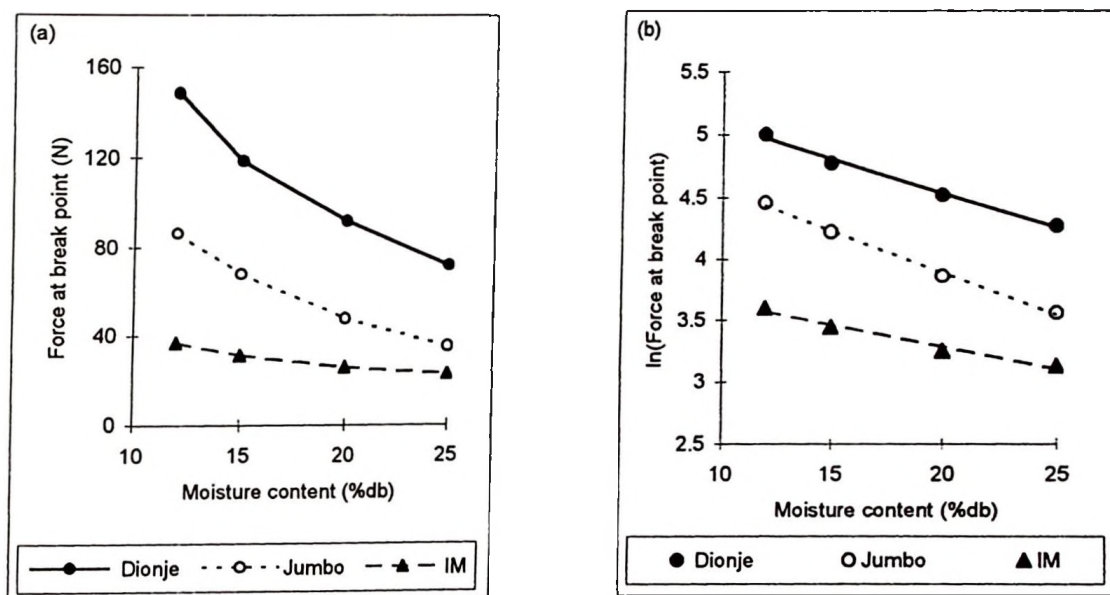


Figure 3.15 (a) Force at sorghum and millet grain kernel break point as a function of moisture content and (b) a log-linear plot of force at break point against moisture content with fitted lines

Grain loaded on flat position required 148 N and 86 to break the grain at 12% mc for Dionje and Jumbo respectively while in side loading position, Dionje required 106 N and Jumbo 46 N to break the grain at the same moisture content. Statistical evaluation of data on rupture force for flat and side loaded grain kernels showed that the difference in rupture force between flat and side loading was significant at ($P < 0.01$). These results are in good agreement with the results of Singh & Goswani (1998) and Paulsen (1978) who also observed that substantially

less force was required for seed rupture in side loading orientation than in flat loading orientation for cumin seeds and soybeans respectively.

3.6.3.2.7 Effect of moisture content on deformation at break point

Deformation at kernel break point increased as the moisture content of the grain increased for both sorghum and millet [figure 3.16 (a)]. On average, deformation at break point increased by 40% from 0.27 mm to 0.38 mm for Dionje, 30% from 0.43 mm to 0.56 mm for Jumbo and by 36% from 0.33 mm to 0.45 mm, for millet as the kernel moisture increased from 12% to 25% (db). This suggested that sorghum and millet grain kernels become softer at higher moisture content and therefore capable of higher deformation before breakage. The relationship between moisture content and deformation at break point is shown in figure 3.16(b) and the values of constants for the fitted lines are given in Appendix A6.

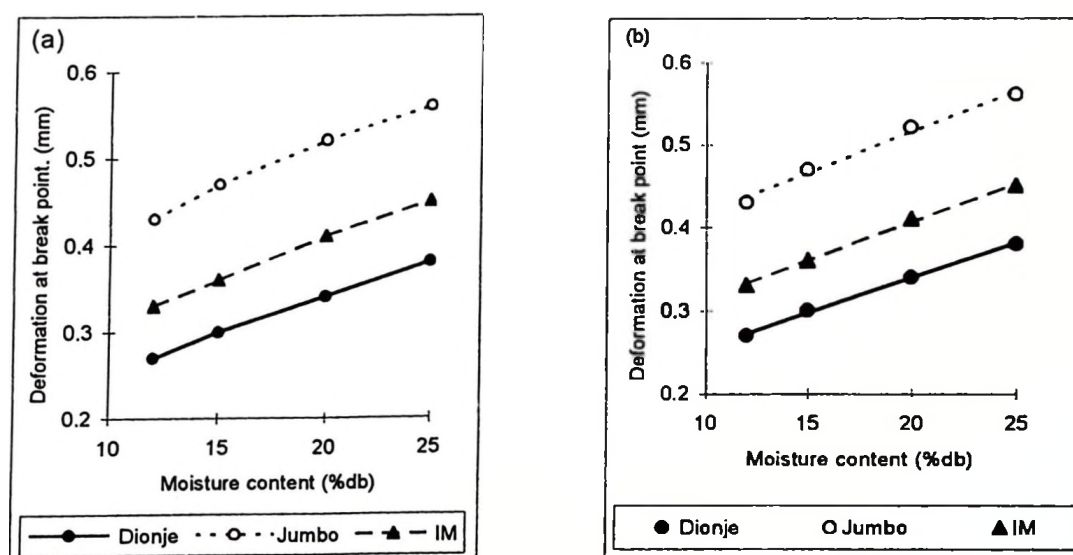


Figure 3.16 (a) Deformation at kernel break point in sorghum and millet as a function of moisture content (b) a linear plot of deformation at kernel break point against moisture content with fitted lines

3.6.3.3 Effect of temperature on the mechanical properties of sorghum and millet

The results of the effect of temperature on the mechanical properties of sorghum and millet showed a similar trend to the results of moisture content. All mechanical properties of sorghum and millet with exception of ultimate strain decreased with increase in temperature. The effect of temperature could be explained by the fact that, grains swell and shrink when heated or cooled. The differential expansion of a composite body such as a grain kernel subject to thermal gradient result in thermal stresses, which can lead to disruption of the cellular structure within the grain kernel thus weakening the strength of the grain kernel. The relationship between grain mechanical properties and temperature could be represented by the following general equation

$$\ln (y) = bT + a \quad (3.26)$$

where Y is the grain mechanical property, a and b are constants and T is temperature ($^{\circ}\text{C}$).

3.7.3.3.1 Effect of temperature on modulus of deformability (E_{mod}) of sorghum and millet

The effect of temperature on E_{mod} of sorghum and millet is shown in figure 3.17(a). For Dionje E_{mod} decreased from 1467 MPa at 20 $^{\circ}\text{C}$ to 804 MPa at 50 $^{\circ}\text{C}$, for Jumbo the decrease was from 1093 MPa to 599 MPa while for millet, E_{mod} decreased from 1226 MPa to 658 MPa within the same temperature range. The relationship between temperature and E_{mod} is shown in figure 3.17(b) and the value of constants for the linear model representing this relationship together with respective R^2 values are given in Appendix A7.

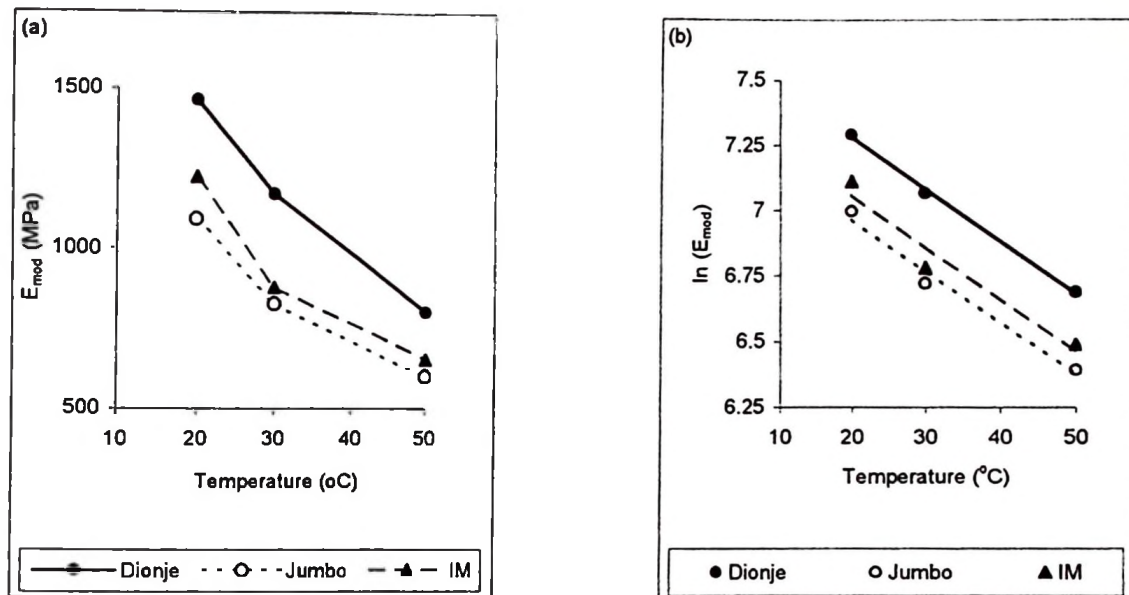


Figure 3.17 (a) E_{mod} of sorghum and millet as a function of temperature (b) a log-linear plot of E_{mod} against temperature with fitted lines

3.6.3.3.2 Effect of temperature on ultimate stress of sorghum and millet

The ultimate stress of all grain varieties decreased as the temperature increased from 20 $^{\circ}$ C to 50 $^{\circ}$ C.[figure 3.18(a)]. On average, ultimate stress of Dionje decreased by 72%, Jumbo by 35% and IM millet by 38.3% within the temperature range considered in this study. Sorghum varieties showed large difference in ultimate stress at low temperature but this decreased as temperature increased. The relationship between temperature and the ultimate stress for sorghum and millet is illustrated in figure 3.18(b) and the values of the constants for the linear model representing this relationship are given in Appendix A7.

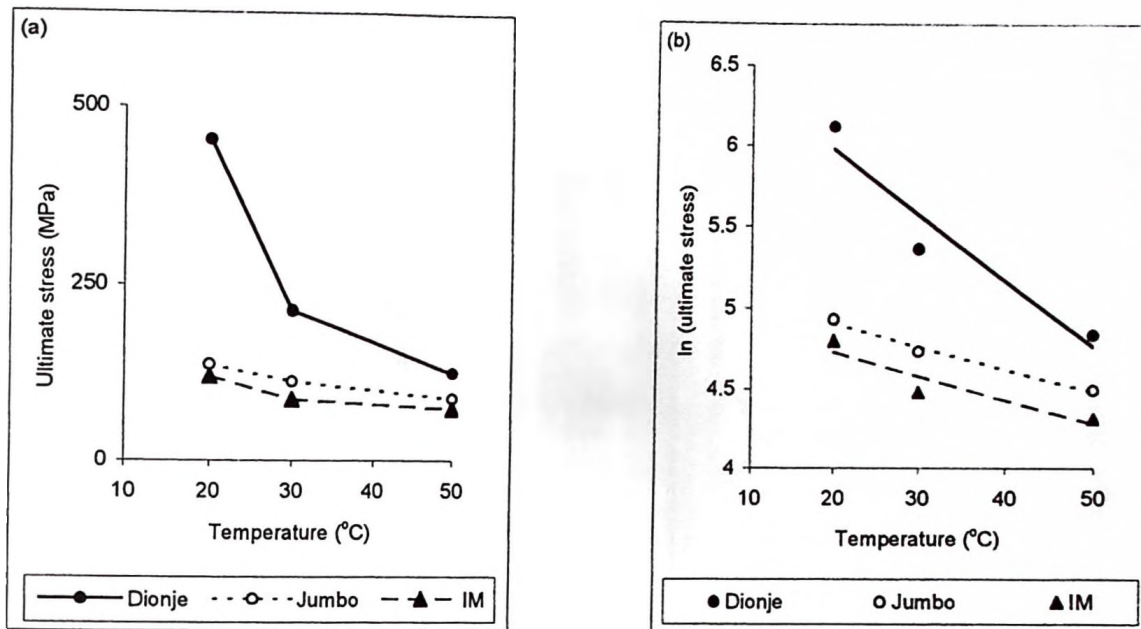


Figure 3.18 (a) Ultimate stress of sorghum and millet as a function of temperature

(b) A log-linear plot of ultimate stress against temperature with fitted lines

3.7.3.2.3 Effect of temperature on energy to break point

For both sorghum and millet, the energy absorbed by the grain kernel to its break point decreased with increase in temperature [figure 3.19(a)]. For sorghum the energy requirement decreased from 75 mJ at 20°C to 20 mJ at 50°C for Dionje and from 19 mJ to 11 mJ for Jumbo, while for millet the energy requirement decreased from 13 mJ to 10 mJ at 20°C and 50°C. respectively. The relationship between temperature and ultimate stress is shown on figure 3.19(b) and the values of constants for the fitted lines representing this relationship are given in Appendix A7.

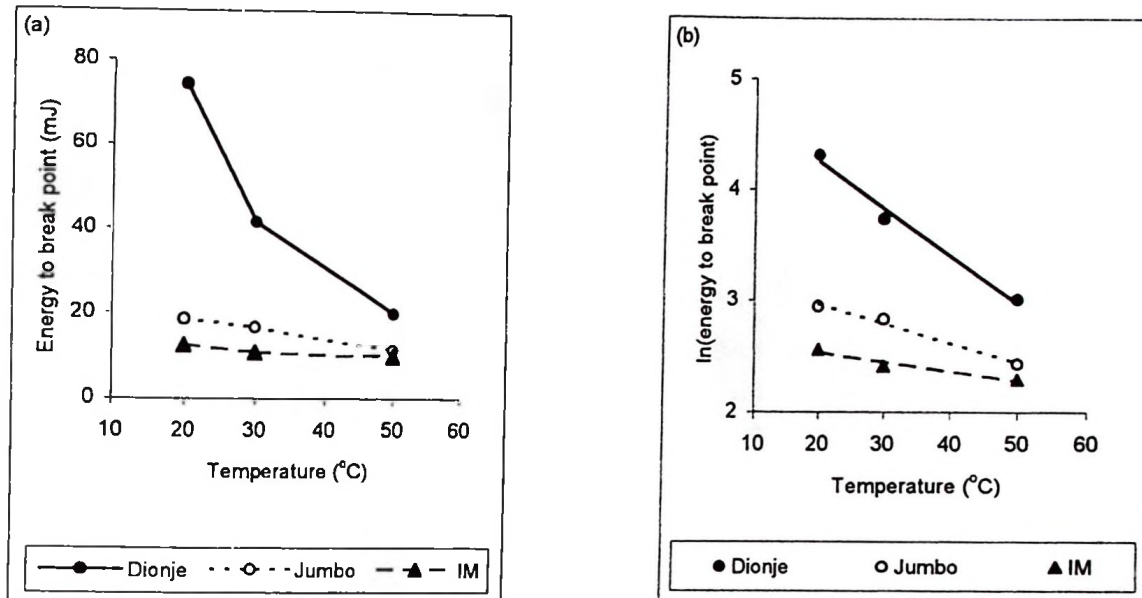


Figure 3.19 (a) Energy absorption to sorghum and millet kernel break point as a function of temperature (b) log-linear plot of energy to break point against temperature with fitted lines

3.6.3.3.4 Effect of temperature on modulus of toughness

Modulus of toughness decreased with increase in temperature for both sorghum and millet [figure 3.20(a)]. For Dionje there was a 73 % decrease, Jumbo, a 40% decrease, whereas for millet there was a 23% decrease in modulus of toughness as the temperature increased from 20⁰C to 50⁰C. The relationship between temperature and modulus of toughness is illustrated in figure 3.20(b) and the values for the constants for fitted lines representing this relationship with respective R² values are given in Appendix A7.

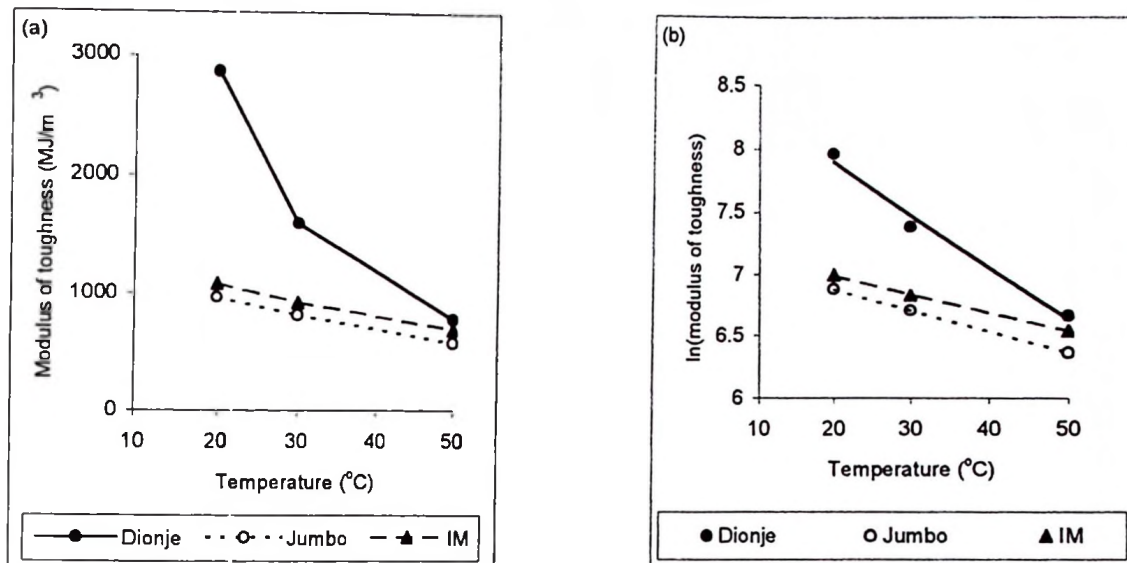


Figure 3.20 (a) Modulus of toughness of sorghum and millet as a function of temperature (b) log-linear plot of modulus of toughness against temperature with fitted lines

3.6.3.4 Effect of tempering on the mechanical properties of sorghum

The results of tempering duration on the strength properties of sorghum and millet are summarised in figure 3.21(a) through to figure 3.21(c). All strength properties of the grain investigated except kernel deformation, decreased with increase in tempering duration. The force required to break the grain kernel decreased from 148 N to 121 N for Dionje, 86 N to 36 N for Jumbo and from 51 N to 31 N for millet after 60 minutes tempering duration [figure 3.21(a)]. The largest rate of decrease in kernel strength was observed in the first 15 minutes of tempering which was then followed by a much slower rate of decrease as the duration increase from 15 to 60 minutes.

The results of the effect of tempering duration on energy absorbed by the kernel up to the break point are summarised in figure 3.21 (b). The energy required to break the grain kernel decreased from 52 mJ for un-tempered grain to 37 mJ after 60 minutes tempering duration for

Dionje, from 18.9 mJ to 13 mJ for Jumbo and from 14 mJ to 5 mJ for millet within the same tempering period. Kernel deformation at break point increased from 0.28 to 0.46 mm for Dionje, 0.27 mm to 0.46 mm for Jumbo and from 0.21 mm to 0.35 mm for IM millet as the tempering duration was increased from 0 minutes to 60 minutes [figure 3.21(c)].

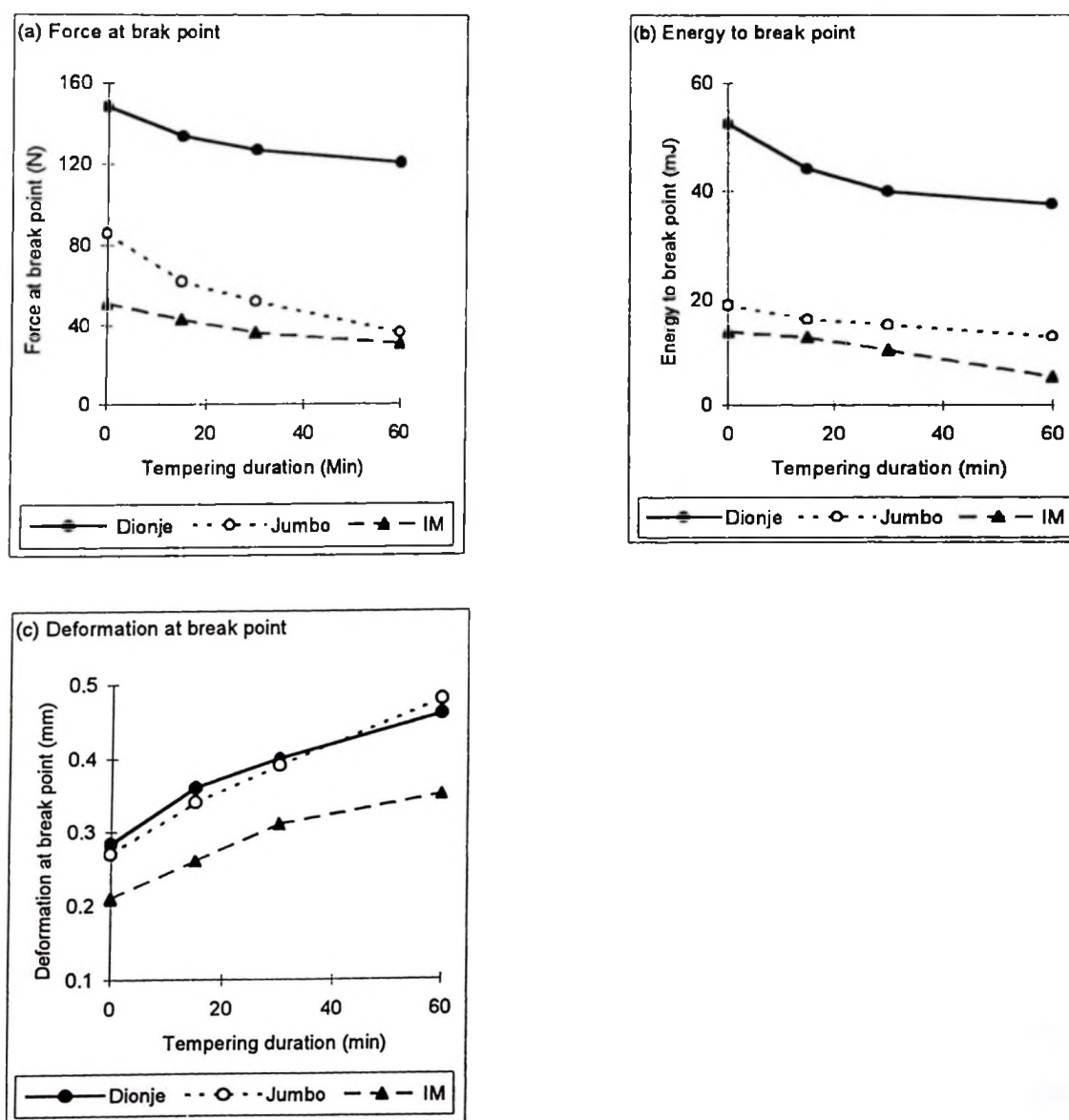


Figure 3.21 Effect of tempering duration on the strength properties of sorghum and millet

The relationship between tempering duration and different strength properties of sorghum and millet grain is illustrated in figure 3.22(a) to (c) and could be represented by the following general equation:

$$\ln (y) = bt + a \quad (3.27)$$

where Y is the grain mechanical property, a and b are constants and t is tempering duration (min).

The relationship between tempering duration and force to break point is shown in figure 3.22(a) and the values of constants for the fitted lines representing this relationship are given in Appendix A8. The rate of decrease in force required to break the grain kernel was much higher in Jumbo variety compared to the other two-grain varieties. This could be explained by the difference in the kernel structure in these varieties. Jumbo which having a soft endosperm, absorbed moisture much faster than the other two varieties resulting in much faster softening of the endosperm compared to the other two varieties which have intermediate (millet) and hard (Dionje) endosperm structures. The relationship between tempering duration and the energy absorbed by the grain kernel at break point is shown in figure 3.22(b) while the relationship between tempering duration and kernel deformation at break point is shown in figure 3.22(c). The values of the constants for the respective fitted lines representing the relationships are given in Appendix A8

Statistical analysis (t-test) of the kernel strength data showed that there was no significant difference ($P < 0.05$) between the force required to break un-tempered grain and grain tempered for up to 15 minutes. However, there was a significant difference ($P < 0.05$) between the force required to break un-tempered grain and grain tempered for more than 15 minutes. These results suggest that short tempering duration of 15 minutes or less could be carried out without significantly affecting the breaking strength of the grain kernel.

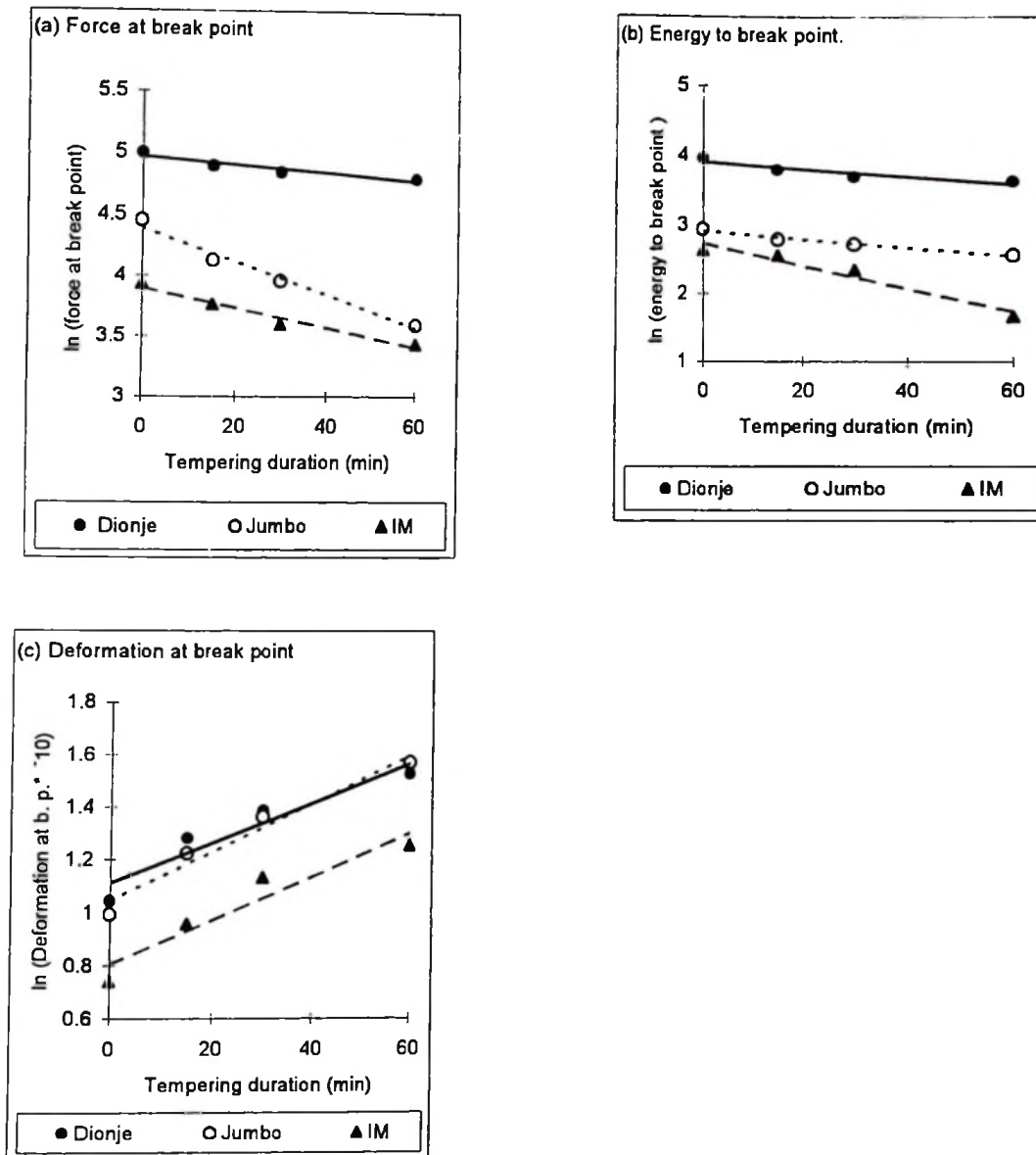


Figure 3.22 Log-linear plots of the grain strength properties against tempering duration with fitted lines.

3.6.3.5 Rheological properties of sorghum and millet

Typical force-relaxation curves for sorghum and millet at 12% moisture content are shown in figure 3.23(a) and 3.23(b) respectively. Evaluation of the stress relaxation curves using the method of successful residuals is illustrated in figures 3.24(a) and 3.24(b) for sorghum and

millet respectively. It was found that the stress-relaxation behaviour of sorghum and millet in compression could be represented by a three term exponential equation of the form:

$$F(t) = A_1 e^{-\frac{t}{\tau_1}} + A_2 e^{-\frac{t}{\tau_2}} + A_3 e^{-\frac{t}{\tau_3}} \quad (3.28)$$

where A_1 , A_2 and A_3 are constants representing initial force at $t=0$ and τ is the relaxation time

This is equivalent to three Maxwell models in series without any spring in parallel.

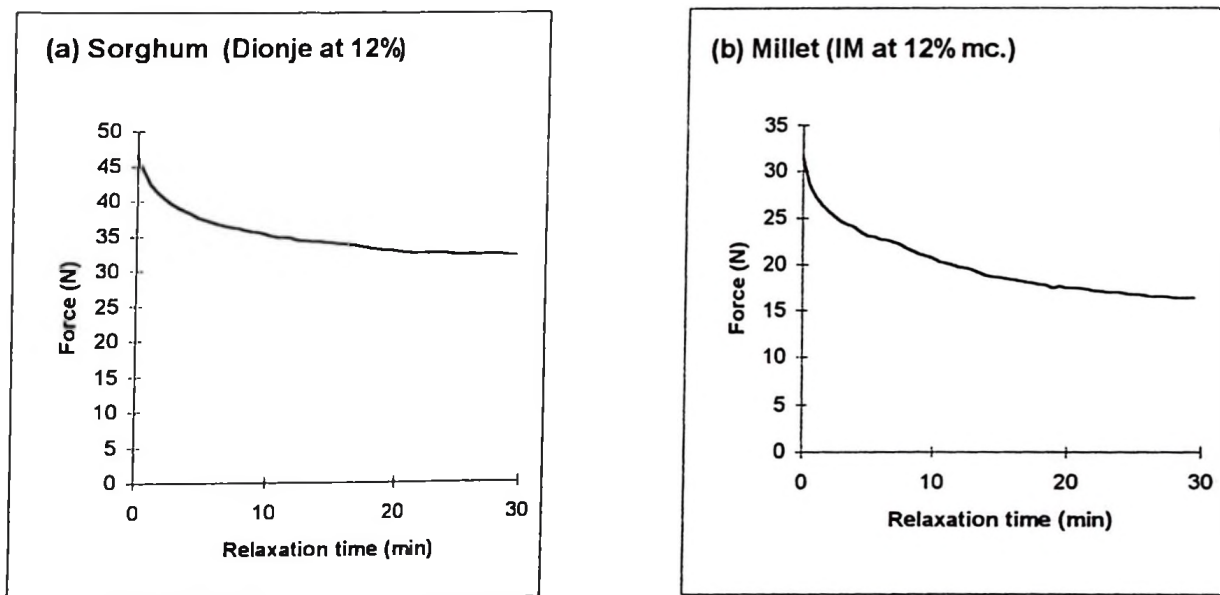


Figure 3.23: Force-relaxation curve for (a) sorghum and (b) millet at 12% (mcdb).

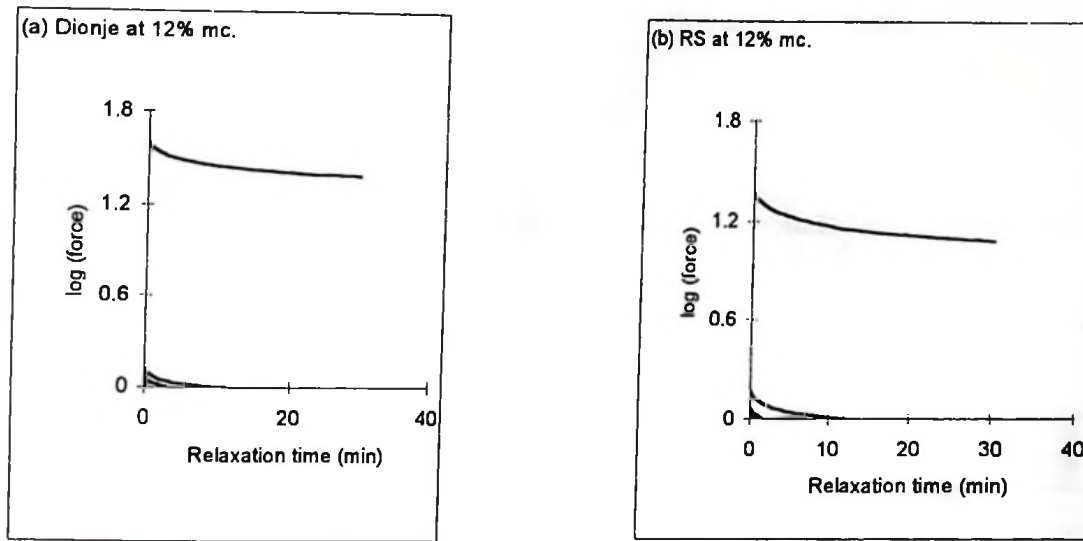


Figure 3.24(a) Force-relaxation curve for (a) Dionje and (b) RS sorghum varieties at 12% (mcdB) represented by a 3 term Maxwell model.

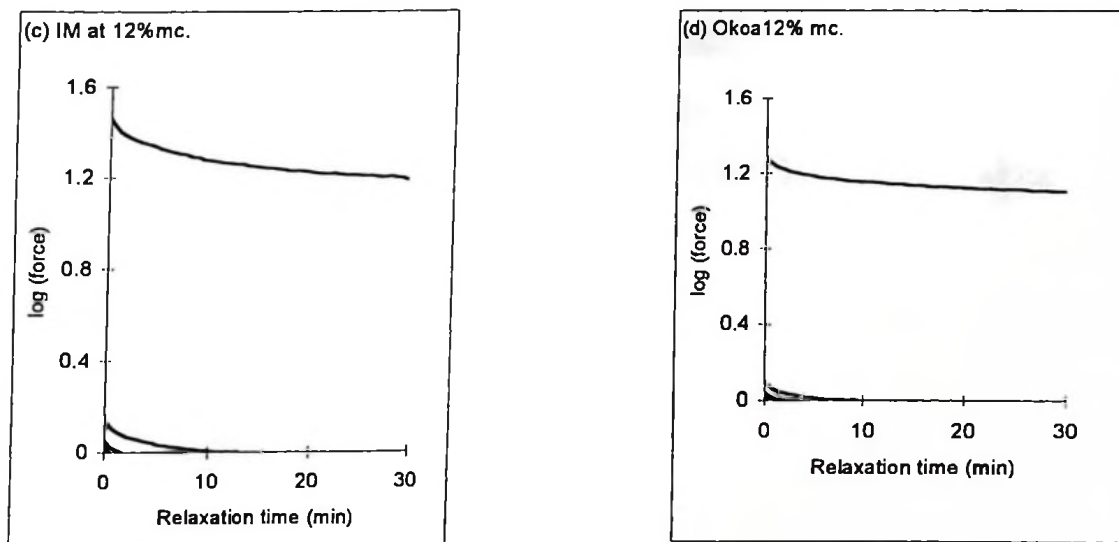


Figure 3.25 Force-relaxation curve for (a) IM and (b) Okoa millet varieties at 12% (mcdB) represented by three term Maxwell model



The constants for the force-relaxation models at different moisture levels are summarised in Table 3.5 for both sorghum and millet.

Table 3.5 Parameters for the three term relaxation models at different moisture contents.

Grain type	Moisture content (%db)	Estimated parameters					
		A ₁ (N)	A ₂ (N)	A ₃ (N)	T ₁ (min)	T ₂ (min)	T ₃ (min)
1. Sorghum							
(a) Dionje	12	32.42	1.11	1.08	299.36	198.34	66.12
	15	27.66	1.17	1.08	200.0	138.23	58.58
	20	27.66	1.18	1.075	153.07	75.13	44.4
	25	24.76	1.15	1.053	139.54	89.55	58.36
(b) RS	12	23.93	1.19	1.11	218.76	104.56	39.99
	15	20.54	1.17	1.08	193.45	92.31	48.87
	20	18.32	1.16	1.08	112.01	101.73	48.41
	25	17.33	1.12	1.103	176.26	87.06	40.29
(2) Millet							
(a) Okoa	12	14.0	1.15	1.08	313.26	175.48	80.78
	15	13.86	1.21	1.105	205.43	148.26	62.15
	20	10.68	1.22	1.14	158.99	98.38	51.29
	25	6.88	1.308	1.12	132.88	73.92	48.88
(b) IM	12	22.17	1.152	1.08	246.88	171.26	76.86
	15	16.99	1.12	1.10	197.92	175.54	52.89
	20	12.18	1.22	1.076	109.87	100.64	60.06
	25	10.54	1.23	1.11	136.55	109.0	51.71

Typical force relaxation curves for sorghum and millet at a specific strain level and deformation rate are presented in figures 3.26 and 3.27 respectively. As the moisture content of the grain increased, the force-relaxation curves shifted downward in both grain types implying less imposed stress for a given strain. A similar trend was observed in cowpeas (Pappas *et al.*, 1988); maize (Sigh, 1985), soy beans (Shelef and Mohsennin, 1967), cannola and wheat (Praveen *et al.*, 1995). Also by increasing moisture content, both the model coefficients and relaxation time showed a decreasing trend. The lower value of relaxation force and relaxation time at higher moisture content may be attributed to plasticizing effect of the water on grain kernel constituents (Husain *et al.*, 1971; Praven *et al.*, 1995)

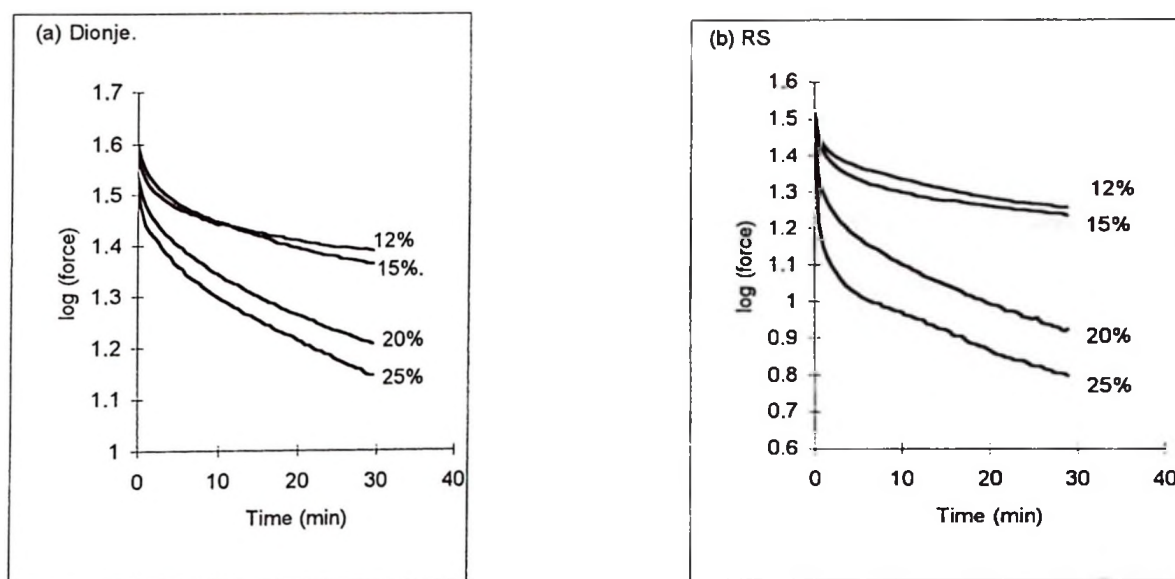


Figure 3.26 Effect of moisture content on force-relaxation of sorghum (a) Dionje and (b) RS.

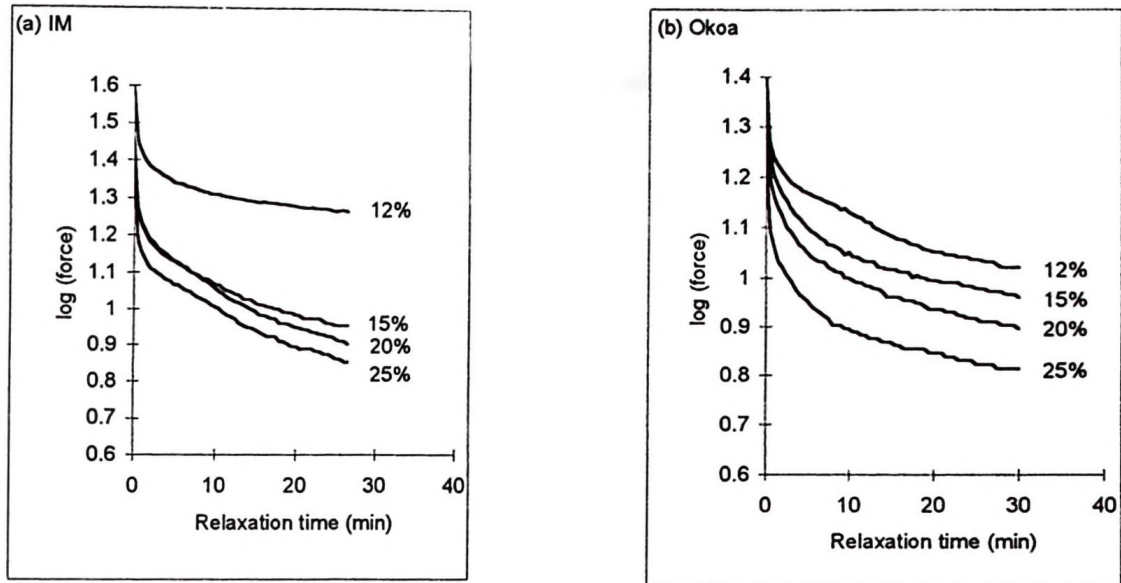


Figure 3.27 Effect of moisture content on force-relaxation behaviour of millet (a) IM and (b) Okoa

The effect of grain texture or hardness on stress relaxation behaviour of the grain is shown in figure 3.28(a) and 3.28(b) for sorghum and millet respectively. Grain texture had a significant effect on the stress relaxation behaviour of both sorghum and millet, with the soft grain (RS and Okoa) curves being shifted downwards relative to the hard (maizeeous) and intermediate grain (Dionje and IM). The relaxation time for sorghum hard variety (Dionje) was higher than the soft variety (Jumbo) while this was the opposite in the case of millet.

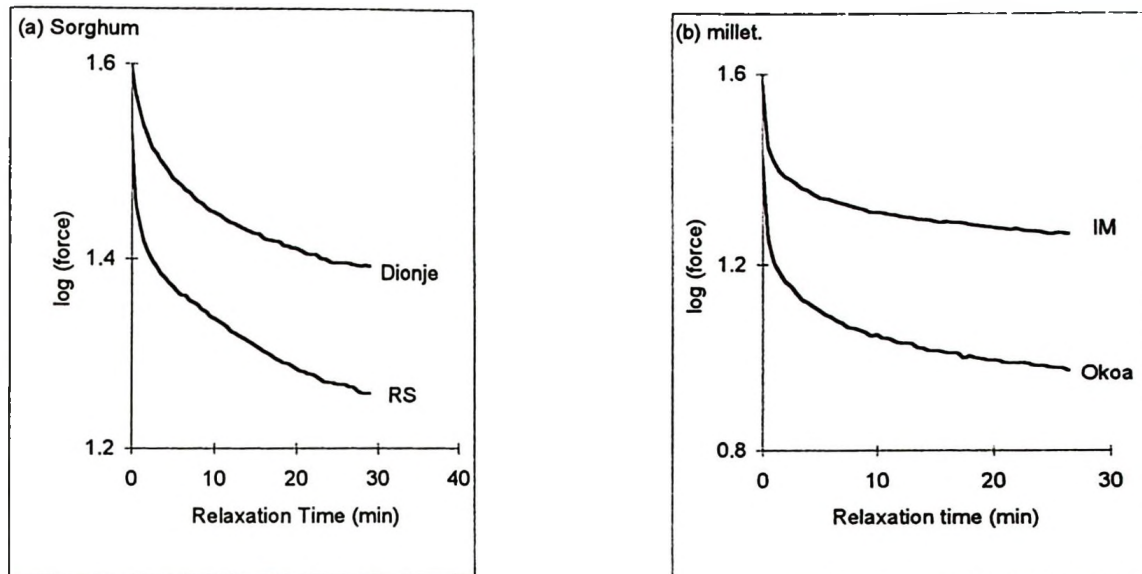


Figure 3.28 Effect of grain texture on force-relaxation of (a) sorghum and (b) millet

Significance tests were conducted to determine the dependence of relaxation force on moisture content of the kernels. The results indicated that relaxation force, logarithmic values of the coefficients (A_1 , A_2 , A_3 , τ_1 , τ_2 , τ_3) of the fitted three-term model and grain texture were all significantly ($P < 0.05$) related to moisture content for both sorghum and millet.

3.7 Summary and conclusions

The main objective of this chapter was to determine the physical, mechanical and viscoelastic properties of individual sorghum and millet kernels and establish their functional relationships with changes in moisture content and temperature. Physical properties of sorghum and millet kernels such as size, shape, density, hardness and weight were evaluated. The kernel size was expressed in terms of kernel weight, arithmetic mean diameter, or geometric mean diameter while kernel shape was expressed in terms of sphericity. Within the 12 to 25% (db) moisture range, kernel linear dimensions (length, width and thickness), geometric mean diameter, sphericity, surface area, thousand grain-weight, kernel density, and porosity were all linearly

related to moisture content of the grain, and increased with increase in moisture content. Conversely, bulk density decreased linearly with increase in moisture content within the same moisture range.

Mechanical properties of sorghum and millet were investigated within the same moisture range and 20–50°C temperature range. Both kernel moisture content and temperature had a significant effect on the mechanical properties of sorghum and millet varieties used in this study. In general, an increase in the grain kernel moisture content or temperature caused a decrease in all grain mechanical properties except ultimate strain. The extent of decrease, however, varied between different varieties and of the two parameters investigated, moisture content had a greater effect on the mechanical properties of the grain than temperature.

These findings could be explained by considering the constituents of the grain kernel and how moisture and temperature affect them. The endosperm comprises about 80 to 84% by weight of sorghum and millet kernel (Sullins and Rooney, 1974). Therefore the endosperm must have a big influence on the mechanical behaviour of the grain. Microscopic study of sorghum endosperm (Sullins and Rooney, 1975) has shown that individual starch granules in both maizeous and floury endosperm are completely embedded in a matrix composed largely of protein, and the majority of the molecules in the network are oriented in a specific pattern. It is recognised that powerful intermolecular binding forces exist in crystalline or oriented high polymeric substances, and this accounts for their toughness (Ferry, 1961). From these considerations, the mechanical properties of the sorghum and millet kernels should be largely related to the whole protein matrix of the endosperm, as well as the size and compactness of the starch granules within the endosperm. At low moisture levels the kernel is very stiff (due to compactness of the starch granules), and hence its deformation in the elastic range is relatively small. When water molecules enter the molecular chain units, which are close to each other, they are forced to rearrange their relative positions. Apparently such geometrical re-arrangement of the chain units affects the compactness of the endosperm structure and hence its mechanical properties, causing them to decrease with increase in number of water molecules present within the chain.

Another factor, which might have led to the observed behaviour of the grain as related to moisture content, is the friction coefficient of the starch granules within the endosperm. Behaviour of dry endosperm can be compared to an undiluted polymer with a relatively high friction coefficient. When the moisture level is increased, the friction coefficient between the starch granules becomes smaller, since some of the nearest neighbours of the starch granules are now solvent molecules, which are much more mobile and hence act as lubricants (Ferry, 1961). Under such conditions the deformations under a given load gradually increase and the moduli together with other strength properties decrease with increase in the number of water molecules present.

Kernel orientation during loading also had a marked effect on the kernel strength properties. Grain kernels loaded in flat loading position (hilum flat on the loading plate) required more force and energy to cause kernel rupture than grain kernels loaded in side loading position (hilum on the side). Values of all other mechanical properties investigated were also higher for the flat loading position compared to the side loading position. Within the moisture range investigated, loading position had a strong influence on all sorghum grain strength properties. This difference in strength properties in two orthogonal directions is therefore an important consideration which needs to be taken into account during determination of kernel properties to be used in the design of handling or processing machines.

The effect of tempering or soaking duration was investigated by soaking the grains for different duration. Tempering had an effect on the strength properties of the grain kernels although to a much lesser extent compared to uniformly distributed moisture content within the kernels. All the grain strength properties decreased with increase in tempering duration for all varieties studied. However, a short tempering duration of 15 minutes or less had no significant effect on the strength properties of the grain kernel.

Viscoelastic response of whole sorghum and millet kernels was studied by means of force relaxation tests at four moisture levels. Results indicated that within the moisture range

covered in this study, i.e. 12-25% (db), sorghum and millet kernels behaved as viscoelastic materials. A rheological model consisting of three Maxwell units in parallel adequately represented the stress-relaxation behaviour of both sorghum and millet. Grain moisture content and grain texture had a significant influence on the force-relaxation behaviour of both sorghum and millet. Relaxation force and time decreased with both increase in moisture content of the grain and change in grain endosperm texture from hard to soft.

Based upon the findings of this study, the following conclusions can be drawn:

- (1) Mechanical properties of single sorghum and millet kernels were highly influenced by both the grain moisture content and temperature. The mean values for material properties of sorghum and millet, with exception of ultimate strain, decreased as moisture content increased from 12 to 25% (db) and temperature from 20 to 50⁰C. Of the two parameters investigated, moisture content had the greatest influence on the mechanical properties of the grain.
- (2) Orientation of the grain kernel during loading strongly influenced the strength properties of the grain kernel. The compressive strength of Sorghum grain kernel, irrespective of kernel moisture content depended on whether the kernel was loaded in side or flat loading position indicating that sorghum grain is anisotropic with respect to mechanical strength properties.
- (3) Short tempering, of 15 minutes or less duration could be carried out without significantly affecting the strength properties of sorghum and millet grain.
- (4) Moisture content of sorghum and millet grain kernels had a significant influence on their stress relaxation behaviour. The stress-relaxation characteristics of single sorghum and millet kernels at different moisture contents could be represented by a three-term generalised Maxwell model.

CHAPTER FOUR

PRE-TREATMENT OF SORGHUM AND MILLET TO IMPROVE DEHULLING EFFICIENCY

4.1 Introduction

Efficient mechanical dehulling of sorghum and millet is one of the major problems facing the development of sorghum and millet processing facilities. This is the area where most sorghum and millet research is now concentrated. Sorghum and millet needs to be dehulled to remove the seed coat which is high in crude fibre and may contain anti-nutritional factors notably tannins, pigments and phytic acid. The principal dehulling methods of sorghum and millet are either the traditional manual system using pestle and mortar or mechanical systems using abrasive or attrition dehullers. However, present levels of recovery (percentage dehulled grain recovered after dehulling) for both methods are very low (often below 80%) and the quality is often poor due to poor seed coat removal, excessive loss of the endosperm and mixing of seed coat fragments with the flour. Percentage recovery is particularly low for the soft endosperm varieties, which are highly prone to shattering during the dehulling process, with mechanical dehulling systems giving the worst results (Nwansaru *et al.*, 1988; Rechert *et al.*, 1988). Due to these problems, coupled with the tediousness and time required to process these grains using the traditional dehulling system, the consumption patterns in sorghum and millet growing areas have been shifting towards non-traditional crops such as maize, wheat and rice even in areas where sorghum and millet used to be major traditional food crops. In addition, important sorghum varieties such as the brown-seeded bird resistant varieties are rapidly being phased out or are used exclusively for making local alcoholic drinks and for animal feeds. Given the economic and food situation in these areas and the overall advantage

offered by sorghum and millet over other cereal grains, the incentive of application of innovative technology in the processing of these grains is urgently needed.

Brown or red-seeded, bird resistant sorghum varieties are very important in parts of the semi-arid tropics where predation by birds (quelea) is severe. These varieties of sorghum are avoided by birds due to the high tannin content in their seed coats, which impart astringency to the grain. They also have a number of agronomic advantages over low tannin sorghums which include, resistance to insect pests, grain moulds and pre-harvest germination (Harris and Burns, 1970; Wasinika *et al.*, 1989). However, negative nutritional and food quality factors counteract these advantages. Tannins bind to and precipitate both endogenous and exogenous proteins, reducing the nutritional contribution of the grain (Asquith and Butler, 1986; Griffiths, 1985). Also tannin and phytic acid interfere with iron, calcium and zinc absorption by complex formation with these minerals in the gastrointestinal lumen rendering them unavailable to the body (Hagerman and Butler, 1981). The fibre content and colour of the grain also plays an important role in consumer acceptance of products prepared from these grains. These compounds (tannins, fibre and pigments) are mainly concentrated in the grain seed coat therefore the removal of the seed coat significantly reduces their concentration with a corresponding improvement in nutritional quality and consumer acceptance of food products made from these grains.

The most common method of removing the seed coat is by dehulling. However, as already mentioned, the yield of endosperm is low and nutrient loss high due to softness of the endosperm, which is characteristic of the vast majority of the high-tannin sorghum genotypes (Mwasaru *et al.*, 1988; Reichert *et al.*, 1988). Efficient mechanical dehulling especially of those varieties with soft floury endosperm, is difficult to achieve due to the fact that the kernel tends to shatter during the dehulling process even before the seed coat is removed. Under such circumstances, materials other than the seed coat are removed throughout the grain kernel and lost with the bran leading to unacceptably high losses of endosperm and important nutrients; also seed coat removal is poor leading to highly speckled flour with poor consumer acceptability.

From a nutritional standpoint, the most desirable dehulling process would remove only the seed coat and leave the high protein germ and aleurone layer attached to the endosperm. The ease with which this can be achieved depends mainly on the degree of adhesion of the seed coat to the endosperm and the degree to which the grain kernel can withstand mechanical action without shattering. The seed coat in sorghum and millet is tightly attached to the endosperm (Reichert, 1982) and hence requires a large amount of force to detach it during the dehulling process; when this force exceeds the grain ultimate strength breakage of the grain occurs. The dehulling efficiency of these grains could therefore be improved either by breeding of varieties with hard endosperm, which could withstand the forces encountered during the dehulling process without shattering or by introduction of pre-treatment methods which could reduce the adhesion strength between the seed coat and the endosperm prior to dehulling so that less force could be used to remove the seed coat.

From an engineering point of view the removal of the seed coat from the grain using a combination of pre-treatments to loosen the seed coat followed by mechanical means to detach the loose seed coat is the most promising line of approach to this problem. Breaking or loosening the adhesion between the seed coat and the endosperm is, therefore, an important initial step for a successful and efficient dehulling process for sorghum and millet.

In most of the sorghum and millet growing areas a range of simple but effective traditional pre-treatment methods of the whole grain before dehulling have been developed (Malleshi, 1988; Vogel and Graham, 1978; Young *et al.*, 1990). These pre-treatment methods involve one or several of the following procedures: the grain may be steamed, parboiled, dried, soaked in water, alkali or acid solutions, germinated or roasted. All these pre-treatments combined are aimed at facilitating the removal of the seed coat as completely as possible with least damage and loss of endosperm. Other effects on the treated grain include:

- (i) Improvement of milling (hand) of the treated dried grain.
- (ii) Improvement of storage quality of dry end products
- (iii) Improvement of flavour and acceptability of the resulting cooked products

- (iv) Improvement of digestibility of the products as well as improved utilisation of micro-elements like minerals and vitamins
- (v) Phytic acid, which depresses uptake of important minerals such as calcium, zinc and iron, is broken down by the appearance of phytase during steeping and germination

It is surprising, however, to note that despite the advantages offered by these traditional pre-treatments, very few if any, of these traditional processes of whole grain processing have survived in westernised urban cultures in the form of industrialised processes. The main objective of this chapter was therefore to study the effect of incorporating some of these traditional pre-treatment methods in the current mechanical dehulling system on the dehulling efficiency of sorghum and millet. Specifically, of interest was the use of hydrothermal pre-treatments (tempering and steam treatment) and alkali as a dehulling agent for sorghum and millet.

4.1.2 Pre-treatment methods

4.1.2.1 Tempering

In grain processing, the word 'tempering' has a multiplicity of meanings. In grain drying, the holding of the grain between passes through a multi-pass drier is called tempering. In grain milling, tempering refers to moistening of the grain before milling and allowing migration of moisture inside the grain kernel, which serves to equalise the moisture concentration throughout the grain. For wheat, this kind of tempering toughens the bran, allowing cleaner separation of bran and endosperm and also increases the friability of the endosperm particles (Abderahmann & Ferrell, 1981). In dehulling of grain like sorghum or millet, tempering refers to addition of water to the grain or soaking the grain for a short duration followed by a rest period to allow the temper water to penetrate only the outer layers of the grain so that the texture of this layer is changed and the seed coat-endosperm bond is weakened. This allows the seed coat to be easily removed from the endosperm during the dehulling process without

much damage to the endosperm. This method of pre-treatment is widely practised in the traditional pestle and mortar dehulling system.

4.1.2 2. Hydrothermal treatments

Hydrothermal treatment refers to the addition or removal of moisture and heat to or from a commodity. Hydrothermal treatment has been shown to have a significant effect on improving the dehulling efficiency of several grains. Sefa Dede and Stanley (1979) found that heat treatment of moistened beans and cowpeas made the seed coat much easier to remove during the dehulling process due to the fact that the cotyledons tended to shrink more than the seed coat during this process resulting in the seed coat being loosened from the cotyledons. Ethiwe *et al.* (1987) studied the effect of hydrothermal treatment on seed coat removal in field peas by using a rubberised aluminium disc in a tangential abrasive-dehulling device (TADD). They found that seed coat breakage from the cotyledons was far easier after hydrothermal treatment. Singh (1995) working on canola (rapeseed) found that hydrothermal conditioning improved the dehulling efficiency by up to 41% compared to unconditioned seeds.

In hydro-thermal treatment the loosening or breaking of the seed coat-endosperm bond is achieved by the generation of an internal cell pressure or stresses due to hydration or heat treatments or combination of both. A grain kernel undergoes several physical changes when subjected to hydrothermal treatment. Moisture absorption or temperature rise causes swelling or expansion, whereas moisture loss or cooling causes contraction or shrinkage. Since a grain kernel (such as sorghum or millet) is a composite structure made of different components each with its own physical and mechanical properties, these components of the kernel tend to expand or contract to a different extent when the kernel is subjected to hydro-thermal treatment. The degree of expansion or contraction of the seed coat (which mainly consists of cellulose) will be different from that of the endosperm (which is mainly made of starch and protein). As a result, during hydro-thermal treatment internal slips tends to occur resulting in

partial separation of the seed coat from the endosperm thus making it possible for less force to be used to remove it during the dehulling process.

Three important conditioning factors, namely grain moisture content, temperature and the rate of change of these factors, have a significant effect on the extent of de-bonding which may be achieved during hydrothermal treatment. One aim of this section was therefore to investigate the effect of different hydrothermal pre-treatments on sorghum and millet dehulling efficiency during mechanical dehulling and to establish the optimum conditions for these pre-treatments for sorghum and millet.

4.1.2.3 Alkali dehulling of sorghum and millet

In areas where brown, bird resistant sorghum varieties are extensively grown, alkaline treatment of the grain has been practised by the local people as one method of detoxifying the grain or reducing the harm-full effects of the polyphenolic compounds (tannins) in their seed coat. Farmers in the Southern highlands of Uganda and neighbouring areas of Tanzania, have discovered a cheap but effective method for reducing the effects of anti-nutritional factors in sorghum and millet. This involves mixing the grain with wood ash slurry (which is alkaline) followed by soaking the grain in water overnight. This treatment effectively detoxifies the grain and improves its nutritional quality to the level of low tannin grains (Mukuru, 1992). Also a mineral soil found in Northern Tanzania known locally as "magadi" (alkaline in nature with pH of 9.7) has been found to be effective in reducing the anti-nutritional effects of high tannin sorghum varieties and improving the nutritional value of these high tannin sorghums to the level of low tannin varieties (Monyo *et al.*, 1992). Although these treatments are able to reduce the levels of tannin in the grain, they are unable to solve the problem of high fibre content and colour imparted to the products made from these brown sorghums; factors, which are very important in consumer acceptance of products made from these grains.

Alkali treatment under controlled conditions of temperature, concentration and soaking duration, has been used to dehull a number of cereal grains, including maize, barley, rye and oats to achieve improved yield and provide attractive ready-to-eat products (Barta *et al.*, 1966). Alkali treatment of maize has been shown to loosen and separate the seed coat from the endosperm to produce seed coat free maize (Mistry and Eckhoff, 1992; Blessin *et al.*, 1970) and seed coat free sorghum in wet milling for starch production purposes (Blessin *et al.*, 1971). The use of alkali as a dehulling agent for sorghum and millet could therefore be a potential method for the production of high quality dehulled sorghum and millet grain, especially from those varieties that are not suitable for current conventional processing methods due to their soft textured endosperm.

The second aim of this section was therefore, to develop an alkali based sorghum and millet dehulling process, that is easy to control, and one which is both time and cost effective than the current dehulling methods. Also one which is capable of achieving higher yields of better quality products than it is possible with any of the current dehulling methods. The possibility of producing high quality and acceptable products from these otherwise rejected or low grade grain could lead to substantial technological advantages, such as the use of sorghum and millet flour combined with wheat for making of high quality products such as bread, biscuits, snacks and other convenient foods which are in high demand especially in urban areas. Also there will be a possibility of using dehulled whole grain sorghum and millet grain as a rice substitute, a product which is cheaper than rice, easier to prepare and stores better than flour products.

4.1.3 Measurement of seed coat adhesion strength in sorghum and millet

Seed coat adhesion strength is an important grain property which determines the dehulling duration and the amount of force (normal and tangential) which has to be applied on the grain in order to separate the seed coat from the endosperm during the dehulling process. Knowledge of the seed coat adhesion strength and the effect of different pre-treatments on

the seed coat adhesion strength is important in developing different pre-treatment methods aimed at improving the dehulling efficiency and in the design of mechanical equipment for dehulling of pre-treated grain.

Several methods have been described to assess abrasion resistance and skin adhesion on fruits and vegetables. Examples are the use of a scuff meter for measuring skin adhesion in potatoes (Muir and Bowden, 1994) and use of a friction apparatus developed by Pulchaski and Brsewitz (1996) for measuring abrasion resistance in watermelon. Unlike vegetables, however, very little information is available in the literature on methods for measuring seed coat adhesion strength in grain. Ethiwe and Reichert (1987) studied seed coat adhesion in cow-peas, pigeon peas and mung beans by nicking the grain with a pocket knife and subjectively evaluating the degree to which the seed coat was attached to the cotyledons as either loose, intermediate or tight. Although such a rating gave a rough idea of the degree of adhesion of the seed coat to the cotyledons or endosperm, it did not provide any quantitative measure of the seed coat adhesion strength. Phirke *et al.* (1995) designed and constructed a shear force measuring apparatus using piezo-electric transducers, and measured the shear force required for the removal of pigeon pea seed coat, splitting the cotyledons and breaking raw and pre-treated pigeon-peas. So far there has not been a method for measuring the seed coat adhesion strength in cereal grains.

The third aim of this section was therefore to design and construct an apparatus that could be used to measure the seed coat adhesion strength in cereal grain and also measure the coefficient of friction between single grain kernel and different structural materials. Such information will be useful in the evaluation of the capabilities of different pre-treatment methods in reducing the seed coat adhesion strength and also in evaluation of friction properties of the grain on different structural surfaces. The apparatus may also be useful to other scientists in field such as breeders in selection of grain varieties that have low seed coat adhesion strength and therefore good dehulling characteristics.

4.1.4 Moisture absorption characteristics of sorghum and millet

Conditioning of sorghum and millet by addition of moisture or soaking (e.g. during tempering, hydrothermal treatment and alkali dehulling) is an integral part of the dehulling process, especially in traditional systems. Knowledge of the moisture absorption characteristics of the grain at different processing conditions is therefore important in development of efficient pre-treatment methods. Different studies have reported that temperature, initial moisture content, kernel size, kernel structure and composition affects the rate of moisture absorption and distribution within the grain kernel (Abdelrahman and Ferrell, 1981; Stenvert and Kingswood, 1977; Muthukumarappan and Gunasekaran, 1994). From an engineering and processing point of view, one is interested not only in knowing how fast the absorption of water can be accomplished, but how it is affected by different process variables, and how one can predict the soaking duration under given conditions.

Quantitative analysis of water absorption in grain has been performed in maize (Becker 1960), wheat (Becker and Sallans, 1955; Jaros *et al.*, 1992), soybean (Haghighi and Sergerlind, 1978) and paddy (Steffel and Sing, 1980; Lu and Sibenmorgen, 1992). Most of these studies were based on Fick's law of diffusion. Recently, a two parameter non-exponential empirical model has been proposed by Peleg (Peleg, 1988). The applicability of this model has been demonstrated for a number of food grains including, soybeans, cow-peas, and peanuts (Sopade and Obekpa, 1990), chick peas and field pea (Hung *et al.*, 1993), maize and sorghum (Sopade and Obekpa, 1992) and field beans (Abu-Ghannanam and Mckenna, 1997). All these investigations showed good agreement between experimental and predicted data.

The fourth aim of this section was therefore to study the effects of process variables (such as temperature and soaking duration), grain physical factors (initial moisture content, endosperm structure and grain variety) on the rate of moisture absorption in sorghum and millet and to compare the capabilities of moisture absorption models based on Fick's law of diffusion and Peleg's model in modelling the moisture absorption characteristics of sorghum and millet

during tempering. The final objective was to develop a predictive model, which could be used to predict tempering duration in sorghum and millet at different conditions of temperature and initial grain moisture content.

4.2 Materials and methods

4.2.1 Materials

4.2.1.1 Grain samples

Two varieties of sorghum, (Dionje, a vitreous white branned sorghum from Tanzania and Jumbo a red branned soft endosperm sorghum from Australia) and one pearl millet variety (IM from India) were used in this study.

4.2.1.2 Chemicals

An aqueous solution of sodium hydroxide was used as the dehulling agent and iodine in potassium iodide solution was used to facilitate visual evaluation of the dehulling efficiency of the alkali-dehulled grain.

4.2.1.3 Equipment

4.2.1.3.1 Dehulling equipment

In order to study the effect of different pre-treatments on mechanical dehulling characteristics of sorghum and millet at laboratory scale, a small laboratory abrasive dehuller using the tangential abrasive dehulling principle was designed and constructed. The tangential dehulling principle was adopted for this dehuller because, when compared to other dehulling methods

ultimately out into the bran exhaust port. Figure 4.1(a) and 4.1(b) shows the schematic diagram of the dehuller

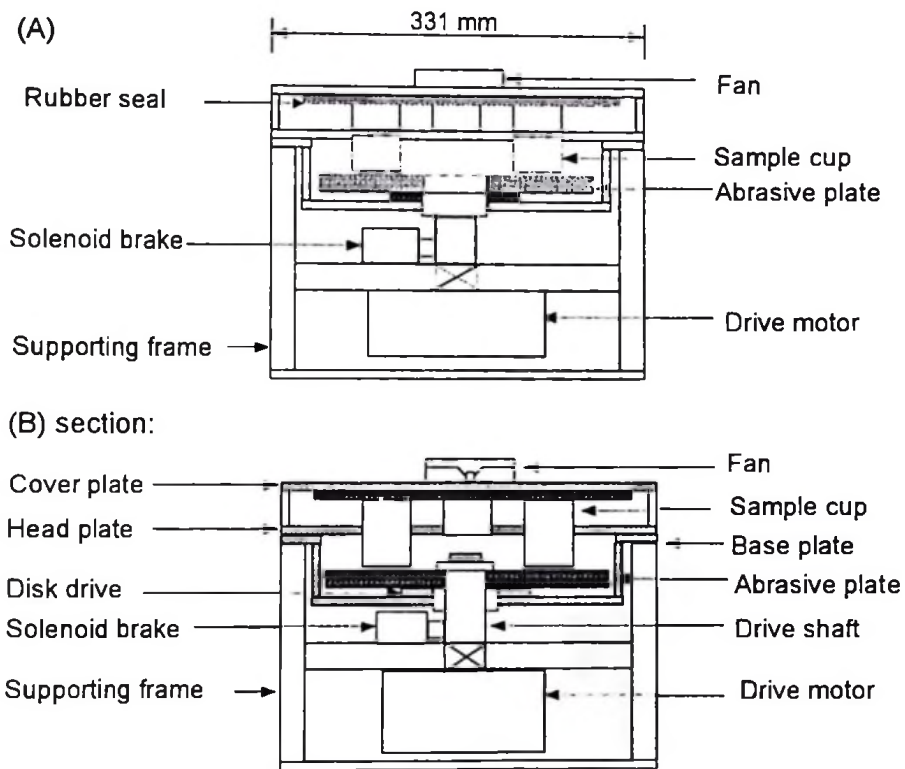


Figure 4.1 Schematic drawing of the Tangential Abrasive Dehulling Device (TADD)

4.2.1.3.2 Seed coat adhesion strength measuring apparatus

Figure 4.2 shows a schematic drawing of the apparatus for the determination of the seed coat adhesion strength and coefficient of friction of a single grain kernel. The apparatus consists of a pair of sample holders *A* and *B* and a sliding friction plate *C* sandwiched between them. The grain samples are clamped on sample holders *A* and *B* such that maximum surface area of the grain is in contact with the sliding friction plate *C*. Sample holder *B* is connected to a movable arm *E*, which is connected to the balancing beam *D* and can slide along *D* to accommodate

different sizes of test samples. The lever system is balanced by use of balance weight S and can be loaded by placing a dead weight W on the loading pan. The sliding friction plate is connected to the load cell attached to a tensile testing machine cross head. When the cross-head is set in motion it applies a pulling force F to the friction plate. The load cell is connected to a computer that records the force and the displacement of the friction plate.

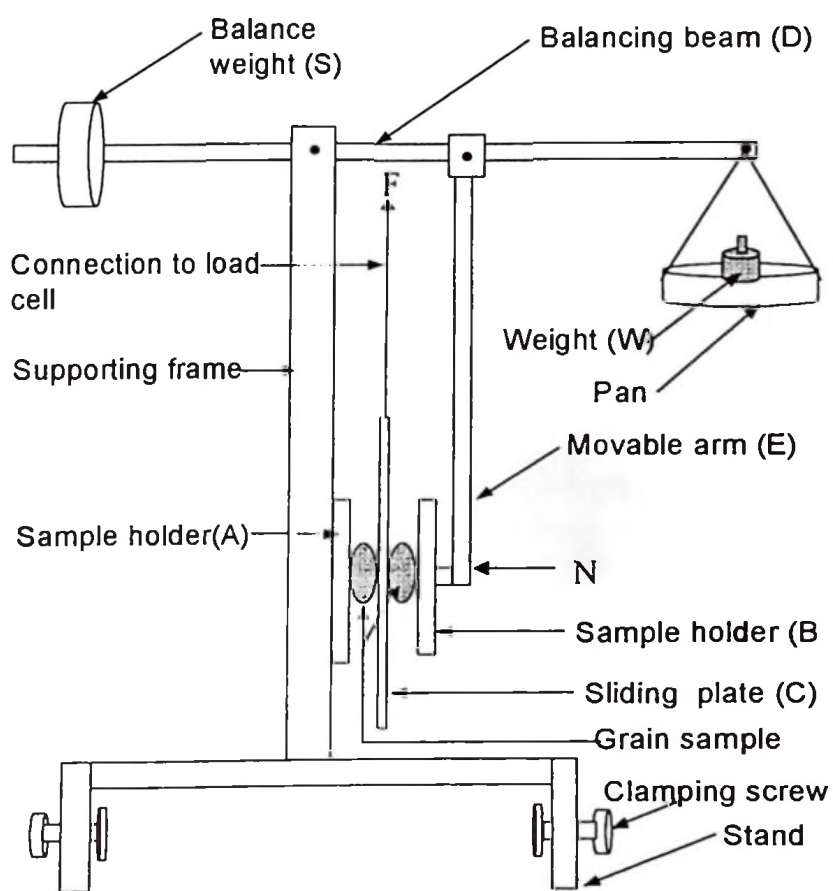


Figure 4.2 Seed coat adhesion measuring apparatus

4.2.2 Methods

4.2.2.1 Evaluation of the performance of the tangential dehulling device

To evaluate the performance of the tangential dehulling device, preliminary dehulling tests were conducted using a heavy-duty 80-grit size abrasive cloth glued to the aluminium disc rotating at 1500 rpm. The influence of sample size and dehulling duration on yield were investigated using different sample sizes (2, 5, 8 and 10g) and different dehulling duration (2, 3, 4 and 5 minutes). Moisture content of the grain samples was maintained at 12% (db) throughout the tests.

4.2.2.2 Hydrothermal treatments

Hydrothermal treatments investigated included:

- (a) Tempering or soaking the grain in distilled water for different durations at ambient temperature (20⁰C) followed by drying
- (b) Steam treatment of the grain for different durations followed by drying to the original moisture content (12% db)

4.2.2.2.1 Grain tempering

Tempering of the grain was carried out by soaking 5 g of each grain variety in distilled water for three different durations, 15, 30 and 60 minutes, resulting in three different moisture levels. After soaking, each sample was divided into two sub-samples and dried, using two different methods as explained below.

4.2.2.2.2 Steam treatment

Steam treatment of the grain was carried out in a specially constructed steaming unit, which consisted of a steam generator and a sample holder. Steam was generated by boiling water in an electric kettle and passing it through the grain sample held in a wire mesh basket. Three steaming durations i.e. 5, 10, and 15 minutes were used. After steaming each sample was divided into two sub samples and dried using two different methods as explained below.

4.2.2.2.3 Drying methods for the conditioned grain samples

Stresses within the grain kernel are dependent on both moisture and thermal gradients. Drying temperature and drying rate are important factors in the development of stress within the grain. Two different drying methods were used to induce thermal stress in the pre-treated grain samples and to reduce the moisture content to 12% (db). These were, slow drying using ambient air at 20⁰C, and oven drying at 60⁰C. It was necessary to reduce the moisture content to 12% (db) to avoid clogging the abrasive surface of the dehuller by moist grain during the dehulling process.

4.2.2.2.4 Mechanical dehulling of the pre-treated grain

Pre-treated and untreated (control) grain samples all at 12% (mcdB) were dehulled in the tangential dehuller for a fixed retention time of four minutes (this was the optimum retention time determined from the preliminary tests, resulting in removal of 10% of the grain sample as bran which was considered equivalent to the seed coat content of the grain). The quality of the dehulled grain and the dehulling efficiency were then evaluated based on the extent of seed coat removed, crude fibre reduction, amount of broken grain and the yield of dehulled grain obtained.

4.2.2.4 Alkali dehulling

The dehulling process used in this study was a modified form of a process developed by Blessin *et al.* (1970) for dehulling of dent yellow maize and sorghum for starch production purposes. Preliminary exploratory experiments were carried out using different combinations of alkali concentration and soaking duration in order to determine the optimum alkali concentration and soaking duration for the dehulling process. These exploratory tests involved soaking 5 g of dry clean grain in 20 ml aqueous solution of sodium hydroxide at three different concentrations (3%, 6% and 10% w/w) for three different soaking durations (6, 8, and 10 minutes). The soaking temperature was maintained at 60°C using a constant water bath maintained at $60 \pm 1.0^{\circ}\text{C}$ (60°C was the mean optimum temperature obtained in previous investigations by Blessin *et al.* (1971), Mistry and Eckhoff (1992) and Sigh *et al.* (1997) for dehulling maize). The grain was stirred frequently during the dehulling process. After a pre-set duration the grain was removed from the water bath and thoroughly washed with hot water to remove the dissolved seed coat and to prevent further action of the alkali. The residual alkali was neutralised by soaking the grain in glacial acetic acid followed by further washing with water to remove excess acid and the detached seed coat. The dehulled grain was air dried and weighed to determine the weight loss and a sample was ground into flour and analysed for protein, ash, crude fibre, and ether extracts according to standard AACC methods (AACC,1995).

4.2.2.5 Evaluation of the dehulling efficiency

Dehulling efficiency refers to the extent to which the seed coat has been removed from the endosperm during the dehulling process at a given extraction level. To evaluate the dehulling efficiency it was necessary to be able to quantify the effect of seed coat removal from the endosperm. Different methods have been used to evaluate the dehulling efficiency in cereal grain. Wasserman *et al.* (1970) used crude fibre measurements of dehulled wheat grain to express the dehulling efficiency as a function of process variables such as milling time,

tempering duration, and the type of abrasive used. Visual methods are also commonly used, mainly because they are simple and fast, but the weakness of these methods is that they have the usual errors of subjective tests. These limitations, however, can be reduced by a visual or optical observation of kernels stained or immersed in dye solutions that preferentially stain the seed coat or the endosperm.

Chemical and optical methods for the evaluation of dehulling efficiency are also commonly used. Chemical methods are based on measuring a component that is more concentrated in the seed coat than in the starchy endosperm. Components proposed for measuring include crude fibre, ash and ash components (Hogan and Deobold, 1965; Raghavendra Rao *et al.*, 1975). Optical methods rely on the reflectance properties of the flour produced after dehulling and grinding the grain (Skarsaune and Shuey, 1975; Murty and Dietz, 1974). In the current study two separate methods were used to evaluate the dehulling efficiency for different pre-treatments:

- (i) The extent of seed coat removal from the grain kernel
- (ii) Crude fibre reduction in the dehulled grain.

4.2.2.5.1 Determination of seed coat content of sorghum and millet grain by manual dissection

To determine the actual proportion of the grain required to be removed as bran during the mechanical and alkali dehulling, the seed coat content of the grain was determined by manual peeling of the seed coat from individual grain kernels after soaking in distilled water for 15 minutes. The peeled grain and seed coat were air-dried and their proportions determined. Five replications each weighing 2 g for each grain type (approximately 60 kernels for sorghum and 120 for millet) were used for the determination of seed coat content.

4.2.2.5.2 Calculation of dehulling efficiency based on the amount of seed coat removed during the dehulling process

In this method, dehulling efficiency was based on the extent to which the seed coat was removed from the endosperm fraction. Replicate samples (5 replicates) each weighing 2 g were drawn from the mechanically dehulled grain and the seed coat remaining on partially dehulled grain kernels was manually removed and weighed. The percent seed coat removed from the dehulled grain by the dehulling process was then determined as:

$$\% \text{ seed coat removed} = 100 - \left(\frac{\% \text{ seed coat on partially dehulled grain}}{\% \text{ seed coat on unde-hulled grain}} \right) \times 100 \quad (4.1)$$

Kernel breakage was another important factor that needed to be considered during the evaluation of the dehulling efficiency because it reflects the quality of the dehulled grain. The percentage of broken kernels was determined by sieving a 5 g sample (in 4 replicates) of the dehulled grain on 2.5 mm or 1.5 mm mesh screens for sorghum and millet respectively. The weight percentage of kernels passing through the screen gave the relative measure of broken kernels in the sample. Dehulling efficiency (D_{eff}) for different pre-treatments was then calculated as:

$$D_{eff} = C_n \times C_w \times C_y \times 100 \% \quad (4.2)$$

where C_n is the coefficient of dehulling which is defined as the extent of seed coat removal from the endosperm during the dehulling process, C_w is the coefficient of wholeness of the dehulled kernels which defines the quality of dehulled grain recovered and C_y is the yield factor which is defined as the proportion of dehulled grain recovered relative to the maximum expected yield. The coefficients C_n , C_w and C_y were determined as:

$$C_n = \frac{M_p}{M_w} \quad (4.3)$$

$$C_w = \frac{K}{K + b} \quad (4.4)$$

$$C_y = \frac{Y_a}{Y_e} \quad (4.5)$$

where M_p is the seed coat removed by the dehulling process (%), M_w is the seed coat content of dehulled grain (%), K is the mass of the whole kernels in the final product and b is the mass of the broken kernels in the dehulled grain sample. Y_a is the actual yield obtained and Y_e is the maximum expected yield of dehulled grain, and were calculated as:

$$Y_a = \frac{x}{M} \times 100 \% \quad (4.6)$$

and

$$Y_e = (100-u)\% \quad (4.7)$$

where x is the mass of the dehulled grain recovered, M is the mass of the grain sample before dehulling, and u is the seed coat content of unde-hulled grain (%). The maximum expected yield is the yield that would have been obtained if only the seed coat was removed from the grain without any loss of endosperm (i.e. 100% recovery of the endosperm).

4.2.2.5.3 Dehulling efficiency based on crude fibre reduction

The second method used to evaluate dehulling efficiency was based on the degree of reduction of crude fibre content in the dehulled grain by different pre-treatments in comparison to the crude fibre reduction in the hand peeled sample which was used here as a standard for comparison purpose. The following formula was used to calculate the dehulling efficiency based on the amount of crude fibre reduction on the endosperm fraction.

$$D_{eff} = \frac{\text{crude fibre reduction by the dehulling process}}{\text{crude fibre reduction in the hand peeled grain}} \times C_v \times 100\% \quad (4.8)$$

4.2.2.5 4 Proximate composition of the dehulled grain

The main interest in dehulling sorghum and millet grain is to improve the overall quality of the final product in terms of its nutritive value, digestibility and palatability by removing the unwanted fibrous part of the grain and the harmful anti-nutritional components. Different dehulling methods and pre-treatments tend to affect the composition of the dehulled grain differently. It was therefore necessary to determine the proximate composition of pre-treated mechanically dehulled grain and compare it with that of hand peeled and whole grain to find the extent to which different pre-treatment methods affected the composition of different essential nutrients in the dehulled grain. The proximate composition (i.e. protein, oil, ash, and crude fibre content) of processed and unprocessed sorghum and millet grain was determined in accordance with standard AACC approved methods (AACC,1995). The composition of manually peeled grain was used as the base value while the whole-undehulled grain was used as control.

4.2.2.6 Determination of seed coat adhesion strength and dynamic friction coefficient of single grain kernel

4.2.2.6.2.1 Determination of seed coat adhesion strength

Seed coat adhesion strength was determined by measuring the tangential force required to remove a unit area of seed coat from the grain using the apparatus shown in figure 4.2. A constant normal force N was applied to hold the seed coat to the friction plate by applying a dead weight (W) on the pan (figure 4.2). Once the normal force was applied, the cross-head was set in motion pulling the abrasive plate up. As the friction plate moves up, it strips off the

part of the seed coat in contact with it. The load cell was connected to a personal computer, which recorded the force required to pull the friction plate. The average peak force recorded was taken as the seed coat adhesion strength and the seed coat area removed was determined using image analysis. The seed coat adhesion strength per unit area was determined from the peak force and the area of seed coat removed. The force required to remove the seed coat from grain kernels tempered for different durations was determined and compared to the force required to remove the seed coat from untempered grain. Grain tempering was carried out by soaking the grain in distilled water at room temperature (20°C) for three different soaking durations, i.e. 15, 30 and 60 minutes.

4.2.2.6.2 Determination of coefficient of friction of single grain kernel

Apart from seed coat adhesion strength measurement the apparatus shown on figure 4.2 could also be used to determine the dynamic coefficient of friction of individual grain kernels on different structural materials. This was carried out by substituting the structural material whose coefficient of friction was required (e.g. plastic, aluminium, wood, steel etc.) for the friction plate (C). By varying the normal force, N , different corresponding values of F were obtained. The coefficient of friction was then evaluated from the Coulomb's law of friction;

$$F = \mu N + C \quad (4.9).$$

where F is the frictional force-recorded by the load cell, N is the normal force, μ is the coefficient of friction and C is the cohesion between grain and material surface. When different values of friction force was plotted against the corresponding values of normal force, the result was a straight-line with the slope equal to μ and y-intercept equal to C . The experiment was repeated with grain at different moisture contents to determine the relationship between μ , C and moisture content.

4.2.2.7 Moisture absorption characteristics of sorghum and millet

Moisture absorption characteristics of sorghum and millet were investigated by soaking 5 g of grain samples previously equilibrated to different moisture contents (12 to 25% db) in beakers containing 20 ml of distilled water. The beakers containing the samples were then placed in a thermostatically controlled water bath fixed at the required soaking temperature ($\pm 1^{\circ}\text{C}$). The soaking temperatures investigated in this study were 20°C , 30°C , 40°C , and 50°C . The grain was removed from the soaking water at 15 minutes intervals, quickly rolled in a paper towel to remove surface water and weighed. The increase in grain weight was taken as the amount of water absorbed during the given soaking period. After weighing, the grain was quickly returned into the soaking water and put back into the water bath. All samples were studied in triplicate and the average moisture gain was expressed in terms of the fraction of total moisture absorbed and in percent moisture content dry basis.

4.2.2.7.1 Modelling water absorption in sorghum and millet

Two moisture absorption models were used to study the moisture absorption characteristics in sorghum and millet

4.2.2.7.1.1 Fickian diffusion model

Fick's law of diffusion has been used to describe water movements in grain during absorption (Becker 1960). If the sorghum or millet grain kernel is assumed to be a porous, solid isotropic material, spherical in shape with uniform moisture content at the start of soaking period and a negligible resistance to water transfer from the medium outside the grain kernel, the diffusion equation in spherical co-ordinates for such a material was provided by Crank (1975) as;

$$\frac{dm}{dt} = \frac{1}{r^2} \frac{\partial}{\partial r} \left(r^2 D \frac{\partial m}{\partial r} \right) \quad (4.10)$$

where m is the mass of water absorbed at time t , r is the radial distance (m), t is the soaking time (hr) and D is the diffusion coefficient (m^2h^{-1}).

By applying appropriate assumptions an analytical solution to this differential equation can be obtained. One of the most widely known analytical solutions was also developed by Crank (1975) under the following assumptions:

- (i) The diffusion coefficient D is constant,
- (ii) Effect of volume change as a result of moisture absorption is negligible,
- (iii) Surface concentration reached that of saturation instantaneously upon immersion in the water,
- (iv) Moisture concentration within the kernel is evenly distributed before immersion.

The result in terms of fraction of total moisture absorption or moisture ratio M_t/M_∞ after time t can be expressed as:

$$\frac{M(t)}{M_\infty} = 1 - \frac{6}{\pi^2} \sum_{n=1}^{\infty} \frac{1}{n^2} \exp\left(-Dn^2\pi^2 \frac{t}{r^2}\right) \quad (4.11)$$

where $M(t)$ is the mass of water absorbed after time t , M_∞ is the mass of water absorbed at saturation, r is the average radius of the grain kernel and t is the soaking duration.

Considering only the first term of the series, equation 4.11 can be simplified to;

$$\frac{M(t)}{M_\infty} = 1 - \frac{6}{\pi^2} \exp\left(-\frac{D\pi^2 t}{r^2}\right) \quad (4.11b)$$

rearranging equation 4.11b, D can be calculated as;

$$D = -\frac{r^2}{\pi^2 t} \ln \left[\frac{\pi^2}{6} \left(\frac{M(t)}{M_\infty} - 1 \right) \right] \quad (4.11c)$$

Equation 4.11b was used to model moisture absorption in sorghum and millet at different temperatures. To verify the applicability of the model to sorghum and millet experimentally, moisture ratios were determined from the absorption data obtained at different temperatures for different soaking duration; these values, as well as measured r values (the average kernel radius), were substituted into equation (4.11b) and the diffusion coefficient D was determined from equation 4.11c. The calculated value of the diffusion coefficient D was then substituted in equation (4.11b) to simulate moisture ratio values at different soaking duration for different temperature levels. The simulated and experimentally determined moisture ratios were then plotted together on the same graph. If equation (4.11b) was truly descriptive of the moisture adsorption behaviour of sorghum or millet, the simulated curve should closely duplicate the experimentally obtained curve.

Previous analyses of water uptake by cereal grains and legumes (wheat, maize and soybeans) have established that diffusion of moisture in grain is influenced by the temperature of the fluid medium according to the Arrhenius function (Hsu, 1983; Steffe and Singh, 1980). The temperature dependency of the moisture diffusivity of sorghum and millet was fitted to an Arrhenius function as follows:

$$D = D_0 \exp \left(-\frac{B_D}{T} \right) \quad (4.12)$$

where D is the diffusion coefficient (m^2h^{-1}), T is the absolute temperature of the soaking water (K), B_D and D_0 are constants. To find whether the moisture diffusivity of sorghum and millet follow the Arrhenius law, log values of the diffusion coefficient D were plotted against the reciprocal of the absolute temperature ($1/T$). This also allowed the activation energy of the soaking process to be evaluated.

4.2.2.7.1.2 Peleg's model

Peleg's model is a simple empirical mathematical model of water absorption during soaking of food grains. The main interest in this model lies in its simplicity compared to other models and its ability to accurately predict water uptake. Peleg's model is:

$$M_t = M_0 + \frac{t}{K_1 + K_2 t} \quad (4.13)$$

where M_0 is the initial moisture content (%db), M_t is moisture content after time t , t is the soaking duration, K_1 and K_2 are constants (frequently known as Peleg's constants).

Equation (4.13) can be rearranged to give:

$$\frac{t}{M_t - M_0} = K_1 + K_2 t \quad (4.14)$$

Plotting $\frac{t}{M_t - M_0}$ against t and fitting a straight line gives K_1 as the y-intercept, and K_2 as the gradient. Such a plot, apart from testing the applicability of the model to the given absorption data, also allows the effect of temperature and other parameters on the values of the constants to be studied. Sopade and Obekpa (1990) observed that K_1 is a function of temperature and K_2 is a constant for a particular food material and hence could be used as a characteristic sorption parameter. It appears that K_1 could be linked to a diffusion coefficient, although K_1 decreases, rather than increasing as temperature increases.

An Arrhenius type function was also used to describe the temperature dependence of the reciprocal of constant K_1 in the following manner

$$\frac{1}{K_1} = K_0 \exp\left(-\frac{B_p}{T}\right) \quad (4.15)$$

where K_0 is a constant, $B_p = E_a/R$, E_a is the activation energy (J mol^{-1}), R is the gas constant ($\text{J mol}^{-1} \text{K}^{-1}$), T is the absolute temperature (K).

Comparison of the abilities of the two models to simulate the moisture absorption characteristics of sorghum and millet was done by comparing the root-mean square error (RMSE) values between the experimental data and predicted data, which was calculated according to the following equation (Mead *et al.*, 1993):

$$RMSE = \frac{1}{n} \sqrt{\sum_{i=1}^n (M_{ei} - P_{ni})^2} \quad (4.16)$$

Where M_{ei} are the experimental values and P_{ni} are the predicted values

4.3. Results and Discussion

4.3.1 Hand peeling of soaked and steamed sorghum and millet grain

Soaking of sorghum and millet grain in cold water for 15 minutes followed by 15 minutes rest period to allow the surface moisture to be absorbed into the grain gave the best results for hand peeling. However, the ease of peeling the seed coat from the endosperm decreased as the grain dried. Steam treatment for 15 minutes also facilitated the removal of the seed coat from the endosperm, however, the effect of steam treatment also diminished as the grain dried. This showed that both soaking and steaming were effective in reducing the strong association between the seed coat and the endosperm as long as the seed coat was removed while the grain was still in moist condition.

4.3.1.1 Seed coat content of hand peeled sorghum and millet grain

The results of seed coat content from hand peeled grain are summarised in Table 4.1. The seed coat content of Jumbo sorghum variety (which has a thick pericarp) was found to be 11.5% while for Dionje (which has a thin pericarp) was 8.3% of the grain weight and for millet the seed coat content was 9.9% of the grain weight. These figures are within the range of seed coat content reported in literature, which for sorghum varies between 4.8% - 11.6% while for millet seed coat content varies from 7.2% - 10.7% among the international collection (Sergio and Rooney, 1995).

Table 4.1. Seed coat content of hand peeled sorghum and millet grain

Grain variety	Endosperm content (%)	seed coat content (%)
Jumbo	89.6 ± 0.33*	11.4 ± 0.4
Dionje	92.4 ± 0.24	8.3 ± 0.28
IM	90.2 ± 0.25	9.9 ± 0.31

Each data point is a mean of 5 replications

* Standard deviation

4.3 2 Effect of hydrothermal treatments on dehulling of sorghum and millet

Soaking (tempering) and steam treatment of the grain resulted in absorption of moisture by the grain, the extent of moisture absorption depended on soaking duration, physical properties of

the grain and the process conditions. Soaking for 15, 30 and 60 minutes at ambient temperature (20°C) resulted in an increase in moisture content of the grain from the initial value of 12% (db) to 24.3, 26.4 and 27.1 % (db) for Dionje, 25.2, 27.4 and 31.4 % (db) for Jumbo and 24.2, 34.4 and 44.0 % (db) for millet respectively. Steaming for 5, 10, and 15 minutes resulted in moisture content of the grain to increase from the initial 12% (db) to 26.6, 29.0 and 33.6% (db) for Dionje, 27.7, 29.9 and 35.4% (db) for Jumbo and 28.6, 29.0 and 33.6% (db) for millet respectively. The soft variety (Jumbo) absorbed more moisture than the hard variety (Dionje) in both soaking at ambient temperature and in steam treatment.

To investigate the effect of these hydro-thermal treatments on dehulling efficiency of sorghum and millet, the pre-treated grain was dehulled in the tangential abrasive dehulling device (TADD) described in section 4.2.1.3.1 and their proximate composition and dehulling efficiency evaluated and compared to hand peeled and untreated grain.

4.3.2.1 Proximate analysis of the grain samples

4.3.2.1.1 Proximate composition of whole grain

The results of proximate composition of the whole (undehulled) grain are summarised in Table 4.2. These values were used as a control to compare how different pre-treatment methods affected the nutrient composition of the grain.

4.3.2.1.2 Proximate composition of manually dissected grain

The proximate composition of manually dissected grain was used as a base values to compare how different dehulling methods or different pre-treatments affected the composition of the dehulled grain. By hand dissection it was possible to obtain seed coat-free endosperm (pure endosperm) and pure seed coat, which were necessary in the evaluation of the proportion of the grain to be removed as bran during the dehulling process. Crude fibre reduction due to

removal of the seed coat from the grain by hand peeling was also used as a base line value to compare the effectiveness of different pre-treatments in reducing the crude fibre content of the dehulled grain. In this case, the amount of crude fibre reduction in hand dissected grain was considered as the maximum amount that could be achieved by an ideal dehulling process.

Table 4.2 Proximate composition of whole and dissected sorghum and millet kernels

Grain variety	Pre-Treatment	Ash (%)	Oil (%)	Crude fibre (%)	Crude protein [N×6.25] (%)
Sorghum		(1.1 - 4.5) ^a	(0.5 - 5.2)	(1.2 - 6.6)	(7.3 - 15.6)
Jumbo	Undehulled	1.66	4.19	6.12	13.06
	H/dissected	1.32	3.34	3.31	13.9
Dionje	Undehulled	1.95	2.85	4.81	9.06
	H/dissected	1.39	2.13	2.75	14.18
Millet		(1.6 - 3.6)	(1.5 - 6.8)	(1.4 - 7.3)	(8.6 - 19.4)
IM	Undehulled	1.98	5.47	7.17	10.18
	H/dissected	1.03	3.14	2.64	11.875

^a Range of proximate composition from literature (Sergio & Rooney 1995)

Each data point is an average of 3 replications.

H/dissected is hand-dissected grain

Proximate composition of the manually dissected grain is given in Table 4.2. Manually dissected grain had on average 45.9 %, 42.8 % and 63.2% less crude fibre than undehulled grain for Jumbo, Dionje and IM millet respectively. There was also a decrease in ether extract and ash content due to the removal of the seed coat, which had high proportions of pigments and ash. On the other hand the protein content of the dissected grain was higher than that of the whole grain. This was due to the relative increase in the proportion of the grain

components which are rich in protein due to the removal of the seed coat, which is very low in protein.

4.3.2.1.3 Proximate composition of mechanically dehulled grain

Proximate composition of mechanically dehulled grain is summarised in Table 4.3. Both untreated and pre-treated grain had lower ash, ether extracts and crude fibre content after dehulling compared to undehulled grain. This was expected due to the removal of the seed coat, which is rich in these constituents. The pre-treated grain had lower ash, crude fibre and ether extracts than the untreated grain, indicating higher removal of the seed coat in the pre-treated grain compared to the untreated grain. Protein content of both pre-treated and untreated dehulled grain was higher than that of undehulled grain, but there was no significant difference between protein content of treated and untreated dehulled grain.

The pre-treated grain had on average 41.1%, 43.6% and 58.1% less crude fibre than the undehulled grain for Jumbo, Dionje and IM millet respectively. While for untreated grain the crude fibre reduction due to dehulling was 34.2% for Jumbo, 31.3% for Dionje and 57.7% for millet. Statistical analysis of the crude fibre reduction data showed that there was a significant reduction of crude fibre in pre-treated grain compared to untreated grain for Jumbo and Dionje ($P < 0.05$) while for millet the reduction of crude fibre due to pre-treatment was not significant ($P < 0.05$). These results showed that pre-treatment of sorghum by hydrothermal treatments before dehulling had a significant effect in crude fibre reduction in the dehulled grain.

Table 4.3 Summary of proximate composition of dehulled sorghum and millet subjected to different pre-treatments

Grain variety	Pre-treatment	Drying method	Ash (%)	Oil (%)	C. fibre (%)	Protein (%) (N×6.25)
Jumbo	Un-treated	-	1.49 ± 0.06 ^a	3.77 ± 0.08	4.05 ± 0.6	11.17± 0.04
	Steamed	Ambient	1.46 ± 0.05	3.73 ± 0.04	3.78 ± 0.08	12.66 ± 0.13
	Steamed	Oven	1.49 ± 0.02	3.67 ± 0.08	3.71 ± 0.03	12.47 ± 0.09
	Soaked	Ambient	1.43 ± 0.08	3.74 ± 0.07	3.56 ± 0.01	12.52 ± 0.24
	Soaked	Oven	1.42 ± 0.04	3.71 ± 0.06	3.37 ± 0.03	12.48 ± 0.09
Dionje	Un-treated	-	1.76 ± 0.02	2.52 ± 0.03	3.30 ± 0.44	8.87±0.014
	Steamed	Ambient	1.68 ± 0.03	2.48 ± 0.08	3.05 ± 0.03	9.02 ± 0.14
	Steamed	Oven	1.71 ± 0.02	2.44 ± 0.1	3.09 ± 0.02	9.29 ± 0.15
	Soaked	Ambient	1.53 ± 0.03	2.47 ± 0.04	2.46 ± 0.03	9.0 ± 0.06
	Soaked	Oven	1.61 ± 0.02	2.49 ± 0.05	2.26 ± 0.04	9.12 ± 0.06
Millet (IM)	Un-treated	-	1.56 ± 0.04	3.67 ± 0.11	3.03 ± 0.53	10.43±0.016
	Steamed	Ambient	1.16 ± 0.01	3.79 ± 0.03	2.90 ± 0.3	10.87 ± 0.16
	Steamed	Oven	1.07 ± 0.03	3.51 ± 0.1	3.00 ± 0.1	10.39 ± 0.29
	Soaked	Ambient	1.04 ± 0.01	3.68± 0.04	2.97 ± 0.16	10.625 ± 0.1
	Soaked	Oven	1.03 ± 0.08	3.53± 0.07	2.90± 0.14	10.75 ± 0.06

Each data point is an average of 3 replications

^a Standard deviation

4.3.3 Evaluation of the dehulling efficiency of sorghum and millet

The major factors used to evaluate the relative dehulling efficiencies of different pre-treatments were the amount of seed coat removed from the dehulled grain and the crude fibre content reduction in the dehulled grain. The pre-treatment capable of removing most of the

seed coat from the grain or reducing more crude fibre content in the dehulled grain at a given retention time in the dehuller was considered the most efficient treatment. Apart from these two major factors, kernel breakage and the product yield were other factors considered in the evaluation of dehulling efficiency. These two factors defined the quality of the recovered grain and the quantity of the recovered grain in comparison to an established base value, which in this case was the yield from hand peeled grain. The appropriate equation used for the calculation of the dehulling efficiency incorporating all these factors was presented in section 4.2.2.5.2.

4.3.3.1 Kernel breakage

Table 4.4 summarises the results of kernel breakage during dehulling of grain subjected to different pre-treatments. For the same retention time in the dehuller, steam treatment and high temperature drying resulted in more kernel breakage than cold water tempering and ambient drying. This could be explained by the fact that both steam treatment and high temperature drying resulted in higher stresses within the grain kernel, leading to development of stress cracks which eventually led to breakage of the grain during the dehulling process.

Table 4.4 Kernel breakage during dehulling for different pre-treatments

Grain variety	Treatment	Drying method	% kernel broken
(a) Jumbo	Soaking	Ambient drying	1.3
	Soaking	Oven drying	2.3
	Steaming	Ambient drying	3.9
	Steaming	Oven drying	5.4
(b) Dionje	Soaking	Ambient drying	0.3
	Soaking	Oven drying	1.8
	Steaming	Ambient drying	2.7
	Steaming	Oven drying	4.2

Each data point is an average of 4 replications

4.3.3.2 Dehulling efficiency in terms of seed coat removal

The results of dehulling efficiency in terms of seed coat removal from the dehulled grain subjected to different pre-treatments are given in Appendix B1-B3 and summarised in Table 4.5. Tempering followed by oven drying resulted in the removal of the highest proportion of seed coat from sorghum giving a dehulling efficiency of 77% for Jumbo and 76.3% for Dionje followed by tempering/ambient drying with a dehulling efficiency of 70.4% for Jumbo and 74.4% for Dionje. The least efficient pre-treatment for the Jumbo variety was steam treatment/ambient drying (65.5%) and for Dionje was steam treatment/oven drying (65.4%). The dehulling efficiency for untreated sorghum grain was 66.7% for Jumbo and 69.2% for Dionje. Therefore, in terms of seed coat removal the use of pre-treatments significantly improved the dehulling efficiency of both Jumbo and Dionje. On average the dehulling efficiency of Jumbo was improved by 10% and of Dionje by 7% over the untreated grain. However, some of the pre-treatments, notably combination of steam treatment and high temperature drying in sorghum, did not result in significant ($P < 0.05$) improvement in the dehulling efficiency of treated grain over untreated grain. This may have been due to high breakage, which was caused by these pre-treatments.

For millet, however, the combination of steam treatment with oven drying resulted in the highest dehulling efficiency (84.6%) followed by steam treatment/ambient drying (80.5%) and tempering/ambient drying was the least efficient (78.2%). The untreated millet grain had a dehulling efficiency of 64.4%. All pre-treatments investigated significantly improved the dehulling efficiency of millet compared to the untreated grain. On average the dehulling efficiency of millet was improved by up to 20% by the use of pre-treatments as compared to untreated grain. In terms of seed coat removal, steam treatment and high temperature drying was more favourable for millet than sorghum in improving the dehulling efficiency.

Table 4.5. Average dehulling efficiency for different pre-treatment in terms of seed coat removal

Grain variety	Treatment	Drying method	D _{eff} (%)	Statistical analysis
(1) Sorghum				
(a) Jumbo	Control	-	66.67 ± 0.7 ^a	
	Soaking	Ambient drying	70.4 ± 0.8	*
	Soaking	Oven drying	77.0 ± 0.6	***
	Steaming	Ambient drying	65.5 ± 1.7	ns
	Steaming	Oven drying	67.6 ± 0.6	ns
(b) Dionje	Control	-	69.16 ± 1.4	
	Soaking	Ambient drying	74.4 ± 3.1	*
	Soaking	Oven drying	76.3 ± 2.7	*
	Steaming	Ambient drying	72.1 ± 1.1	*
	Steaming	Oven drying	65.4 ± 2.5	ns
(2) Millet	Control	-	64.3 ± 1.9	
(IM)	Soaking	Ambient drying	78.2 ± 5.0	*
	Soaking	Oven drying	79.6 ± 2.7	*
	Steaming	Ambient drying	80.5 ± 3.2	*
	Steaming	Oven drying	84.6 ± 0.5	***

Each data point is an average of 3 replications

*** Significant at P < 0.001, ** Significant at P < 0.01, * Significant at P < 0.05, ns=not significant.

^a Standard deviation

4.3.3.3 Dehulling efficiency in terms of crude fibre reduction in the dehulled grain

Results for dehulling efficiency in terms of crude fibre reduction due to different pre-treatments are presented in Appendix B4 – B6 and summarised in Table 4.6 for both sorghum and millet. For sorghum, crude fibre analysis tended to confirm the order of dehulling efficiency of different pre-treatments previously determined in terms of seed coat removal. A combination of soaking and oven drying was the most efficient pre-treatment in reducing the crude fibre content of the dehulled grain for both Jumbo and Dionje with a dehulling efficiency of 75% for Jumbo and 82.2% for Dionje. The least efficient pre-treatment was steam treatment/ambient drying for Jumbo (67.3%) and steam treatment/oven drying for Dionje (62.6%). On the basis of crude fibre reduction all pre-treatments significantly ($P < 0.05$) improved the dehulling efficiency of Dionje over the untreated grain. In case of Jumbo steam treatment irrespective of the drying method used, did not improve the dehulling efficiency of Jumbo significantly ($P < 0.05$) over that of untreated grain. On average the highest improvement in dehulling efficiency for Jumbo was 14.5% (tempering/oven drying) and for Dionje was 27.3% (tempering/oven drying). For millet, tempering/oven drying was the most efficient in terms of crude fibre reduction followed by soaking/ambient drying and the least efficient was steam treatment/ambient drying. Tempering followed by either ambient or oven drying significantly improved the dehulling efficiency of millet over the untreated grain. The highest improvement in dehulling efficiency in terms of crude fibre reduction for millet was 13.7% (tempering/oven drying).

Table 4.7 summarises the mean dehulling efficiency when both seed coat removal and crude fibre reduction are considered together. In this case the most efficient pre-treatment for both Jumbo and Dionje was the combination of tempering and oven drying in which the average dehulling efficiency was 75.8% and 80.4% for Jumbo and Dionje respectively. This is an improvement of 12% for Jumbo and 17.3% for Dionje over the untreated grain. The least efficient pre-treatment was steam treatment/ambient drying for Jumbo and steam treatment/oven drying for Dionje. For millet, steam treatment/oven drying was the most

efficient pre-treatment with a dehulling efficiency of 86.8%, followed by tempering/oven drying (85.6%) and the least efficient was steam treatment/ambient drying (80.5%).

Table 4.6 Average dehulling efficiency for different pre-treatment in terms of crude fibre reduction

Grain variety	Treatment	Drying method	D _{eff} (%)	Statistical analysis
(1) Sorghum				
(a) jumbo	Control	-	60.5 ± 1.3 ^a	
	Soaking	Ambient drying	73.5 ± 0.4	***
	Soaking	Oven drying	75.0 ± 0.5	***
	Steaming	Ambient drying	67.3 ± 2.8	ns
	Steaming	Oven drying	69.4 ± 1.1	ns
(b) Dionje	Control	-	54.9 ± 1.4	
	Soaking	Ambient drying	80.5 ± 1.1	***
	Soaking	Oven drying	82.2 ± 1.7	***
	Steaming	Ambient drying	64.8 ± 6.8	**
	Steaming	Oven drying	62.6 ± 12.0	**
(2) Millet	Control	-	77.9 ± 4.1	
(IM)	Soaking	Ambient drying	91.2 ± 3.4	*
	Soaking	Oven drying	91.6 ± 3.6	*
	Steaming	Ambient drying	80.4 ± 7.0	*
	Steaming	Oven drying	89.2 ± 1.6	*

Each data point is an average of 3 replications

*** Significant at P < 0.001, ** Significant at P < 0.01, * Significant at P < 0.05, ns=not significant.

^a Standard deviation

Table 4.7 Mean dehulling efficiency for different pre-treatment considering both seed coat removal and crude fibre reduction.

Grain variety	Treatment	Drying method	Average D_{eff} (%)
(1) Sorghum			
(a) Jumbo	Control	-	60.5
	Soaking	Ambient drying	71.9
	Soaking	Oven drying	76.0
	Steaming	Ambient drying	66.4
	Steaming	Oven drying	68.5
(b) Dionje	Control	-	62.0
	Soaking	Ambient drying	77.5
	Soaking	Oven drying	79.3
	Steaming	Ambient drying	68.5
	Steaming	Oven drying	64.0
(2) Millet	Control	-	71.1
(IM)	Soaking	Ambient drying	84.7
	Soaking	Oven drying	85.6
	Steaming	Ambient drying	80.5
	Steaming	Oven drying	86.8

4.3.4 Alkali dehulling of sorghum and millet

4.3.4.1 Optimum conditions for alkali dehulling of sorghum and millet

The weight of material removed from the grain under different combinations of alkali concentration and soaking duration was used to determine the optimum combination of alkali concentration and soaking duration for dehulling of sorghum and millet. The percentage weight

loss of the grain during soaking in 6% and 10% alkali concentration for different durations is shown in figure 4.3. The combination of alkali concentration and soaking duration that resulted in removal of material from the grain approximately equal to the mean seed coat content of the three grain varieties determined from the hand peeling (i.e. 9.9% indicated by the dashed line) was selected as the optimum combination for the alkali dehulling process.

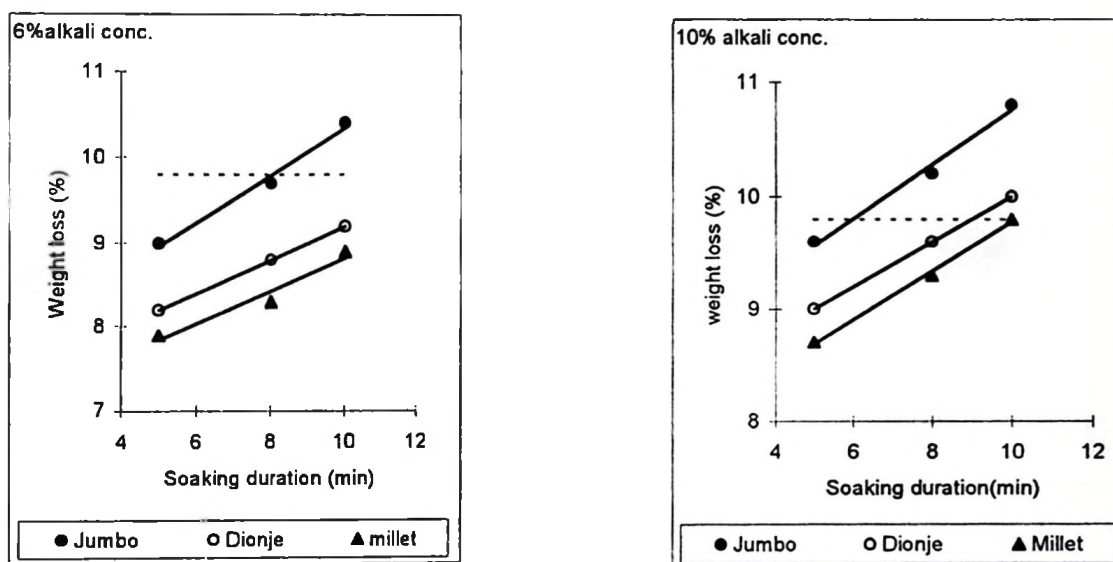


Figure 4.3. Effect of soaking duration on weight loss at (a) 6% and (b) 10% alkali concentration

On the basis of these results, 10% alkali concentration and 10 minutes soaking duration at 60^oC were selected as the optimum dehulling conditions for Dionje and millet, while 6% alkali concentration and 8 minutes soaking duration at 60^oC were the optimum conditions for Jumbo. The results of the percentage endosperm recovered at different soaking durations are summarised in Table 4.8. The average yield of dehulled grain obtained under the optimum conditions was 90.1 % for Jumbo, 90% for Dionje and 90.2% for millet.

Table. 4.8 Endosperm recovery levels at different alkali concentrations and soaking duration

Grain variety	Alkali concentration		Soaking duration (min)
	6%	10%	
Dionje	91.8 ± 0.1*	91.0 ± 0.2	5
	91.2 ± 0.1	90.4 ± 0.2	8
	90.8 ± 0.2	90.0 ± 0.1	10
Jumbo	90.0 ± 0.2	90.3 ± 0.1	5
	90.1 ± 0.1	89.7 ± 0.1	8
	89.6 ± 0.2	89.2 ± 0.1	10
Millet	93.1 ± 0.1	91.3 ± 0.1	5
	91.7 ± 0.1	90.7 ± 0.1	8
	91.1 ± 0.07	90.2 ± 0.2	10

* Standard deviation

Each data point is an average of 5 replicates

4.3.4.2 Effect of alkali dehulling on proximate composition of the dehulled grain

Proximate composition for both alkali dehulled and untreated grain is given in Table 4.9. Alkali dehulling significantly reduced the fibre content of both sorghum and millet. The crude fibre content of Dionje was reduced by approximately 37.6%, of Jumbo by 41.8% and of millet by 32%. The ash content decreased slightly for the dehulled grain while protein and ether extracts of the dehulled grain were slightly higher than that of untreated grain. The pH of the dehulled grain varied between 6.0 and 6.7 indicating that the final product was slightly acidic, this was probably caused by the acetic acid used to neutralise the alkali after dehulling was completed.

Due to short soaking duration used in this dehulling process, there was no evidence of leaching of pigments from the seed coat to the endosperm for the coloured varieties.

4.3.4.3 Dehulling efficiency of the alkali process

Two different methods were used to evaluate the dehulling efficiency of alkali dehulling process. These were visual evaluation and crude fibre reduction methods. The removal of the seed coat was mainly due to dissolution of the seed coat rather than loosening and removal by mechanical action. A similar effect was observed by Blessin *et al.* (1970) for yellow dent maize and sorghum in wet milling process. The dehulling process caused no kernel breakage although stress cracks were evident in many of the dehulled kernels. For Jumbo, the removal of the seed coat from the kernel was readily apparent by visual inspection of the dehulled grain due to the highly pigmented seed coat of this variety compared to the rest of the kernel. However, a direct visual evaluation of the extent of seed coat removal was more difficult in the case of Dionje for which both the seed coat and the endosperm are white in colour and for millet where both seed coat and endosperm are grey in colour. More quantitative visual evaluation data on the degree of removal of seed coat and aleurone layer from Dionje and millet grain was acquired by staining the dehulled kernels with iodine solution. Under these conditions the endosperm, which is mainly starch, stained blue/black while the seed coat did not stain or stain yellow. Results obtained from visual observation after iodine staining showed that the alkali dissolved the seed coat from all parts of the grain kernel except at the tip cap. The results of crude fibre content of the alkali-dehulled grain are given in Table 4.9. Based on crude fibre reduction data, the dehulling efficiency of this dehulling process as calculated using equation (4.8) was 83.5% for Dionje, 91.1% for Jumbo and 74.4 % for the millet.

Table 4.9 Proximate composition of alkali dehulled and untreated sorghum and millet

Grain variety	Protein (N×6.25) (%)	Ash (%)	Ether extracts (%)	Crude fibre (%)
Sorghum:	(7.3 - 15.6) ^a	(1.1 - 4.5)	(0.5 - 5.2)	(1.2 - 6.6)
(i) Dionje				
Unprocessed	9.06	1.95 ± 0.01*	2.85 ± 0.06	4.81 ± 0.05
A/dehulled	9.37	1.85 ± 0.05	2.96 ± 0.02	3.09 ± 0.07
H/peeled	10.9	1.39 ± 0.01	2.13 ± 0.03	2.75 ± 0.09
(ii) Jumbo				
Unprocessed	13.06	1.66 ± 0.07	4.19 ± 0.1	6.12 ± 0.03
A/dehulled	13.44	1.58 ± 0.06	4.33 ± 0.2	3.56 ± 0.14
H/peeled	13.9	1.32 ± 0.02	3.34 ± 0.06	3.31 ± 0.09
(iii) Millet (IM):	(8.6 - 19.4) ^a	(1.6 - 3.6)	(1.5 - 6.8)	(1.4 - 7.3)
Unprocessed	10.18	1.98 ± 0.01	5.47 ± 0.06	7.17 ± 0.02
A/dehulled	10.31	1.69 ± 0.01	5.94 ± 0.05	4.89 ± 0.09
H/peeled	11.87	1.63 ± 0.01	3.14 ± 0.06	3.64 ± 0.06

^a Figures in bracket are range of proximate composition values of whole grain from literature (Sergio and Rooney, 1995)

* Standard deviation

Each data point is an average of 5 replicates.

A/dehulled = Alkali dehulled, H/peeled = Hand peeled

4.3.5 Seed coat adhesion strength

The results of the effect of different tempering durations on the seed coat adhesion strength are given in Appendix B10 and summarised on figure 4.4 for Dionje, Jumbo and IM millet.

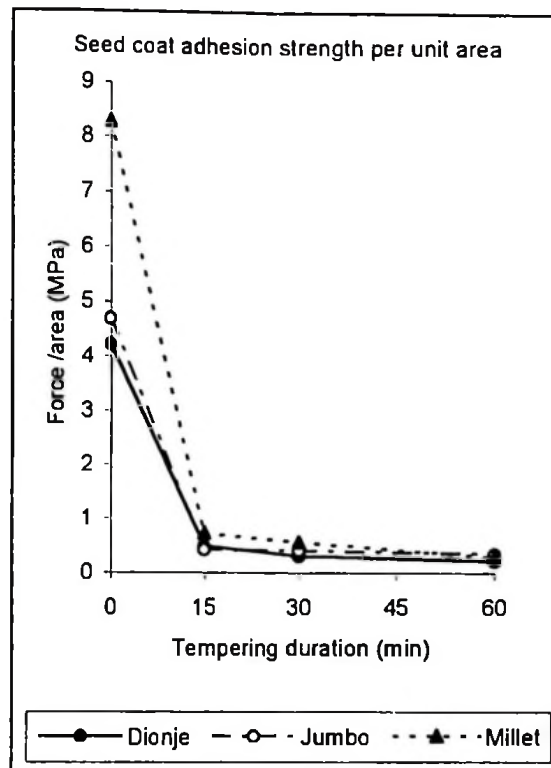


Figure 4.4 Effect of tempering on seed coat adhesion strength in sorghum and millet

Tempering resulted in a significant reduction in the amount of force required to remove a unit area of the seed coat from the endosperm for both sorghum and millet. Tempering the grain for 15 minutes, followed by 15 minutes rest period, reduced the force required to remove a unit area of the seed coat from the endosperm from 4.2 MPa for untempered grain to only 0.48 MPa for Dionje, 4.7 MPa to 0.42 MPa for Jumbo and from 8.2 MPa to 0.73 MPa for IM millet. Further soaking of the grain up to 60 minutes led to further reduction of the seed coat adhesion strength to 0.21 MPa for Dionje, 0.3 MPa for Jumbo and 0.3 MPa for millet. However, the reduction in force required for seed coat removal between 15 and 60 minutes tempering was significantly smaller compared to the reduction in the initial 15 minutes tempering as indicated by the slope of the two sections of the curve i.e. between 0 to 15, and 15 to 60 minutes tempering duration. The results therefore indicated that, tempering grain for 15 minutes or more, could significantly reduce the amount of force required to remove the seed coat during

the dehulling process. This could lead to higher dehulling efficiency, less loss due to endosperm breakage and better quality end product.

4.3.5.1 Dynamic coefficient of friction of sorghum and millet

The dynamic coefficient of friction and the cohesion between aluminium and the grain kernel are given in Table 4.10. Both the cohesion and dynamic coefficient of friction of sorghum and millet increased with increase in moisture content. However, the increase in dynamic coefficient of friction was much less than cohesion indicating that cohesion is a significant factor with respect to change in grain moisture content. The results of the variation of friction force with normal force for sorghum and millet on aluminium at different grain moisture contents are given in Appendix B11.

Table 4.10. Dynamic coefficient of friction for sorghum and millet on aluminium at different moisture contents

Grain variety	Moisture cont. (% db)	Coefficient of friction(μ)	Cohesion (C) (N)	R ²
(1) Dionje	12	0.33	0.06	0.999
	20	0.36	0.36	0.999
	25	0.42	0.56	0.989
(2) Jumbo	12	0.33	0.09	0.997
	20	0.37	0.43	0.999
	25	0.42	0.63	0.995
(3) Millet	12	0.34	0.41	0.998
	20	0.36	0.59	0.998
	25	0.43	0.64	0.997

4.3.6 Moisture absorption characteristics of sorghum and millet

4.3.6.1 Effect of temperature

The results of moisture absorption measurements for Dionje, Jumbo and IM millet at different temperatures are given in Appendix B12. Temperature had a significant effect on the amount of water absorbed for both sorghum and millet. For all grain varieties moisture absorption increased with the increase in soaking water temperature. Similar results have been reported for other grain such as soybeans (Hsu, 1983) and rice (Steffel & Singh, 1980; Lu and Siebenmorgen 1991).

4.3.6.2 Effect of initial grain moisture content

The results of the effect of initial grain moisture content on moisture absorption rate for Dionje, Jumbo, and IM millet are given in Appendix B13. Initial grain moisture content had no significant effect ($P < 0.05$) on the moisture uptake by the grains. This trend was true for all temperature levels investigated in this study.

4.3.6.3 Effect of grain texture and variety on moisture absorption

Figure 4.5(a) summarises the effect of different varieties of sorghum (soft and hard varieties) on the moisture absorption characteristics. Jumbo had slightly higher absorption rate than Dionje. This could have been contributed by the difference in endosperm texture of the two varieties. Dionje endosperm is hard and highly maizeous where as Jumbo's endosperm is soft and floury. Studies on the rate of water absorption in wheat have indicated that compact endosperm structure and higher kernel hardness reduce the rate of moisture absorption (Stenvert and Kingswood, 1977). Also Jumbo being softer than Dionje has more loosely packed endosperm structure and hence more spaces to absorb moisture than Dionje.

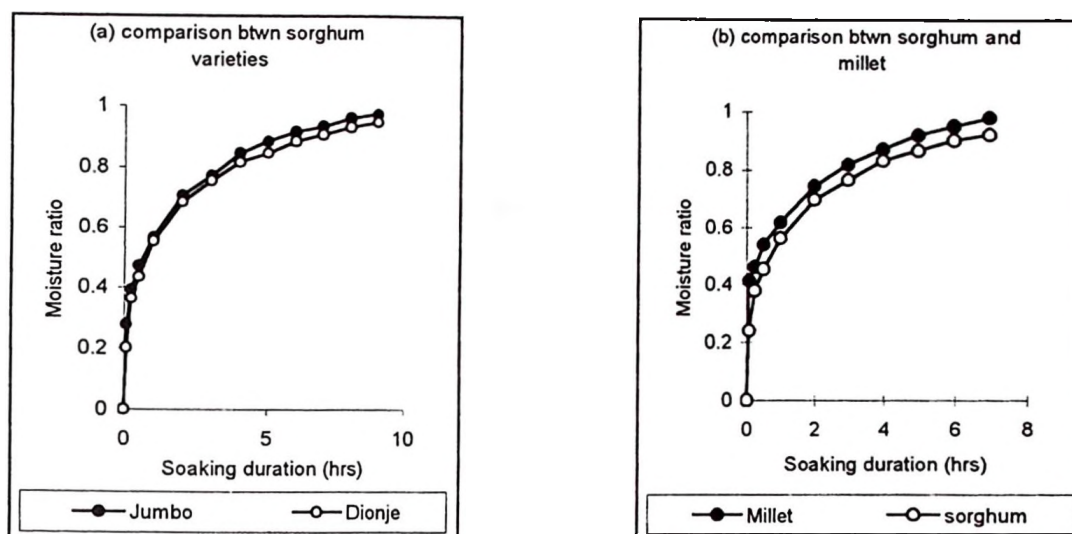


Figure 4.5. Effect of variety and grain type on moisture absorption

Figure 4.5(b) shows the comparison between sorghum and millet in moisture absorption characteristics. Under similar conditions, millet had a higher moisture absorption rate than sorghum (average between Jumbo and Dionje). This could have been contributed by both physical as well as chemical properties of the grains. Millet being smaller in size had larger surface area per unit weight exposed to the diffusing liquid than sorghum and hence was able to absorb more water than sorghum, which are much bigger in size (2:1). On the other hand millet also has a higher protein content than both Dionje and Jumbo. Protein content has been found to be positively correlated to the rate of moisture absorption in grain (Hsu, 1983).

4.3.7 Simulation of water absorption in sorghum and millet

4.3.7.1 Fickian diffusion model

The results of both experimental measurement and simulation of moisture absorption using the Fickian diffusion model (equation 4.11) are summarised in figure 4.6 for Dionje, and in

Appendix B14 and B15 for Jumbo and IM millet respectively. There was a fairly good agreement between the model prediction and the experimental results at higher soaking temperatures (40⁰C and 50⁰C), while at lower temperatures (20⁰C and 30⁰C) the model initially over-predicted and then under-predicted the moisture ratio for both sorghum and millet. The deviation between experiment and simulation was higher at the initial soaking period and at lower soaking temperatures.

The possible reason for this discrepancy may be due to the fact that some of the assumptions made in derivation of the solution to equation (4.11) are not valid for sorghum and millet. One of the assumptions, which most likely contributed to the inadequacy of the model, is that of constant diffusion coefficient. It has been found that the diffusion coefficient in grains is not a constant but depend very much on the moisture content of the system (Hsu 1983). The heterogeneous nature of sorghum and millet kernels is another factor, which might have affected the results. The seed coat and the endosperm of cereal grains have been shown to have different diffusion coefficients (Muthukumarappan and Gunasekaran, 1994). This factor was not considered during the derivation of equation (4.11).

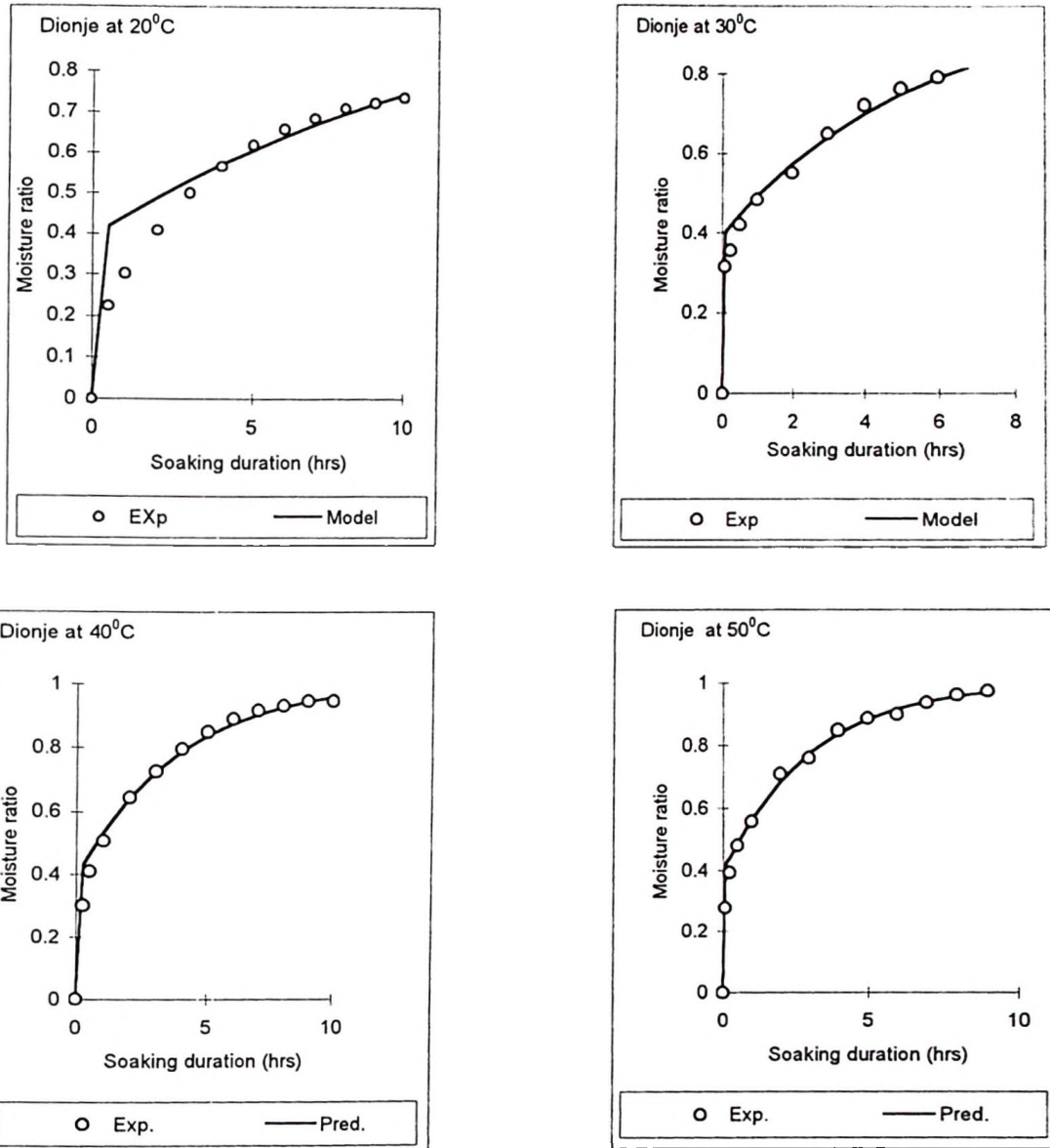


Figure 4.6 Experimental moisture ratio with curve fitted using the Fickian diffusion model (Equation 4.11) for Dionje

4.3.7.1.1 Effect of temperature on the diffusion coefficient of sorghum and millet

The results of the effect of temperature on the diffusion coefficient of sorghum and millet are given in Appendix B16 and summarised in Table 4.11. The diffusion coefficients of both sorghum and millet increased with increase in temperature.

Table 4.11 Diffusion coefficients of sorghum and millet at different temperatures

Grain variety	20 ^o C (D×10 ⁸)m ² h ⁻¹	30 ^o C (D×10 ⁷) m ² h ⁻¹	40 ^o C (D×10 ⁷) m ² h ⁻¹	50 ^o C (D×10 ⁷) m ² h ⁻¹
Dionje	4.65	1.11	1.215	1.93
Jumbo	8.24	1.57	1.74	2.44
IM	8.29	1.69	2.52	3.15

4.3.7.2 Modelling water absorption in sorghum and millet using Peleg's model

The fit of the experimental data by the Peleg's model is shown in figures 4.7(a), (b) and (c) for Dionje, Jumbo and IM millet respectively. The linear regression analysis parameters for the fitted lines are given in Table 4.12. The coefficient of determination, (R^2) varied between 0.992 to 0.999 indicating a very good fit between the model and experimental data for all the three grain varieties within the temperature range investigated in this study.

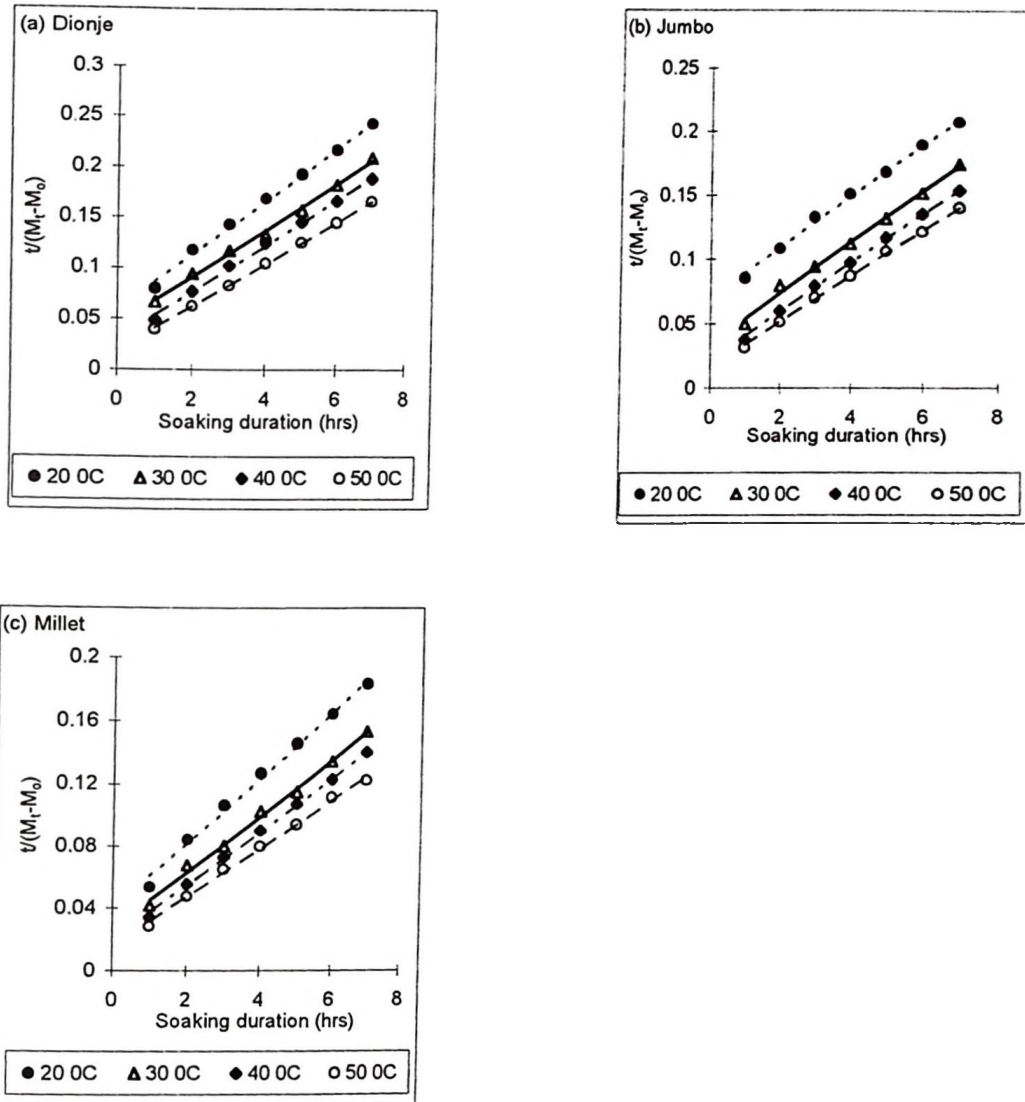


Figure 4.7 Fit of experimental moisture absorption data of sorghum and millet by Peleg's model

4.3.7.2.1 Evaluation of the constants in Peleg's model

The values of the constants K_1 and K_2 were obtained from regression equations for the regression lines in figure 4.7 and are given in Table 4.12. It was observed that K_1 was inversely related to temperature for both sorghum and millet, while K_2 was fairly constant at all four temperatures investigated (the difference between K_2 values at different temperatures

was not statistically significant at $P < 0.05$ despite slightly higher values at 20°C). Previous studies by Sopade *et al.* (1992) and Hung *et al.* (1993) also showed K_1 to be temperature dependent, while K_2 is a constant.

Table 4.12 Values of constants K_1 and K_2 for sorghum and millet at different temperatures.

Grain variety	Soaking temp (°C)	K_1	K_2	mean K_2	R^2
(a) Sorghum					
(i) Dionje	20	0.069	0.024		0.999
	30	0.045	0.023	0.0229	0.996
	40	0.030	0.023		0.997
	50	0.021	0.021		0.998
(ii) Jumbo	20	0.068	0.020		0.997
	30	0.034	0.019	0.0192	0.995
	40	0.021	0.019		0.999
	50	0.015	0.018		0.999
(b) Millet					
(i) IM	20	0.039	0.020		0.992
	30	0.027	0.018	0.018	0.995
	40	0.019	0.018		0.998
	50	0.016	0.018		0.995

4.3.7.3 Temperature dependency of diffusion coefficient D and constant K_1

The temperature dependency of the diffusion coefficient D and $1/K_1$ was modelled as an Arrhenius-type function. The quality of fit of the two parameters for sorghum variety - Dionje is shown in figure 4. 8 (a) and (b) for D and $1/K_1$, respectively. The results for other varieties are given in Appendix B17 and B18 for D and $1/K_1$, respectively. The model coefficients D_0 , K_0 , and the values of activation energies and root mean square deviations are summarised in Table 4.13.

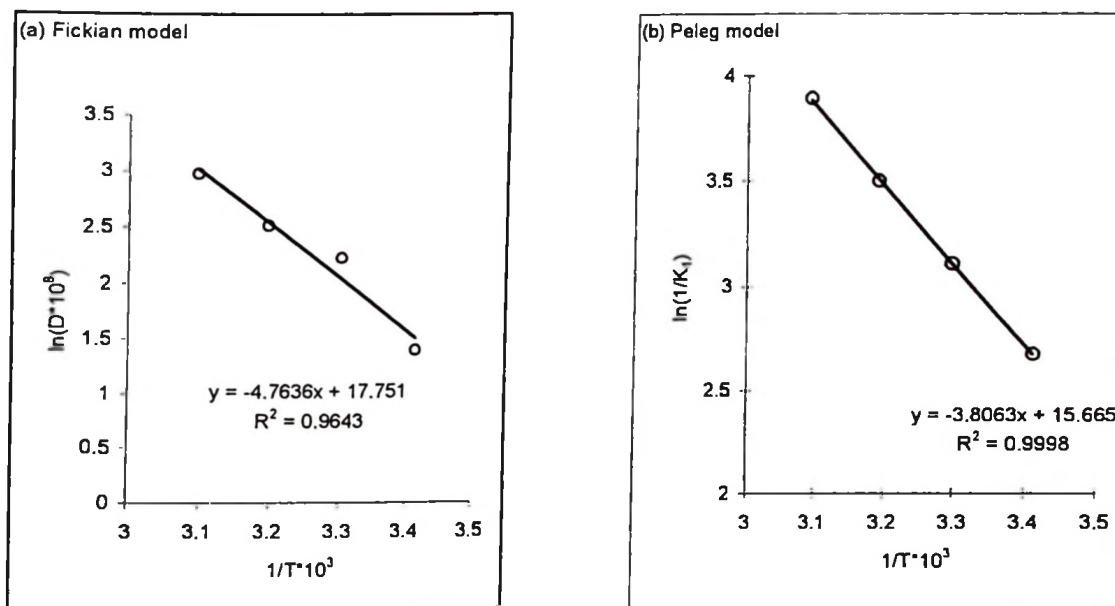


Figure 4.8 Relationship between Diffusion coefficient D , constant $1/K_1$ and absolute temperature for Dionje

Table 4.13 Coefficients of the Arrhenius model for temperature dependency of diffusion coefficient D and $1/K_1$ for sorghum and millet

Grain variety	Fickian model				Peleg model			
	$\ln(D_0 \times 10^8)$ (m^2/h)	E_a (kJ/mol)	RMSE	R^2	$\ln(K_0)$ (g/h)	E_a (kJ/mol)	RMSE (% db)	R^2
Dionje	17.75	39.60	0.06	0.95	15.67	31.7	0.003	0.99
Jumbo	12.88	26.58	0.12	0.96	18.95	39.5	0.04	0.98
IM	8.01	34.89	0.02	0.98	13.35	24.6	0.01	0.99

RMSE = Root mean square error

The good fit of a linear regression as indicated by high values of coefficient of determination ($R^2 = 0.95 - 0.99$) indicated that both D and $1/K_1$ are Arrhenius function of temperature. However, Peleg model gave a better fit than the Fickian diffusion model as witnessed from the higher coefficients of determination (R^2) and lower RMSE values. The values of activation energy obtained for both Fickian and Peleg models were well within the range of activation energies found in literature for different cereal grains during moisture absorption ie 12.6 - 50.2 kJ/mol (Hsu, 1984).

4.3.7.4 Comparison between Fickian diffusion model and Peleg model in modelling the moisture absorption during the tempering of sorghum and millet

Tempering of sorghum and millet for dehulling purposes is usually carried out with water at ambient temperature and for only a short duration, (less than 2 hrs). The initial absorption period within the 20–30°C temperature range is therefore of more importance than long duration soaking at higher temperatures for the tempering of sorghum and millet. The ability of the two models to simulate the moisture absorption during this period was judged by comparing the goodness of fit between experimental data and data predicted by the two

models. Root mean square error between experimental values and predicted values was used in this comparison. The model with lower RMSE values was judged as the best model for the simulation of the absorption behaviour of sorghum and millet during tempering. The computed RMSE values for both models are summarised in Table 4.14.

The results showed that, Peleg model had approximately 10 times lower RMSE values than the Fickian diffusion model for the temperature range and soaking duration considered in this investigation for both sorghum and millet. This suggested that Peleg model was more accurate in simulating the moisture absorption characteristics of sorghum and millet within the 20-30°C temperature range than the Fickian diffusion model. Peleg's model was therefore further investigated with the aim of developing a modified model, which could be used for prediction of tempering duration at different temperatures.

Table 4.14 Root mean square error values for Fickian diffusion and Peleg models at different soaking temperatures

Grain variety	Model	RMSE values	
		20°C	30°C
Dionje	Fickian	2.3×10^{-2}	1.17×10^{-2}
	Peleg	1.4×10^{-3}	1.1×10^{-3}
Jumbo	Fickian	2.12×10^{-2}	2.15×10^{-2}
	Peleg	8.2×10^{-4}	1.1×10^{-3}
Millet	Fickian	1.7×10^{-2}	1.5×10^{-2}
	Peleg	1.4×10^{-3}	1.0×10^{-3}

4.3.7.5 Development of predictive equations for modelling water absorption in sorghum and millet at different temperatures

Using the mean values of K_1 and K_2 from Table 4.12, predictive equations were derived based on Peleg's model to simulate water absorption in Sorghum and Millet at each of the soaking temperatures. These equations are presented in Appendix B19. The agreement between prediction by the derived equations and experimental data for Sorghum (Dionje) and IM millet is shown in figures 4.9 and 4.10 respectively. From these results it is evident that the proposed equations were able to simulate the water absorption characteristics of both sorghum and millet very well at each of the respective soaking temperature as shown by the good agreement between the fitted line and experimental data.

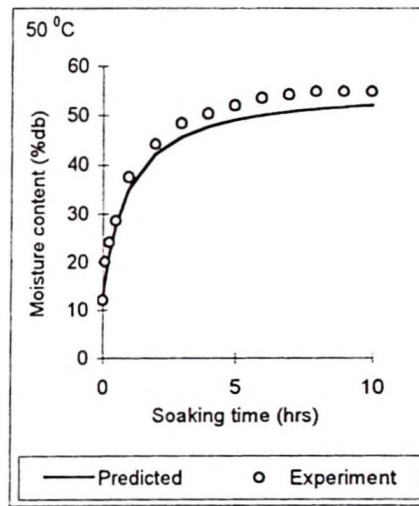
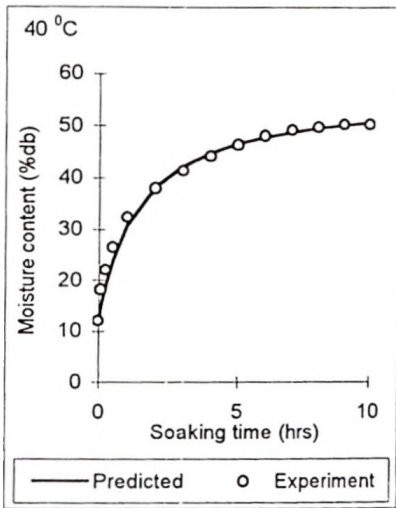
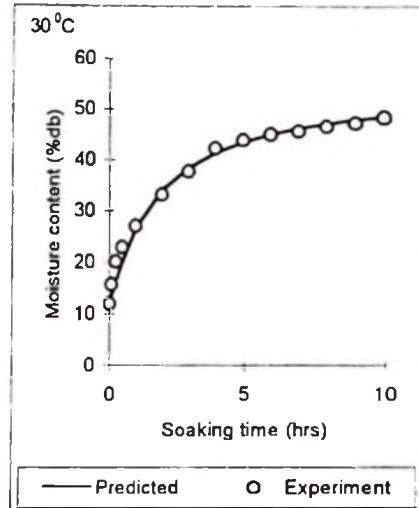
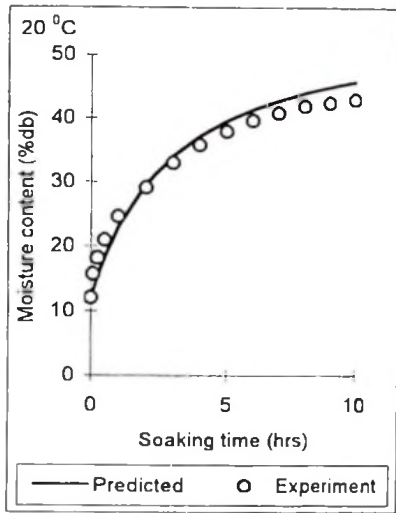


Figure 4.9. Experimental and predicted moisture content for Dionje at 20, 30, 40 and 50

°C soaking temperatures using derived equations.(Appendix B19)

$$M_t = M_0 + \frac{t}{\frac{1}{K_0} e^{\frac{B_p}{T}} + K_2 t} \quad (4.17)$$

Which can be simplified to;

$$M_t = M_0 + \frac{K_0 t}{e^{\frac{B_p}{T}} + K_2 K_0 t} \quad (4.18)$$

The values of K_0 and B_p were obtained from the Arrhenius fit of $1/K_1$ on temperature in figure 4.8 and Appendix B18. For individuals grain varieties the following Equations were derived

(i) Dionje:
$$M_t = M_0 + \frac{15.7t}{\frac{3.806}{e^T} + 0.36t} \quad (4.19)$$

(ii) Jumbo:
$$M_t = M_0 + \frac{18.95t}{\frac{4.745}{e^T} + 0.36t} \quad (4.20)$$

(iii) Millet:
$$M_t = M_0 + \frac{18.35t}{\frac{2.959}{e^T} + 0.24t} \quad (4.21)$$

where, t is the soaking time (hr), T is soaking temperature (K), M_t is moisture content after time (t), and M_0 is the initial moisture content (% db)

The capability of the derived equations to simulate moisture absorption characteristics of sorghum and millet at different temperatures is demonstrated in figure 4.11 for Dionje and figure 4.12 for Millet. The good quality of the fit obtained indicated that the derived equations could be used to predict the soaking characteristics of sorghum and millet at different

temperatures within the 20 to 50°C temperature range. Thus if the initial moisture content and the soaking duration is known, the moisture gain can be evaluated at any given temperature within this temperature range. Also the tempering duration required to attain a given moisture content at a given temperature can also be estimated if the grain initial moisture content is known.

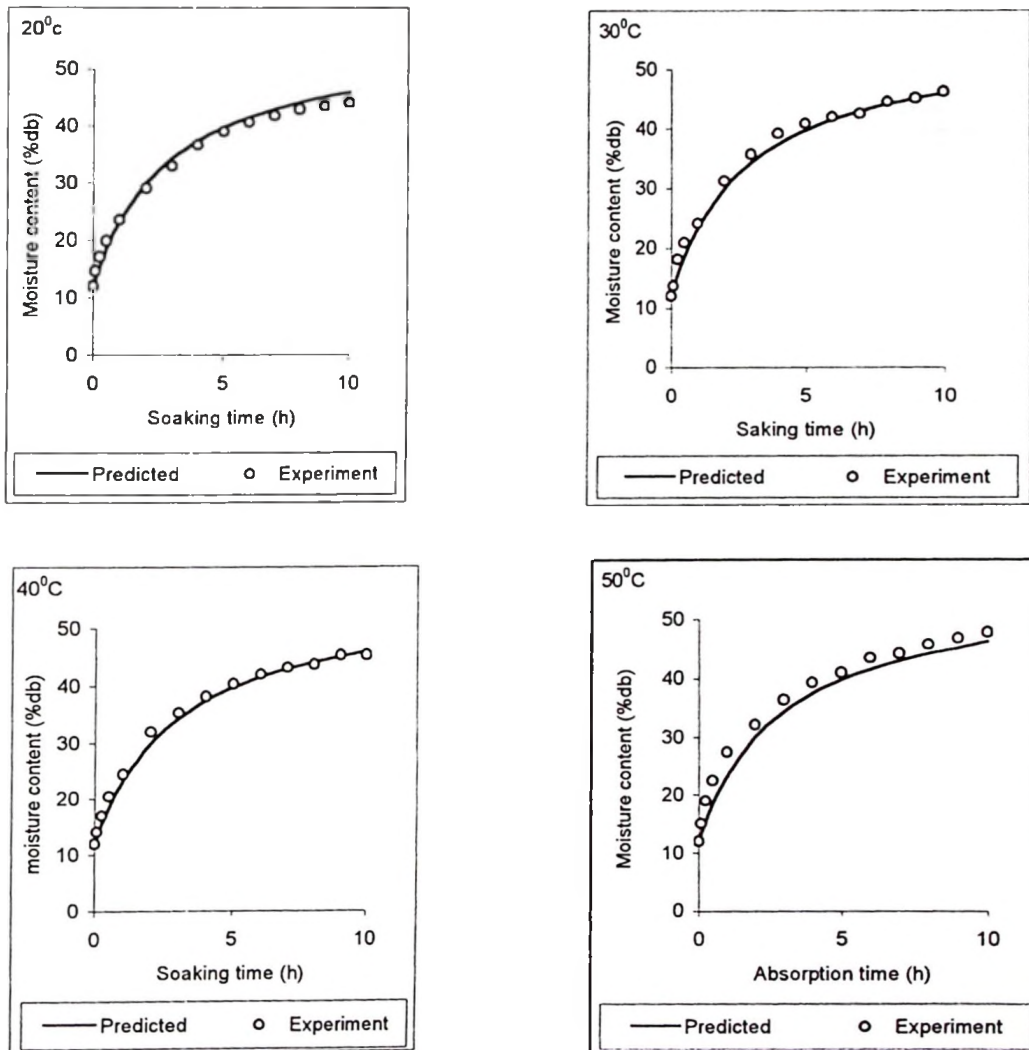


Figure 4.11. Experimental and predicted moisture content of sorghum (Dionje) at different temperatures using the proposed general equation.

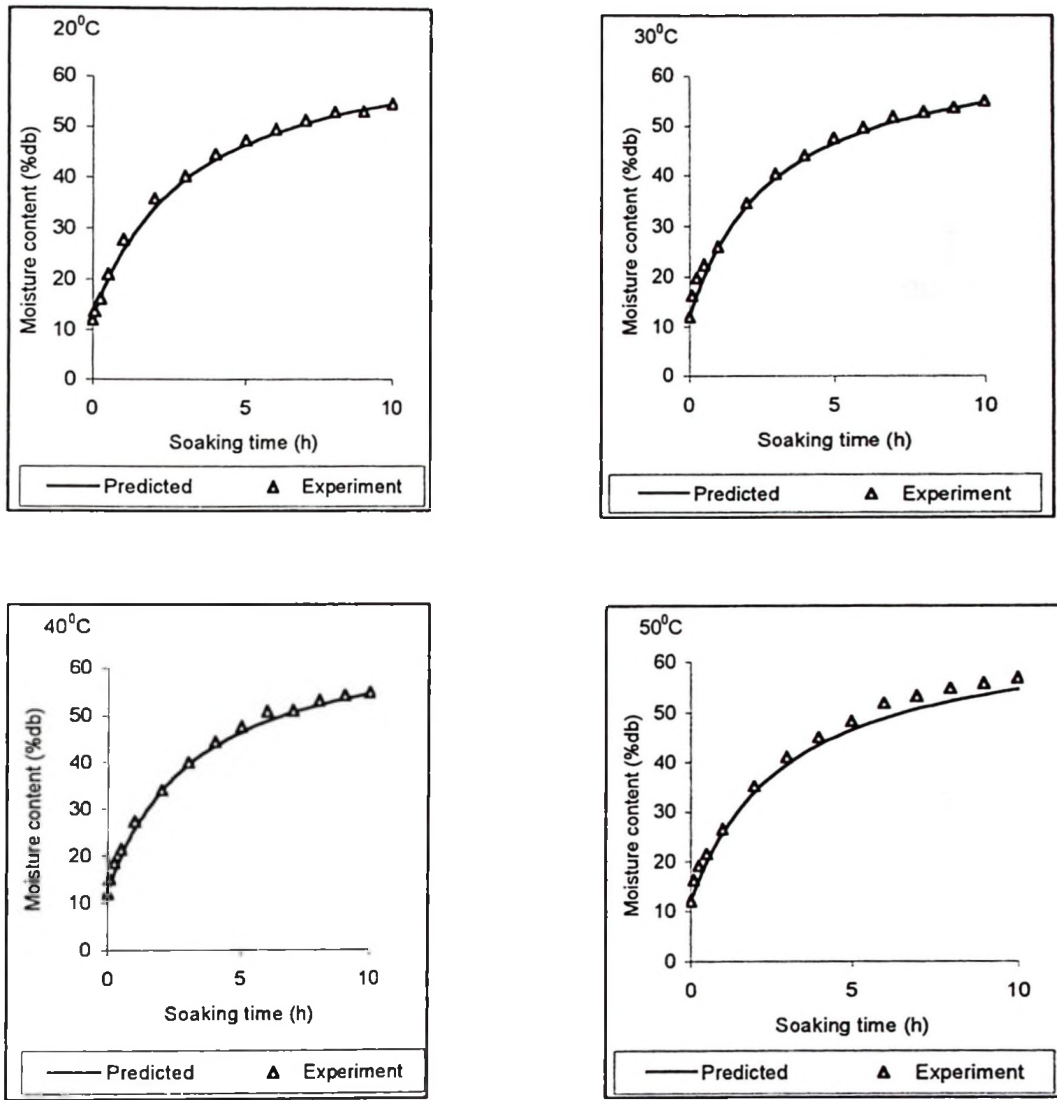


Figure 4.12. Experimental and predicted moisture content of millet at different temperatures using the proposed general equation

4.4. Summary and Conclusions

Experiments were conducted to investigate the effect of different pre-treatments on the dehulling efficiency of sorghum and millet. Pre-treatments used included hydrothermal treatments and alkali dehulling. Hydrothermal treatments involved soaking the grain in cold water (tempering) and steam treatment followed by drying to 12% (mcdB) using ambient temperature (20°C) or oven drying at 60°C. The pre-treated grain was then abrasively dehulled to remove materials equivalent to the seed coat content of the grain (10%). The extent of seed coat removal and crude fibre reduction in the dehulled grain was used as the criteria for judging the dehulling efficiency for different pre-treatments used in this study.

Hand peeling of soaked and steamed grain samples was carried out as a preliminary experiment to investigate the effect of soaking and steam treatment on seed coat adhesion strength and to obtain the actual proportion of the seed coat and endosperm for the grain varieties used in this investigation. Soaking or steaming the grain for 15 minutes or more facilitated hand peeling of both sorghum and millet grain. This indicated that soaking or steam treatment was able to reduce the seed coat adhesion to the endosperm substantially. However, the effect of seed coat loosening was reversed as the grain dried up indicating that to obtain maximum benefit from the seed coat loosening effect brought about by soaking or steam treatment, the grain must be processed while still in a moist condition.

Hydrothermal treatments improved the dehulling efficiency of both sorghum and millet compared to untreated grain in mechanical abrasive dehulling. The dehulling efficiencies of Jumbo, Dionje and IM millet were improved by an average of 10%, 7% and 20% respectively over the untreated grain in terms of seed coat removal. Soaking in cold water at ambient temperature (20°C) for 30 minutes followed by oven drying to original moisture content (12% mcdB) gave the best dehulling performance for Jumbo (Appendix B1), while for Dionje 15 minutes soaking followed by oven drying was the most efficient pre-treatment method (Appendix B2). Steam treatment for 5 minutes followed by oven drying gave the highest

dehulling efficiency for IM millet in terms of seed coat removal (Appendix B3). In terms of crude fibre reduction, hydrothermal treatments improved the dehulling efficiency of Jumbo, Dionje and IM millet by 14.4%, 27.3% and 13.7% respectively. Soaking for 15 minutes followed by oven drying gave the best performance for Jumbo, 60 minutes soaking followed by ambient drying gave the highest dehulling efficiency for Dionje, while 60 minutes soaking followed by oven drying gave the highest dehulling efficiency for IM millet. In terms of both seed coat removal and crude fibre reduction, soaking significantly improved the dehulling efficiency of all grain varieties irrespective of the drying method used.

The results obtained here indicated that the use of simple and cheap pre-treatments were able to improve the dehulling efficiency of sorghum and millet substantially in the conventional mechanical abrasive dehulling system. They also indicate that, much higher improvements in the dehulling efficiency could be achieved if the grain could be dehulled while still moist. However, mechanical dehullers currently available in the market are not capable of dehulling moist grain due to the clogging problem associated with wet grain in these machines. Therefore, if maximum benefit of hydrothermal pre-treatments is to be fully exploited, there is a need for design and development of dehullers, which can dehull moist grain without the problems encountered in the current dehullers. The initial attempt to address this problem is presented in chapter six of this thesis.

Alkali dehulling of sorghum and millet was investigated using an aqueous a solution of sodium hydroxide under controlled conditions of temperature, alkali concentration and soaking duration. The dehulling process was found to be very effective for both sorghum and millet, resulting in high recovery levels of high quality seed coat free endosperm. The optimum conditions for the alkali dehulling process were found to be 10% aqueous solution of sodium hydroxide (w/w) for 10 minutes soaking duration at 60⁰C temperature for Dionje and IM millet. While for Jumbo, 6 % aqueous solution of sodium hydroxide for 8 minutes soaking duration at 60⁰C temperature was the best combination. Crude fibre content in the dehulled grain was reduced by approximately 40% indicating that the process was highly effective in removing the seed coat from the grain kernels. The alkali dehulling process was also able to achieve higher

levels of recovery (90%) of dehulled endosperm at high dehulling efficiency (91%) from soft and pigmented grain (Jumbo) than is practically possible using any of the conventional dehulling methods.

Although the alkali dehulling process develop here, may not seem technologically suitable or economically feasible for traditional or other small scale processing of sorghum and millet due to the nature of chemicals involved, it might, however, be very appropriate for industrial scale process in urban or semi-urban areas for production of the much-needed high quality sorghum and millet flour and other convenient food products such as rice analogue for the fast growing urban population. The consumption of sorghum and millet as a whole grain offers several advantages, which include easy preparation and cost-wise is cheaper than rice or products prepared from flour because it does not require further milling. The recovery levels from this process are significantly higher than can possibly be obtained using any of the current dehulling systems. This improves the cost effectiveness of utilising sorghum and millet as rice substitute or wheat flour substitutes for the production of high quality products such as composite flour bread, biscuits and snacks, which are not currently possible to produce from these grains.

A device for measurement of seed coat adhesion strength in cereal grain was designed and constructed to quantify the effect of loosening of the grain seed coat by different pre-treatments. This device was used to study the effect of tempering grain for different durations on seed coat adhesion strength in sorghum and millet. It was shown that tempering the grain for 15 minutes reduced the seed coat adhesion strength from 4.2 MPa to 0.48 MPa for Dionje, 4.7 MPa to 0.42 MPa for Jumbo and from 8.3 MPa to 0.73 MPa for Millet. The device could also have a wide range of other practical applications in other grain-processing fields. These include, determination of the dynamic coefficient of friction of single grain kernel on different structural materials, aid in design of dehulling machines for pre-treated grains, and in the field it could provide a simple measure, for plant breeders in development and selection of grain varieties with good dehulling qualities.

Finally, moisture absorption characteristics of sorghum and millet were studied at different temperatures, grain initial moisture contents, and endosperm textures. Temperature had a significant effect on the rate of water uptake of the grain for all grain varieties studied with higher rates associated with higher temperatures. Endosperm texture also had an effect on the moisture absorption characteristics of the grain. Moisture absorption was higher for soft texture endosperm grain than in hard texture endosperm grain. On the other hand, initial grain moisture content had no significant effect on the moisture absorption rate of the grain. Moisture absorption behaviour of sorghum and millet was modelled using a model based on Fick's diffusion law and Peleg's model. Peleg's model was able to simulate the soaking characteristics of sorghum and millet more accurately than the model based on Fickian diffusion, especially for the initial soaking period and at lower soaking temperatures within 20-30°C range. A general model for prediction of soaking characteristics of sorghum and millet at different temperatures was developed based on Peleg's model and Arrhenius function. The proposed model could be used to predict moisture gain at a given soaking duration or the required soaking duration to attain a given final moisture content at any specified temperature within 20-50°C range for known initial moisture content. This model therefore provides a useful tool for the determination of tempering duration for sorghum and millet at different temperatures instead of the trial and error method currently used.

CHAPTER FIVE

MODELLING THE ABRASIVE DEHULLING PROCESS OF SORGHUM AND MILLET

5.1 Introduction

Although empirical studies can provide useful information in the design and operation of the dehulling equipment, they do not address the more fundamental problem of understanding the mechanical behaviour of the grains with respect to their interaction with each other and the machinery. The major thrust in sorghum and millet dehulling research today lies in understanding of the dehulling mechanism which in turn could lead to the design and development of more efficient mechanical dehulling equipment. The practical significance of an accurate understanding of what is really happening inside a dehulling mill cannot be over-emphasised. Such knowledge, if established, would be a basic step towards the determination of important parameters such as force distribution inside the mill and the breakage of grain kernels during the dehulling process, which cause the high losses and poor dehulling efficiency experienced in current systems.

Studies so far conducted on the dehulling process of sorghum and millet have mainly been through experimental and analytical methods. The data gathered by these methods is still inadequate to provide quantitative information about what actually happens to individual grain particles inside the mill. Hence detailed understanding of the dynamic behaviour of the grain kernels inside the mill and the interaction between grain and mill is severely hampered by the deficiencies of methods so far used. The alternative to the experimental approach to this problem is the computational approach. Computational methods, provided the physical models

are accurate, could enable accurate prediction of forces and stress-strain responses at both the microscopic and macroscopic scale during the dehulling process.

In the dehulling process, grain motion within the mill consists of complex movements and interactions between grain and grain and between grain and the surface of the dehulling mill. A numerical scheme for simulating such a process must therefore, be able to consider each grain particle and mill surface as distinct entities while at the same time preserving the boundary of the entities during contact. The best approach to this problem is the Discrete Element Method (DEM), which is a numerical scheme developed for simulating the behaviour of discrete interacting bodies.

5.1.1 Discrete element method approach to the dehulling process

The discrete element method (DEM) is a numerical method for modelling the mechanical behaviour of granular materials. The method was developed by Cundal (1971) for the analysis of rock mechanics problems and later extended by Cundal and Strack (1979) to granular media such as sand. It has since been successfully used for numerical modelling of the mechanical behaviour of a wide range of granular materials. Unlike conventional numerical techniques such as finite element, boundary element or finite difference methods that are suited to modelling continua, DEM treats granular material as an assemblage of distinct particles, whose dynamic behaviour is modelled at particle scale. Each particle interacts with its neighbours through particle-to-particle contacts, which can be formed or broken at each time step, it also keep track of the motion of individual particles and monitors or updates any contact with neighbouring particles.

Particle motion results from any out of balance force and is determined by the application of Newton's second law, while application of an appropriate force-displacement law at contact points gives the current inter-particle contact force. It also allows finite displacements and rotations of discrete particles where complete loss of contact and formation of new contacts take place as the calculation progresses. Because of these features, DEM is highly suitable for

simulating processing of granular materials such as dehulling of grain where a large number of discrete particles are interacting with each other and the walls of the dehulling machine.

DEM was devised originally in the geotechnical engineering field as a tool for modelling discontinua. However, it has found increasing application in diverse range of fields such as, deformation in granular media (Cundal *et al.*, 1982) stability of rock masses (Cundal, 1988) flow of powders and grain (Campbell and Brennen, 1983), mechanical behaviour of granular soil under monotonic loading (Ng, 1989), sea ice ridging process (Hopkins and Louge, 1991), and hydraulic fracture in granular assemblies (Thallak *et al.*, 1990). Others include, large deformation flow of arbitrarily shaped particles (Walton, 1988), constitutive behaviour of granular soils (Dobry and Ng., 1989; Issa and Nelson, 1989), creep of soils (Kuhn and Mitchell, 1989), fluidisation (Tsuji *et al.*, 1993), flow phenomenon in silos and hoppers (Rong *et al.*, 1995; Sakaguchi *et al.*, 1994), failure of bio-materials under impact loading (Schembri and Harris, 1996), flow of irregular shaped particles (Abbaspour *et al.*, 1998) and deformation of bulk agricultural particulates (Raji, 1999).

A number of computer programs based on the DEM have been developed for different fields of study. Researchers have either used programs developed by Cundal and his co-workers such as BALL and TRUBAL (Cundal and Strack, 1979) or have modified these programs to suit their own needs such as CONBAL (Ng and Dobry, 1990) and DISC (Ting *et al.*, 1989). CONBAL 3.4 (Raji, 1999; Abbaspour *et al.*, 1998). While other researchers have developed their own programs, such as MASOM (Issa and Nelson, 1989), and GLUE (Bathrst and Rotenburg, 1990).

Despite the many advantages offered by DEM, there are also some disadvantages associated with it. The main disadvantage of DEM is its enormous computational expense (Ting *et al.*, 1987). The explicit nature of the algorithm in which each element has to be treated individually and the necessity to use a very small time step of simulation to guarantee numerical stability and accuracy, imposes limitations on its capabilities. Hence, any realistic simulation becomes very time intensive. So far with the available computer facilities, only a

limited number, (hundreds to few thousands) of particles, can be dealt with at the same time, which is far from the scale required for practical engineering problems. However, despite this setback, the advantages weigh significantly in favour of the DEM over physical simulation as long as the DEM models are scaled appropriately with the physical system.

In summary therefore, from the work done so far, it has been shown that DEM is a competent numerical scheme capable of handling problems dealing with multi-body interactions. It has succeeded reasonably well in providing valuable information to researchers studying a wide range of subjects and is gaining rapid acceptance as an important method for handling problems of a dynamic nature such as grain flow. However, it remains a slow workhorse due to the necessary algorithmic details it has to follow.

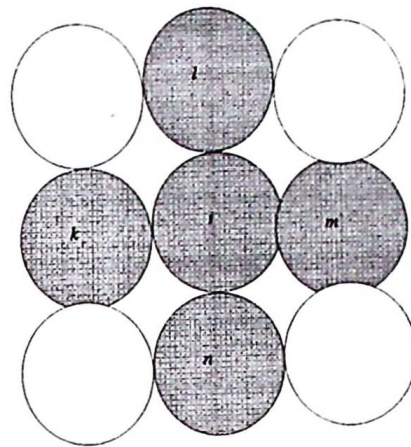
The study of the mechanics of dehulling process is a complex multi-body interaction problem, and hence quite suitable for DEM analysis. However, at the moment there is no DEM program available that fits the requirement for the study of the dehulling process. The objective of this chapter was therefore to develop a DEM program tailored to the study of the abrasive dehulling process of sorghum and millet by modifying one of the existing DEM programs. Such a program if successfully developed could be very useful tool in providing more insight on how the current mechanical dehulling system can be improved for higher dehulling efficiency.

5.2. The DEM algorithm

The numerical scheme adopted in DEM formulation computes incrementally the movement of each particle in the system in two or three dimensions by applying Newton's second law to the particles in motion and a force-displacement law to particles in contact. Newton's second law gives the motion of the particles resulting from the forces acting on them while the force-displacement law gives the current inter-particle contact force. Each cycle is carried out over a time step, a length of which is chosen such that during a single time step disturbance cannot propagate from any particle further than its immediate neighbours. Each particle in the assembly is identified separately by its radius, mass, moment of inertia and contact properties.

5.2.1 Contact representation

In DEM contacts are classified as either soft or hard, the type being determined by the strength properties of the material in use. In a system where the particles make soft contacts, they deform at the contact points as the result of stress and friction. Deformation is represented as an inter-penetration of the two contacting particles at the contact point, although physically, surface deformation occurs rather than inter-penetration. In the case of hard contact, no inter-penetration occurs between the contacting bodies, only shear movement (sliding), rolling and loss of contact occurs. Figure 5.1(a) shows a cluster of particles where particle i is in contact with particles k , l , m and n . At every contact point the forces developing due to collision are modelled by a pair of normal and tangential spring and dashpots to represent contact compliance and energy absorption. The spring-dashpot arrangement for contact made between particle n and i is shown in figure 5.1(b). The contact spring may be linear or non-linear, and in some cases has been based on Mindlin's solution for Hertzian contacts (Cundal, 1988; Dobry and Ng, 1989). The amount and rate of overlap between neighbouring particles is used to determine the contact force at each instant in time. The total unbalanced forces and moments acting on each particle is computed based on local equilibrium of direct neighbours and are used to estimate each particle's accelerations. The accelerations are then integrated for velocities and displacements using a second order leap frog scheme proposed by Cundal and Strack (1979).



For particle *i* contact forces are summed over neighbours *k, l, m* and *n*

Figure 5.1(a) Contact between particles

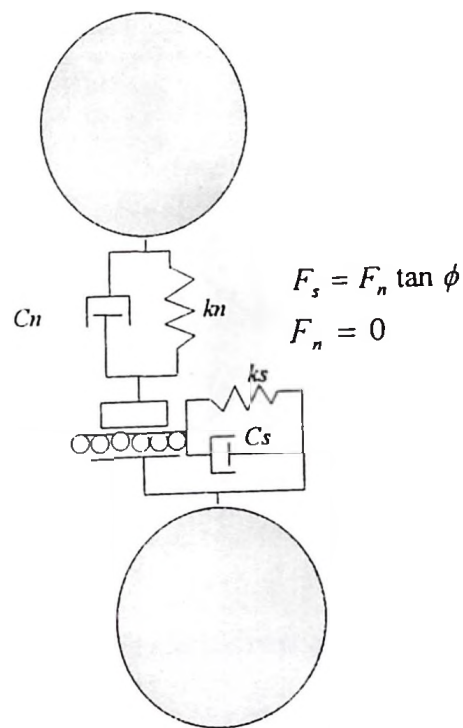


Figure 5.1(b). Contact representation between two particles in DEM

5.2.2 Contact detection

The purpose of contact detection is to identify particles that have established new contacts and those which have lost contacts. This computational operation is the most time consuming part of the DEM analysis; therefore efficiency becomes a major requirement in the implementation of contact detection procedures. As DEM considers particles to be quasi-rigid with deformable contacts, one can arbitrarily define the point of contact C between two particles as mid point of the line connecting the midpoints of the two particles as shown in figure 5.2.

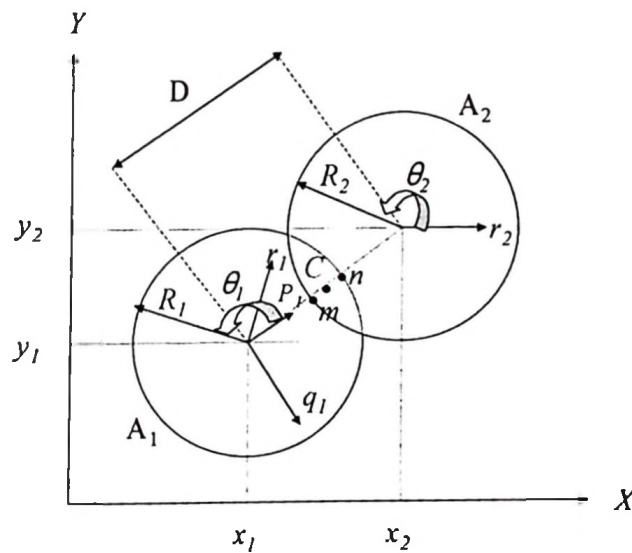


Fig.5.2.Contact between two spherical particles

For the two spherical particles A_1 and A_2 with radius R_1 and R_2 , a contact is registered between them when an overlap is detected between them. The condition for overlap is that the distance between their centres of mass should be less than the sum of their radii. For example in figure 5. 2 contact is registered when:

$$D \leq R_1 + R_2 \quad (5.1)$$

5.2.3 Calculation cycle in DEM

Having determined that a contact exists between two particles, the relative velocity of one particle with respect to the other is evaluated. The equations for the calculation of the relative velocities, accelerations, displacement and incremental contact forces between particles are summarised in the following sections.

5.2.3.1 Determination of relative velocity and contact force

If we consider the contact of the two particles A_1 and A_2 , shown in figure 5.2, the position vectors of the centre of mass of particles A_1 and A_2 are represented as r_1 and r_2 and the angular velocities are denoted as $\dot{\theta}_1$ and $\dot{\theta}_2$. A unit vector p_1 is defined pointing from the centre of particle A_1 to the centre of particle A_2 , and the unit vector q_1 is obtained by a clockwise rotation of p_1 through 90° . The magnitude of these vectors can be determined from the following equation:

$$\begin{aligned} P_i &= \left(\frac{x_1 - x_2}{D} \right) \bar{i} + \left(\frac{y_1 - y_2}{D} \right) \bar{j} + \left(\frac{z_1 - z_2}{D} \right) \bar{k} \\ &= \cos \theta_i \bar{i} + \cos \theta_j \bar{j} + \cos \theta_k \bar{k} \end{aligned} \quad (5.2)$$

where $\bar{i}, \bar{j}, \bar{k}$ are the unit vectors in the x, y and z directions respectively and $\cos \theta_i, \cos \theta_j, \cos \theta_k$ are direction cosines of the normal unit vector.

The unit tangential vector q_1 from A_1 to A_2 is obtained by a clockwise rotation of P_1 by 90° , therefore;

$$q_1 = \sin \theta \bar{i} + \sin \theta \bar{j} + \sin \theta \bar{k} \quad (5.3)$$

The relative velocity V_i of particle A_1 with respect to particle A_2 at contact point can then be calculated as;

$$V_i = (r_1 - r_2) - (\dot{\theta}_1 R_1 + \dot{\theta}_2 R_2) q_1 \quad (5.4)$$

where R_1 and R_2 are the radii of particles A_1 and A_2 respectively.

The normal V_{in} and tangential V_{is} components of relative velocity are the projections of V_i into p_1 and q_1 respectively and are given by:

$$V_{in} = V_i p_i = (r_1 - r_2) p_i \quad (5.5)$$

and

$$V_{is} = V_i q_i = (r_1 - r_2) q_i - (\dot{\theta}_1 R_1 + \dot{\theta}_2 R_2) \quad (5.6)$$

Integration of the relative velocity component with respect to time gives the components Δn and Δs of the relative displacement increment in normal and tangential directions respectively as;

$$\Delta n = V_{in} \Delta t = (r_1 - r_2) p_i \Delta t \quad (5.7)$$

and

$$\Delta s = V_{is} \Delta t = \left\{ (r_1 - r_2) q_i - (\dot{\theta}_1 R_1 + \dot{\theta}_2 R_2) \right\} \Delta t \quad (5.8)$$

These relative displacement increments are used with an appropriate force displacement law to calculate increments in normal (ΔF_n) and shear forces (ΔF_s), as;

$$\Delta F_n = k_n \Delta l = k_n (r_1 - r_2) p_i \Delta t \quad (5.9)$$

and

$$\Delta F_s = k_s \Delta s = k_s \left\{ (r_1 - r_2) p_i - (\dot{\theta}_1 R_1 + \dot{\theta}_2 R_2) \right\} \Delta t \quad (5.10)$$

where k_n and k_s represent the normal and shear stiffness, respectively.

Finally at each time step the force increments ΔF_n and ΔF_s are added to the sum of all force increments F_n and F_s determined from previous time steps to get the total normal and shear force $(F_n)_{tot}$ and $(F_s)_{tot}$ respectively as:

$$(F_n)_{tot} = (F_n)_{N-1} + \Delta F_n \quad (5.11)$$

and

$$(F_s)_{tot} = (F_s)_{N-1} + \Delta F_s \quad (5.12)$$

where the indices N and $N-1$ refer to times t_N and t_{N-1} respectively

If damping is considered the normal and tangential force increment in the dashpots must be added to the total force. Force increment in the dashpots can be calculated as follows:

$$\Delta D_n = C_n \Delta V_{in} \quad (5.13)$$

$$\Delta D_s = C_s \Delta V_{is} \quad (5.14)$$

where C_n and C_s are normal and shear damping constants respectively for normal and tangential dashpots

The total normal contact force $(F_n)_{tot}$ is then calculated by addition of D_n to $(F_n)_{tot}$

$$(F_n)_{tot} = (F_n)_{N-1} + \Delta F_n + D_n \quad (5.15)$$

Also the total shear force $(F_s)_{tot}$ is calculated by the addition of D_s to $(F_s)_{tot}$

$$(F_s)_{tot} = (F_s)_{N-1} + \Delta F_s + D_s \quad (5.16)$$

A Coulomb-type friction law is incorporated in the calculation as follows: The magnitude of the shear force F_s found from equation (5.12) is checked against the maximum possible value $(F_s)_{max}$ that can exist at a contact which is given by:

$$(F_s)_{max} = F_n \tan \phi + C \quad (5.17)$$

where ϕ is the smaller of the inter-particle friction angles of the two particles in contact and C is the smaller of their cohesion. If the absolute value of $(F_s)_{tot}$ as found from equation (5.12) is greater than $(F_s)_{max}$, then slip is presumed to occur. In such a case the total shear contact force is calculated by setting the shear force $(F_s)_{tot}$ equal to $(F_s)_{max}$

Once the normal and tangential or shear forces have been determined for each contact of a particle, they are resolved into components in the x , y , and z directions. The sum of these contact force components gives the resultant forces $\sum F_{(i)x}$, $\sum F_{(i)y}$, and $\sum F_{(i)z}$ acting on the particle. The resultant moment acting on particle A_i $\sum M_{(i)}$ is taken positive if acting in the counter-clockwise direction and is found from:

$$\sum M_{(i)} = \sum F_s R_i \quad (5.18)$$

where summation is taken over all contacts of particle A_i and R_i is the radius of the particle

The resultant moment and forces acting on particle A_i are then used with Newton's second law of motion to calculate the motion and the new accelerations (\ddot{x}_i and $\ddot{\theta}_{(x)}$) of the particle.

However it has been noted that summing incremental normal contact forces at each time step sometimes could lead to significant accumulated error. It is therefore recommended to compute the total normal overlap at each instant then use this to obtain the total contact force while the tangential force can still be obtained using incremental forces (Ting *et al.*, 1993).

5.2.3.2 Particle motion and acceleration

The forces generated at contacts along with the body forces present dictates the motion of the particles within the system. The co-ordinates of the centre of mass and the radius of the particle define the geometry and the position of the particles. The incremental acceleration of the centre of mass and the angular acceleration of the particle about its centre of mass are determined at each time step from the contact force acting on the particle. By integrating these values twice over the time step, the increment in the position vector of the centre of mass and incremental rotation of the particle can be obtained. These increments are used to update the position of the particle. The main governing equation is the dynamic equation of equilibrium which can be written for a particle characterised by position x , mass m and moment of inertia I as:

$$m\ddot{x}_i + \sum_n (c\dot{x}_i + kx_i) = F_i \quad i = 1,2,3 \quad (5.19)$$

$$I\ddot{\theta}_i = M_i \quad i = 1,2,3 \quad (5.20)$$

where F_i is the force acting on the particle, M_i is the moment about the centroid of the particle, and m is the mass of the particle, \ddot{x} is the acceleration of the particle, I is the moment of

inertia of the particle, $\ddot{\theta}$ is the angular acceleration, and the directions $i = 1, 2, 3$ refer to the x , y , z co-ordinates respectively.

New velocities and positions of the particles are obtained by numerical integration of equation (5.19) and (5.20) over a short time interval Δt (or time step) from $t_{N-\frac{1}{2}}$ to $t_{N+\frac{1}{2}}$ assuming that

\ddot{x} and $\ddot{\theta}$ remain constant over the time interval Δt :

$$(\dot{x}_i)_{N+\frac{1}{2}} = (\dot{x}_i)_{N-\frac{1}{2}} + \ddot{x}_i \Delta t \quad (5.21)$$

$$(\dot{\theta}_i)_{N+\frac{1}{2}} = (\dot{\theta}_i)_{N-\frac{1}{2}} + \ddot{\theta}_i \Delta t \quad (5.22)$$

Further numerical integration of the new velocities leads to new displacements and rotational increments, which are used to update the position and rotations of each particle as follows:

$$(x_i)_{N+1} = (x_i)_N + (\dot{x}_i)_{N+\frac{1}{2}} \Delta t \quad (5.23)$$

$$(\theta_i)_{N+1} = (\theta_i)_N + (\dot{\theta}_i)_{N+\frac{1}{2}} \Delta t \quad (5.24)$$

The new values for the displacements can then be used in a force displacement law to find new force increments at contact points (provided a check is made to ensure that contacts still exist), and the cycle is then repeated for the next time step. Body forces, such as gravitational forces may be incorporated into the resultant force to obtain the actual resultant force when desired. In which case a term mg_i is added to the force term in equation (5.19) such that equation (5.19) now becomes:

$$m\ddot{x}_i + \sum_n (c\dot{x}_i + kx_i) = F_i + mg_i \quad (5.19b)$$

Thus by repeating these calculations, which alternate between application of force-displacement law and Newton's law of motion for each particle, new positions of all the particles in the system can be determined, and the time evolution of all the particles motion in the x, y and z co-ordinates is given by repeating the entire set of calculations at successive time steps until equilibrium is achieved.

5.2.3.3 Energy dissipation and damping

Energy is dissipated in the model through friction, contact and global damping. Frictional damping occurs during sliding when the absolute value of the shear force (F_s) at any contact is greater than a maximum value which is equal to the frictional force between the two particles or particle and wall as shown in equation (5.17).

Contact damping operates on the relative velocities at contacts and may be envisioned as resulting from dashpots acting in the normal and shear direction at the contact points (see figure 5.1b). Contact damping in the shear direction is not applied when sliding occurs, in such a case friction damping alone operates. If contact damping is taken into account, the damping forces must be included in the force sums in equation (5.21) and (5.22), which now became:

$$(\dot{x})_{N+\frac{1}{2}} = (\dot{x})_{N-\frac{1}{2}} + \left\{ \frac{\sum [F_i + D_i]}{m} \right\}_N \Delta t \quad i = 1, 2, 3 \quad (5.25)$$

$$(\dot{\theta}_i)_{N+\frac{1}{2}} = (\dot{\theta}_i)_{N-\frac{1}{2}} + \left\{ \frac{\sum M_i}{I} \right\}_N \Delta t. \quad (5.26)$$

where $\sum D_i$ represents the sum of the components of the contact damping forces, and $\sum M_i$ now includes the contribution of the contact damping forces to the moment sum.

Global damping operates on the absolute velocities of the particles and may be envisioned as the effect of dashpots connecting each particle to the ground. These dashpots operate both on the velocity vector components and on rotational velocity. Global damping is usually used to simulate particles with high velocity in a viscous medium. If global damping is included in addition to contact damping, the equations of motion (5.19) and (5.20) now become:

$$m\ddot{x}_i = \sum(F_i + D_i) - C\dot{x}_i \quad (5.27)$$

$$I\ddot{\theta}_{(i)} = \sum M_{(i)} - C^*\dot{\theta}_{(i)} \quad (5.28)$$

where C and C^* are the coefficients of global damping operating respectively, on \dot{x}_i and $\dot{\theta}_i$. A central difference scheme is used to integrate equation (5.27) and (5.28), whereby velocities are evaluated halfway through the time step to obtain the new velocities and rotations as:

$$(\dot{x}_i)_{N+\frac{1}{2}} = \left\{ (\dot{x}_i)_{N-\frac{1}{2}} \left[1 - \frac{C \Delta t}{m} \right] + \sum (F_i + D_i)_N \frac{\Delta t}{m} \right\} / \left\{ 1 + \frac{C \Delta t}{m} \right\} \quad (5.29)$$

and

$$(\dot{\theta}_x)_{N+\frac{1}{2}} = \left\{ (\dot{\theta}_{(i)})_{N-\frac{1}{2}} \left[1 - \frac{C^* \Delta t}{I_{(i)}} \right] + \left(\sum M_{(i)} \right)_N \frac{\Delta t}{I_{(i)}} \right\} / \left\{ 1 + \frac{C^* \Delta t}{I_{(i)}} \right\} \quad (5.30)$$

5.2.5 The time step

The stability of the numerical scheme in DEM depends very much on the time step chosen, which is the time during which force is transmitted from one contact point to another along the particle surface. The time step chosen should be as large as possible to ensure simulation efficiency but small enough to make the assumption of constant acceleration within each time

step valid. The idea works on the assumption that, the time step is so small that no new contacts occur in that time step, except for those that have already been identified at the beginning of the time step. Hence, the resultant force acting on any particle over one time step is composed of the forces arising exclusively from the contacts the particles shared in that time step.

Two methods have been proposed for computing the critical time step. Both are based upon the frequency determined from a single degree of freedom in the system of particles with the mass element connected to the ground. The first one, which was proposed by Ning *et al.* (1997), uses the frequency of propagation of Rayleigh surface waves on one of the bodies on application of force. The frequency f_R of wave propagation is given by:

$$f_R = \phi \sqrt{\frac{G}{\rho}} \quad (5.31)$$

where ρ is the density of the particle, G is the modulus of rigidity of the particle and ϕ is a parameter dependent on the Poisson ratio (ν), which can be approximated from:

$$\phi = 0.1631\nu + 0.8766$$

The critical time step is then calculated from:

$$\Delta t_c = \frac{\pi R_{min}}{f_R} = \frac{\pi R_{min}}{\phi} \sqrt{\frac{\rho}{G_{max}}} \quad (5.32)$$

where R_{min} is the radius of the smallest particle in the system and G_{max} is the maximum modulus of rigidity in the assembly. The minimum and the maximum values of the parameters are chosen such that the least value from those determined from different materials within a system is used.

The second method, which was proposed by Cundal and Strack (1979), uses the natural frequency $\left(f = \sqrt{\frac{m}{k}} \right)$ in a linear spring system thus giving the critical time step as:

$$\Delta t_c = \frac{2\pi}{\omega} = 2\pi \sqrt{\frac{m}{k_{\max}}} \quad (5.33)$$

where m is the mass of smallest particle in the system and k_{\max} is the largest contact stiffness. This method is suitable for systems where the contact stiffness is known or fixed. When damping is introduced the critical time step becomes;

$$\Delta t_c = \frac{\pi}{\sqrt{\frac{k_{\max}}{m_{\min}} \left(1 - \frac{\ln^2 e}{\pi^2 + \ln^2 e} \right)}} \quad (5.33b)$$

where e is the coefficient of restitution. For the current model, the Ning and Ghadiri method was used. In most cases the calculated time step is not short enough to guarantee numerical stability. Therefore a fraction of the theoretical critical time step is usually used in most DEM simulations. The actual critical time step is then given by;

$$\Delta t_{\text{critic}} = \text{frac} \times \Delta t_c \quad (5.34)$$

The user has to specify the fraction of this time step that is to be used for calculation in case instability occurs during simulation.

5.3 The abrasive dehulling process

Abrasive dehulling is the most commonly used and the most efficient mechanical dehulling method for sorghum and millet. The method employs carborundum or other abrasive disks or

drums mounted on a vertical or horizontal rotor to progressively abrade the outer layers of the grain. The process is closely related to the interaction between the grain particles, and the abrasive surface. Therefore to understand the dehulling mechanism inside an abrasive dehulling mill, it is necessary to be able to trace the motion of individual grain particles and the contact forces experienced by the particles as they interact with each other and the surface of the mill and the abrasive surface. An accurate description of what happens inside the mill is the key to the understanding of various important operational and mill parameters that are required for better design and operation of these dehullers.

5.3.1 The theory of abrasive dehulling

To investigate the mechanics of the abrasive dehulling process, the Tangential Abrasive Dehulling Device (TADD) was used as a model mill. TADD was used in this particular modelling exercise because of its ability to closely simulate the abrasive dehulling action of commercial abrasive dehullers together with the fact that this mill can effectively dehull grain samples as small as one grain (Reichert *et al.*, 1986). These features together with its ability to process multiple samples at a time made it very useful experimental model for the DE model validation.

Details of the mill design and operation of TADD are described on section 4.2.1.3.1 of this thesis and in Reichert *et al.* (1986). Abrasion is provided by a horizontally mounted dehulling disk which rotates below and in close proximity (within 0.25-0.35 mm) to bottomless sample cups mounted on a sample-cup plate with their centres equally spaced around a circle 188 mm diameter. The number of the sample cups can vary from 1 to 12. As the grinding wheel rotates, grain kernels roll freely in the sample cups. The combination of the rotational motion of the horizontal abrasive disk and the static pressure of the grain column in the sample cup imposes a resultant circulatory motion to the grain mass in the cup. This produces a uniform mixing action that moves the grain from the bottom to the top of the sample cup and back to the bottom again, thus permitting each individual grain kernel to be briefly and cyclically

subjected to the abrasive action of the dehulling disk. The grain particles which are in contact with the moving abrasive plate, are pulled by the abrasive grit due to friction between the grain and the abrasive grit until they hit the cup wall and are re-circulated to the top of the grain mass in the cup by the push of kernels following behind. During this process the part of the grain in contact with the abrasive disk is sheared off by the abrasive surface and lost as bran through the gap under the sample cups. A fan mounted on the cover plate blows away the abraded fines beneath the sample cups to the bran collection bag. This process is repeated until a pre-determined retention time is reached. Only dry grain can be dehulled in TADD due to the clogging problem associated with wet or damp grain in abrasive dehullers.

The abrasive system in TADD is very similar to the classical physical model for the determination of coefficient of dynamic friction (figure 5.3a). However, in the current formulation, this has been modified slightly to more closely resemble the real situation in the mill, in which a force is applied to the surface and the surface is moved under the object.

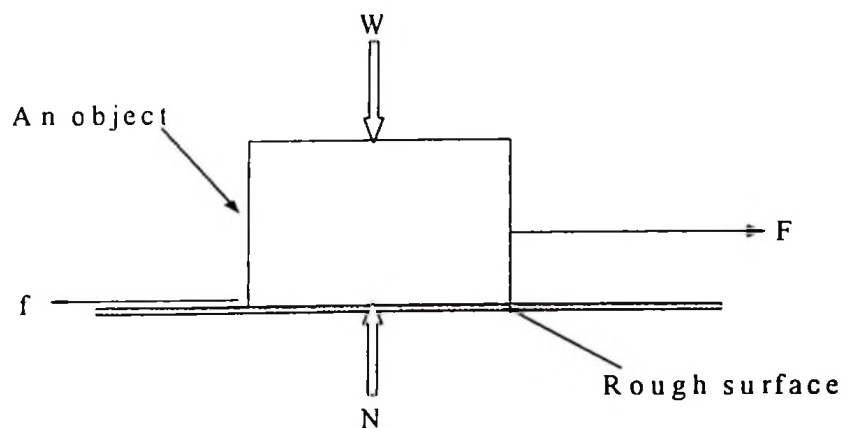


Figure 5.3a Forces affecting a moving object

W = weight, N = normal reaction, f = friction force opposing the motion, F = force causing motion

In the classical system there is a friction force that opposes the movement of the surface, abrading the object and the surface. In the mill, the interlocking of the grain particles and the

friction force between the grain and the dehulling disk opposes the movement of the abrasive surface, which results in abrasion of the grain and hence the removal of the seed coat portion in contact with the dehulling disk. The friction force between the grain particles and the dehulling surface can be related to the normal force acting on the surface of the grain by the Coulomb law of friction;

$$F = \mu F_n + C \quad (5.35)$$

where F is the friction force, μ is the coefficient of dynamic friction, and F_n is the normal force, in this case equivalent to the weight of the grain particle and mass of the grain above it in the cup, and C is the cohesion between the grain and the surface.

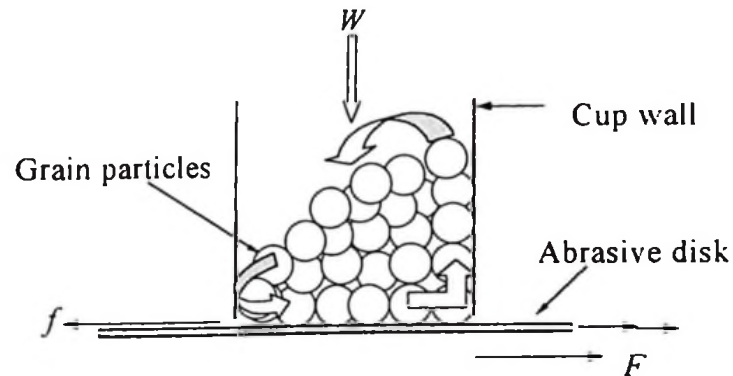


Fig..5.3(b). Forces affecting the dehulling process in TADD (F =force moving the surface, f =friction force)

The dehulling action in TADD can be explained by considering figure 5.3(b). The grain to be dehulled is the mass inside the cup, with the kernels above increasing the weight on the kernels in contact with the abrasive disk. As the abrasive disk rotates, the friction force between the grain and the abrasive disk opposes the motion of the disk. If the limiting tangential force is reached the dehulling disk moves, shearing off the portion of the grain in contact with it which is lost as bran. The amount of material removed depends on the normal force acting on the grain particle in contact with the abrasive disk. Grain to grain friction also occurs as the grain particles come into contact and rub against each other due to the constant mixing action provided by the rotation of the abrasive disk. This also contributes to the dehulling process although to a much lesser extent compared to the abrasive disk.

5.3.2 Determination of contact area and volume of materials removed

The amount of material sheared off depends on the magnitude of the normal force together with the physical and mechanical properties of the grain. Assuming the mechanical properties of the grain to be similar, their deformation should therefore be proportional to the normal force acting on them. The amount of material sheared off by the abrasion between grain and grain or between grain and the abrasive disk due to this deformation will be proportional to the normal force. Assuming the grain particles to be perfect elastic spheres, the deformation of the grain kernel due to the normal force F_n can be deduced from Hertz contact theory for elastic spheres. For two grain particles in contact or for a grain particle in contact with a rigid plate such as a wall or the dehulling disk, the following relationship between the normal force, deformation and material properties can be derived (Peleg, 1984);

$$F_n = \frac{4\alpha^{\frac{3}{2}}}{3\lambda(\delta_1 + \delta_2)} \quad (5.36)$$

where α is approach of the particle centres or total deformation of both particles at the contact area, λ is a constant which depends on the geometry of the system and δ_1 & δ_2 are material property constants, which can be defined as;

$$\delta = \delta_1 + \delta_2 = \left(\frac{1-\nu_1^2}{E_1} + \frac{1-\nu_2^2}{E_2} \right) \quad (5.37)$$

where E is the modulus of elasticity and ν is the Poisson's ratio. For contact between a soft and a hard material where E_2 is very large compared to E_1 , then δ_2 can be neglected and equation (5.37) can be written as;

$$\delta = \delta_1 = \left(\frac{1-\nu_1^2}{E_1} \right) \quad (5.37b)$$

For the dehulling process in the TADD, three geometrical configurations of interest can be encountered. These include, contact between two grain particles, contact between a grain particle and a flat surface (the abrasive disk) and contact between a grain particle of radius R_1 and a curved surface (e.g. sample cup wall) of radius of curvature R_2 . For these configurations λ is given by:

(i) For two grain particles of the same radius R in contact

$$\lambda = \sqrt{\frac{1}{R}} + \sqrt{\frac{1}{R}} = \sqrt{\frac{2}{R}} \quad \delta_1 = \delta_2 = \delta \quad (5.38)$$

(ii) For a grain particle of radius R_1 in contact with a rigid flat wall of radius $R_2 \gg R_1$ (i.e. with an infinite radius of curvature)

$$\lambda = \frac{1}{\sqrt{R}} \quad \delta_1 = \delta, \delta_2 \cong 0 \quad (5.39)$$

(iii) For a grain particle of radius R_1 in contact with a curved wall of radius R_2

$$\lambda = \sqrt{\frac{R_2 - R_1}{R_1 R_2}} \quad \delta_1 \neq \delta_2 \quad (5.40)$$

The general case for two grain particles in contact equation (5.36) can therefore be written as:

$$F_n = \frac{4\alpha^{\frac{3}{2}}}{3} \left(\frac{R_1 R_2}{R_1 + R_2} \right)^{\frac{1}{2}} \left[\frac{1 - \nu_1^2}{E_1} + \frac{1 - \nu_2^2}{E_2} \right]^{-1} \quad (5.41)$$

The deformation at contact area can be represented as:

$$\alpha = \left\{ \frac{3}{4} F_n \left[\frac{1 - \nu_1^2}{E_1} + \frac{1 - \nu_2^2}{E_2} \right] \left(\frac{R_1 + R_2}{R_1 R_2} \right)^{\frac{1}{2}} \right\}^{\frac{2}{3}} \quad (5.42)$$

If E is substituted with shear modulus of rigidity G , where

$$E = \frac{2G(1 - \nu^2)}{1 - \nu} \quad (5.43)$$

Then

$$F_n = \frac{8\alpha^{\frac{3}{2}}}{3} \left(\frac{R_1 R_2}{R_1 + R_2} \right)^{\frac{1}{2}} \left[\frac{1 - \nu_1}{G_1} + \frac{1 - \nu_2}{G_2} \right]^{-1} \quad (5.44)$$

$$\alpha = \left\{ \frac{3}{8} F_n \left[\frac{1-\nu_1}{G_1} + \frac{1-\nu_2}{G_2} \right] \left(\frac{R_1 + R_2}{R_1 R_2} \right)^{\frac{1}{2}} \right\}^{\frac{2}{3}} \quad (5.45)$$

The contact area of the deformed grain particle in these cases is to a good approximation circular in shape (figure 5.4). The radius of the contact circle for a given normal force F_n is given as (Pelleg, 1984):

$$a = \left\{ \frac{3}{8} F_n \left[\frac{1-\nu_1}{G_1} + \frac{1-\nu_2}{G_2} \right] \left(\frac{R_1 R_2}{R_1 + R_2} \right) \right\}^{\frac{1}{3}} \quad (5.46)$$

which for two grain particles in contact or grain particle in contact with a flat wall (assuming $R_2 = \infty$ & $\delta_2 = 0$) is given as;

$$a = \left[\frac{3F_n R}{8G} (1-\nu) \right]^{\frac{1}{3}} \quad (5.47)$$

From this the contact area A_c can be calculated as;

$$A_c = \pi \left[\frac{3F_n R}{8G} (1-\nu) \right]^{\frac{2}{3}} \quad (5.48)$$

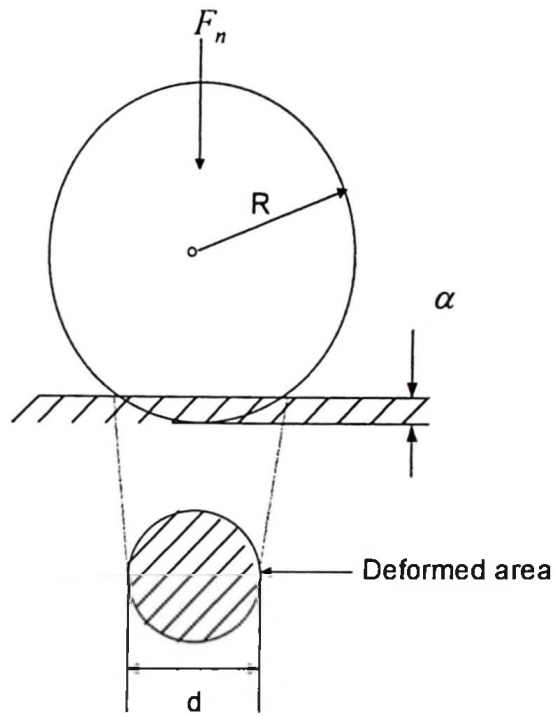


Figure 5. 4. Contact between a particle and a flat surface

For contact between a grain particle of radius R_1 and a curved wall of radius R_2

$$a = \left\{ \frac{3}{8} F_n \left(\frac{1-\nu_1}{G_1} + \frac{1-\nu_2}{G_2} \right) \left[\frac{R_1 R_2}{R_1 - R_2} \right] \right\}^{\frac{1}{3}} \quad (5.49)$$

where G_1 , G_2 and ν_1 , ν_2 are moduli of rigidity and Poisson's ratios of the grain and wall materials respectively. The contact area in this case will be equal to:

$$A_c = \pi \left\{ \frac{3}{8} F_n \left(\frac{1-\nu_1}{G_1} + \frac{1-\nu_2}{G_2} \right) \left[\frac{R_1 R_2}{R_1 - R_2} \right] \right\}^{\frac{2}{3}} \quad (5.50)$$

Assuming G_2 to be very large compared to G_1 , equation (5.50) can be simplified to:

$$A_c = \pi \left[\frac{3F_n R_1 R_2 (1-\nu)}{8G_1 (R_2 - R_1)} \right]^{\frac{2}{3}} \quad (5.51)$$

The volume of deformed area can be determined from the deformation and radius of the particle using the following equation (Arzt, 1982);

$$V = \alpha^2 \pi \left(R - \frac{\alpha}{3} \right) \quad (5.52)$$

where α is the deformation (m) and R is the radius of the particle (m)

Dehulling occurs only when grain particles slide over each other or on the dehulling disk or the mill walls. The force component responsible for the sliding of the grain particles is the shear or tangential force F_s the magnitude of which depends on the friction force between the two surfaces in contact. Sliding of the grain particles take place only when the maximum possible shear force is greater than or equal to the absolute value of the limiting friction force at the point of sliding;

$$F_{s(max)} \geq |F_n| \tan \phi \quad (5.53)$$

$F_{s(max)}$ is therefore the force responsible for the removal or shearing off the seed coat from the endosperm during the dehulling process. The maximum shear force per unit area is obtained by dividing the maximum tangential force $F_{s(max)}$ by the contact area for a given normal force as determined from equation (5.48) or (5.50) depending on the contact conditions.

In the current model it is assumed that dehulling or removal of the seed coat takes place only when the maximum shear force per unit area is greater or equal to the seed coat adhesion strength per unit area. (Determination of the seed coat adhesion strength per unit area is

described in section 4.2.2.6 of this thesis). If this condition is satisfied the volume of the deformed portion of the grain due to the normal force at that instant is computed and removed as bran. If the shear force per unit area is less than the seed coat adhesion strength per unit area, no seed coat or material is removed from the grain.

5.4 Model implementation

The dehulling process describe above was implemented as part of the DEM program CONBALL 3-4. This is a well documented three dimensional program based on two programs, TRUBAL, which was developed by Cundal and Strack (1979) and CONTACT, which was incorporated in TRUBAL by Ng and Dobry (1990) to take account of the non linear force-deformation relation at inter-particle contacts based on Mindlin's solution. This program was initially modified by Raji (1999) and used in the study of compression of agricultural materials and was further modified by Abbaspour *et al.* (1998) for the investigation of flow properties of irregular shape particles. While the structure of the parent code was kept the same, a number of important features unique to dehulling process were introduced. Also some of the features in the code pertaining to problems in flow and compression were discarded. The major changes included (see Appendix C):

- (i) Modification of the program to simulate both straight and curved or circular walls (Appendix C1)
- (ii) The original code was meant for simulation of multi-particle irregular bodies, it was therefore modified to simulate spherical particulate bodies.
- (iii) The program was changed from the simulation of gravity flow to a combination of flow and abrasion between particle/ particle and particle and wall.
- (iv) Wall creation for flow purposes was deleted and creation of curved wall was introduced.
- (v) Particle - wall contact detection was modified to include both particle contact with straight and with curved walls (Appendix C2).

5.4.1 Structure of the program

The components and subroutines of the modified CONBAL 3-4 and their sequence of call are summarised in figure 5.5.

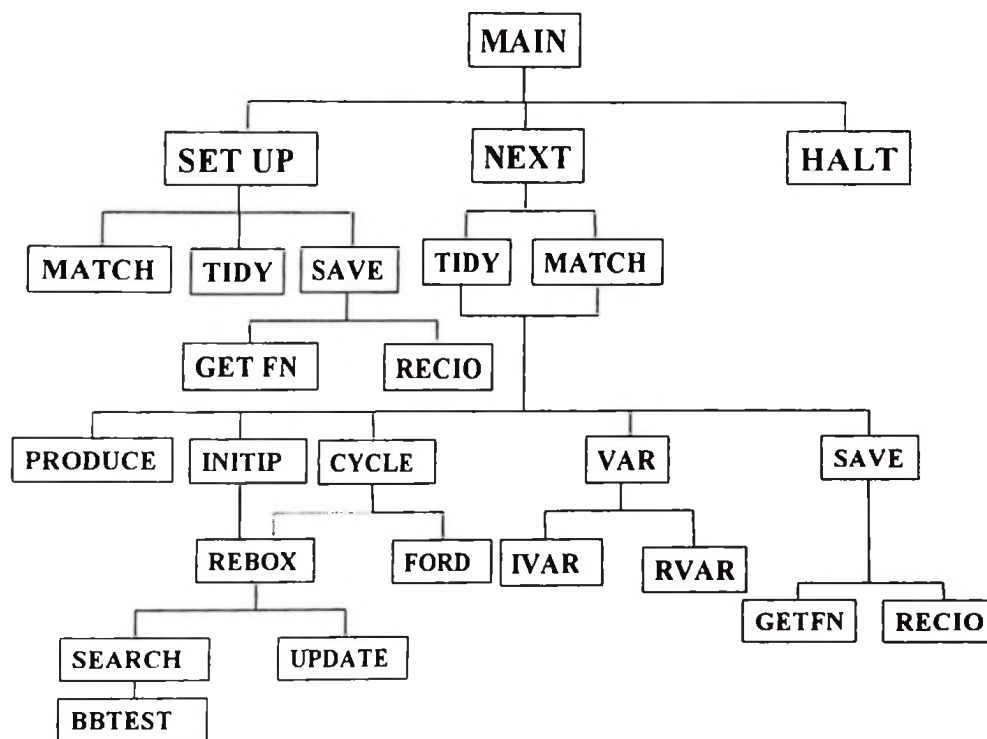


Figure 5.5 Components of CONBAL3-4

5.4.2 The functions performed by different subroutines

The functions performed by various subroutines are as follows:

SET UP To start or restart a new problem. Initialise arrays and variables, specify constants, material properties and parameters needed for particle generation are read and necessary calculations done and saved.

NEXT To interpret the command lines for each operation and locates the position for reading or calculating the necessary parameters for input line for successive operations.

HALT	Terminates the program when there is an error or at the end of the operation.
TIDY	Eliminate blanks in the input lines and makes the index to location of parameters by recognising the separator between parameters and the terminator at the end of a line.
MATCH	Matches input string to keyword in table of data in the program, which are index to parts of the program where parameters following key word are required.
SAVE	Save or restore state of data, information and results.
GETFN	To create files, also interprets the file name parameters in the input file as a filename.
REBOX	Locate the positions of particles with respect to the sub-boxes within the working space and delete when necessary.
SEARCH	Searches for neighbouring particles that are potential contact partners and assign identification address to each contact.
BBTEST	Test for contact between particles and particles and walls.
UPDATE	Update particle positions and put particles in position when necessary.
INITP	Perform calculation of initial parameters prior to the calculation cycle.
CYCLE	Cycle through the main calculation loop, calculates and updates the periodic working space, velocity, acceleration, displacement, and contact forces.
FORD	Apply force-displacement law to each contact to obtain the deformation and contact forces.
PRODUCE	Generation of particles and the working space walls.

Changes were made in the following sub-routines;

PRODUCE	Generation of spherical particles and curved walls.
BBTEST	To test contact between particles and curved walls.
REBOX	Locating the position of the curved walls.
FORD	Modification to handle force calculation for curved walls, rotating bottom wall and calculation of material removed as bran from the grain during simulation.

5.4.3 Simulation steps

Simulation using the modified CONBAL 3-4 essentially consists of three major steps: Detection of contacts, computation of contact forces and computation of particle motion. This cycle of dynamic calculations is repeated thousands of times as the simulation proceeds. Briefly stated, this three dimensional DEM algorithm proceed as follows:

5.4.3.1 Initialisation

- (i) Each physical entity in the system (grain particle or wall) is identified separately by a set of geometrical properties, physical properties, Initial x , y , and z co-ordinates, and velocities.
- (ii) A computational scheme termed boxing is implemented to reduce the number of elements that have to be tested for potential contact with each entity. To do so the entire working space is divided into small boxes, and a set of pointers is used to store all elements inside each box in a linked list called the contact list. Hence test for potential contacts is done only between elements in the same or neighbouring boxes.

5.4.3.2 Iteration for each time step

- (i) For each particle, forces and moments at all contact points are calculated, and reduced in their resultant x , y , and z components.
- (ii) Newton's second law of motion is applied to find translational and rotational accelerations. These accelerations are integrated to update velocities, which are in turn integrated to update particle position.
- (iii) For those particles in contact with others or wall, the incremental force at each contact during the time step is calculated.
- (iv) For each box, pointers to the elements/particles that has moved out of the box are dropped and new pointers are assigned for incoming entries.

- (v) For each particle, new contacts are formed while some old contacts are broken, and a new iteration cycle is launched.

5.4.4 Input parameters

The input parameters that must be specified to run numerical tests with the current DEM program may be divided into two main groups;

- (i) The geometrical and physical property data: The geometrical data which describes the position and orientation of the rigid boundaries (the walls) and the positions and radii of the particles with respect to global co-ordinate system. The physical properties which includes; particle radius, density, friction coefficients, number and types of the particles to be used.
- (ii) Other parameters which apply to the field as a whole include, damping ratio, the fraction of the critical time step (*frac*) and the number of cycles required.

5.4.5 Determination of the input parameters

Since the model deals with individual particle to particle or particle to wall contacts, it was necessary to choose realistic values of contact properties for both particle-particle and particle-wall contact. Therefore experiments were carried out to determine the input parameters as accurately as possible. The input parameters needed for the numerical calculations and simulation included coefficient of restitution, damping ratio, and coefficient of friction.

5.4.5.1 Coefficient of restitution.

Coefficient of restitution (e) is a measure of energy loss upon collision and is equal to the ratio of the final to initial relative velocity components of the colliding bodies in the direction normal to the contact surfaces. The ratio can be expressed as (Mohsennin, 1986);

$$e = \frac{v_2}{v_1} = \sqrt{\frac{h_2}{h_1}} \quad (5.54)$$

where the subscripts 1 and 2 represent the initial and final velocity and h_1 and h_2 denote height of drop and rebound in free fall respectively. Generally two types of collision can be observed in a dehulling process, grain-grain collision and grain-wall collision. For grain-wall collision the following experiment was carried out to determine the coefficient of restitution. A single grain kernel was dropped on an aluminium block from a known drop height. The impact was captured on a video camera and the video frames were analysed using image analysis techniques to calculate the drop and rebound height. The same experiment was repeated with a single kernel dropped on a layer of grain kernels glued together on a flat rigid surface to determine the coefficient of restitution between grain and grain.

5.4.5.2 Damping constant

Contact damping is relative velocity related damping and operates on the relative velocity at the particle contacts in both normal and tangential directions. The relative velocity dependent forces are $C_n V_n$ and $C_s V_s$ where C_n and C_s are the coefficients of contact damping in normal and shear directions respectively. These coefficients are dependent on the particle's coefficient of restitution e , mass m and normal stiffness k_n and can be computed from the following relationship with different values of e for particle -particle and particle-wall collision (Corkum *et al.*, 1986):

$$C_n = -\frac{2 \ln(e) \sqrt{k_n m^*}}{\sqrt{(\ln e)^2 + \pi^2}} \quad (5.55)$$

where $m^* = \frac{m_1 m_2}{m_1 + m_2}$ and m_1 and m_2 are the masses of the colliding particles. If m_1 is very large in comparison to m_2 as in the case of a wall, then m is the mass of the particle only.

ratio to be calculated independent of stiffness coefficient, this can then be used to calculate the damping coefficient dynamically within the program. During sliding the shear damping is switched off as the tangential contact forces are restricted by the inter-particle friction. Global damping was not used in this model.

5.4.5.3 Coefficient of friction

In the light of spring and dashpot model of collisions, the shear force due to the dashpot is limited by the maximum that can exist at the contact. This maximum tangential force at the contact is related to the current normal spring force using a Coulomb type friction given by:

$$F_{s \max} = \mu F_n + C \quad (5.64)$$

where μ is the coefficient of friction, F_n is the normal force at contact and C is the cohesion. If the absolute value of the force in the shear spring and dashpot exceed the value given by the above equation then slip is presumed to occur. In this situation, during computation tensile strength normal to the contact is set to zero (i.e. the dashpot in the shear direction is omitted) and friction loss is computed.

Friction coefficient of grain on wall was determined by the use of the seed coat adhesion measuring apparatus, as described in section 4.2.2.6, while grain to grain friction coefficient was obtained from literature (Mohsenin, 1986).

Ning *et al.* (1997) using the Hertz theory derived an equation for calculation of damping force as a function of a damping ratio and material stiffness coefficient as:

$$F_n = 2V_n\beta\sqrt{\frac{10}{3}}k_n m^* \quad (5.56)$$

and

$$F_s = 2V_s\beta\sqrt{\frac{10}{3}}k_s m^* \quad (5.57)$$

where V_n and V_s are normal and tangential relative velocities respectively and β is the damping ratio which can be calculated from:

$$\beta = -\frac{\ln e}{\sqrt{(\ln e)^2 + \pi^2}} \quad (5.58)$$

where e is the coefficient of restitution of the contacting particles.

From equation (5.56) and (5.57) the normal and tangential damping coefficient can be derived as;

$$C_n = \frac{-2\ln e\sqrt{k_n m^*}}{\sqrt{(\ln e)^2 + \pi^2}} \left(\sqrt{\frac{5}{6}}\right) = -2\beta\sqrt{k_n m^*} \left(\sqrt{\frac{5}{6}}\right) \quad (5.59)$$

and

$$C_s = \frac{-2\ln e\sqrt{k_s m^*}}{\sqrt{(\ln e)^2 + \pi^2}} \left(\sqrt{\frac{5}{6}}\right) = -2\beta\sqrt{k_s m^*} \left(\sqrt{\frac{5}{6}}\right) \quad (5.60)$$

which is similar to equation (5.55) reported by Corkum *et al.* (1986) (except for the last term, which is approximately equal to one). The derivation by Ning *et al.*, (1997) allow the damping

ratio to be calculated independent of stiffness coefficient, this can then be used to calculate the damping coefficient dynamically within the program. During sliding the shear damping is switched off as the tangential contact forces are restricted by the inter-particle friction. Global damping was not used in this model.

5.4.5.3 Coefficient of friction

In the light of spring and dashpot model of collisions, the shear force due to the dashpot is limited by the maximum that can exist at the contact. This maximum tangential force at the contact is related to the current normal spring force using a Coulomb type friction given by:

$$F_{s \max} = \mu F_n + C \quad (5.64)$$

where μ is the coefficient of friction, F_n is the normal force at contact and C is the cohesion. If the absolute value of the force in the shear spring and dashpot exceed the value given by the above equation then slip is presumed to occur. In this situation, during computation tensile strength normal to the contact is set to zero (i.e. the dashpot in the shear direction is omitted) and friction loss is computed.

Friction coefficient of grain on wall was determined by the use of the seed coat adhesion measuring apparatus, as described in section 4.2.2.6, while grain to grain friction coefficient was obtained from literature (Mohsenin, 1986).

5.4.5.4 Results of simulation parameters.

The input parameters determined are summarised in Table 5.1.

Table 5.1 Input parameters

Grain type	Coefficient of restitution	Coefficient of friction			Damping ratio
		Grain/grain	Grain/wall	Grain/disk	
Sorghum	0.34	0.4	0.3	0.65	0.3
Millet	0.47	0.4	0.33	0.65	0.25

5.5 Model validation

To validate the model, comparison was made between simulation results and experimental results using TADD. To ensure that experimental and numerical results are comparable, the properties of experimental materials and the simulation were made similar.

5.5.1 Experimental set-up and procedures

One sorghum variety (Dionje) and one millet variety (IM) was used in these experiments. The physical properties of the grain used are given in Table 5.2.

Table 5.2. Grain physical properties.

Grain type	moisture (%db)	G/radius (m)	G/density (kg/m ³)	Coefficient of friction			M/Rigidity (MPa)
				Grain/grain	Grain/wall	Grain/disk	
Sorghum	12	0.00179	1265	0.4	0.3	0.65	821.4
Millet	12	0.00125	1035	0.4	0.33	0.65	875.0

Dehulling tests were carried out in a tangential abrasive-dehulling device (TADD) using a 6-cup cover-plate and an 80-grit resin bounded abrasive cloth fixed to a 250 mm diameter aluminium disk as the abrasive disk. The dimensions of the sample cups were 50 mm diameter and 35 mm in height. The same dimensions were used for the working space in the simulation.

The effect of operating variables, such as the retention time of the grain in the dehuller on the amount of materials removed as bran from the grain were investigated using a 2 g, grain sample. After dehulling for pre-determined time intervals of 15, 30, 45, and 60 seconds, the dehulled grain was removed from the sample cups using a vacuum device. The device simultaneously collected and cleans the dehulled grain, removing any residual fine material that had not escaped under the sample cups. A 2 g sample was also dehulled for a total time of 240 seconds which was the time required to remove material equivalent to the seed coat content of the grain (i.e. 8.3% of the grain by weight) as bran.

The dehulled grain was weighed and the weight loss (%) was designated as materials removed. The intent of abrasive dehulling of sorghum is to remove the seed coat from the grain while preserving the interior of the grain from the aleurone layer inwards. However, when grain is placed in an abrasive mill intending to remove only the seed coat other tissues other than the seed coat may be separated and included in the bran fraction or decorticate. Therefore the term 'material removed' as used here may include both the seed coat and other

parts of the grain kernel abraded during the dehulling process. Three replications were carried out for each sample.

The simulation was run for 60 and 240 seconds, the same duration as the experiment. The proportion of material removed in the simulation was recorded every 15 seconds and compared with results obtained from the experiment. The parameters used in the simulation are summarised in Table 5.3. Apart from direct comparison with experimental results, the effect of different grain, mill and input parameters such as grain hardness, damping ratio, time step, disk speed, and disk roughness on the amount of material removed predicted by the model was simulated by varying these parameters one at a time.

Table 5.3 Parameters used in the simulation

Grain type	D/speed (rpm)	No of particles	Time step (sec)	Work space dimensions		Damping ratio	
				Diameter(mm)	Height(mm)	g/g	g/w
Sorghum	1500	63	1.0×10^{-5}	5.0	3.5	0.33	0.3
Millet	1500	120	4.5×10^{-6}	5.0	3.5	0.23	0.25

g/g – grain to grain collision, g/w – grain to wall collision

5.5.2 Results and discussion

5.5.2.1 Simulation tests

Figures 5.6(a) to 5.6(f) show the results of the simulation of the abrasive dehulling process of 1000 sorghum grain particles (approximately 30g of grain for demonstration purposes) in TADD using the modified program stage by stage. Figure 5.6(a) shows the particle generation stage where particles are being generated systematically in the dehulling cup.

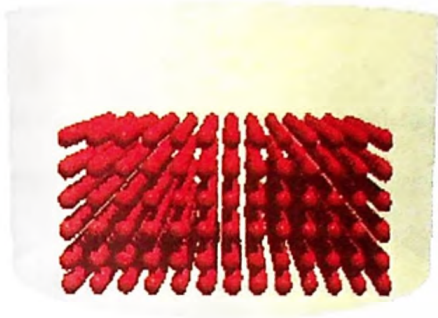


Figure 5.6(a) Particle generation stage

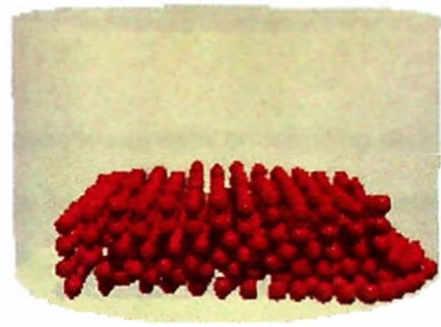


Figure 5.6(b) Particle consolidation (first layer of particles just touching the dehulling disk)



Figure 5.6(c) Particles in contact with the dehulling disk are pulled to the cup wall

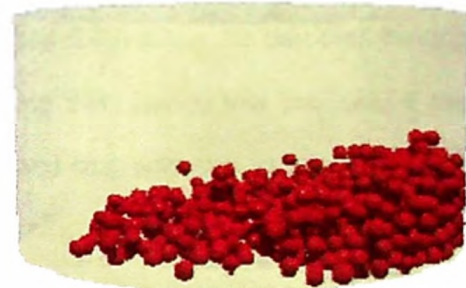


Figure 5.6(d) Particles reach the cup wall and are force up the wall by particles following behind



Figure 5.6(e) Particles forced up the cup wall reach the top of grain mass and roll/slide back t the dehulling disk

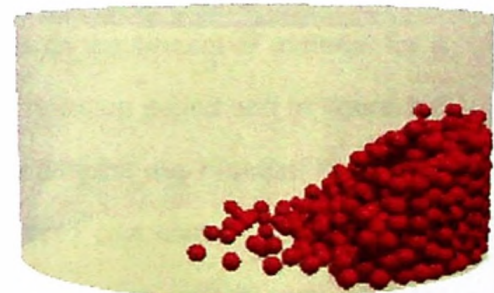


Figure 5.6(f) The cycle is repeated until the required retention time is reached

Figure 5.6 Simulation of the tangential abrasive dehulling process in TADD

There is no contact between particle and particle or particle and the cup walls or dehulling disk at this stage. Figure 5.6(b) shows the consolidation stage where the grain particles are consolidating under gravity until they come into contact with the rotating dehulling disk. As the first layer of particles touched the dehulling disk, it is pulled towards the cup wall by the rotating dehulling disk. Figure 5.6(c) shows the grain particles as they hit the dehulling cup wall and bounce back, colliding with the particles behind them and those, which are still at consolidation stage. Figure 5.6(d) shows the grain particles after reaching the cup wall are forced to move up the sample cup wall by the force exerted by the rotating disk and the push from the grain particles following behind. Figures 5.6(e) and 5.6(f) show the particles having reached the top of the grain mass roll down to the rotating disk. During this process, if the tangential force per unit area is greater or equal to the seed coat adhesion strength per unit area, the portion of the seed coat in contact with the dehulling disc is removed as bran (material removed). The process is repeated until the pre-set retention time is reached.

5.5.2.2 The effect of retention time on the amount of materials removed

The comparison between experimental and simulation results on the amount of material for a given retention time is shown in figure 5.7 for a 60 seconds retention period and in figure 5.8 for 240 seconds retention period. 240 seconds retention in the dehuller was required to remove 8.5% of the grain sample which was equivalent to the grain seed coat content as determined from hand peeling tests (section 4.3.1.1). The short and long retention periods were used for both experiment and simulation. In the current study the term 'material removed' refers to the amount of the material removed from the grain sample as bran and was determined from the following equation:

$$\% \text{ materials removed} = \frac{\text{Initial sample weight} - \text{final sample weight}}{\text{Initial sample weight}} \times 100 \quad (5.65)$$

In both experiment and simulation the amount of material removed from the grain increased with the increase in retention time in the dehuller. There was a good agreement between the

predicted and the experimental results in short and long retention periods for both sorghum and millet. Figure 5.7(a) and (b) show the results for short time retention (60 seconds retention) for sorghum and millet respectively while figure 5.8(a) and (b) show the results for long time (240 seconds) retention. For both short and long retention times, the amount of material removed in the experiment was slightly higher than the amount predicted by the model for both sorghum and millet. For short retention time the difference between the rate of material removal from the grain sample as predicted by the simulation and from actual experiment was constant as evidenced by the closeness of the slopes for the experimental and predicted curves. The difference between experimental and predicted material removed after 60 seconds retention was approximately 0.1% for sorghum and 0.13% for millet.

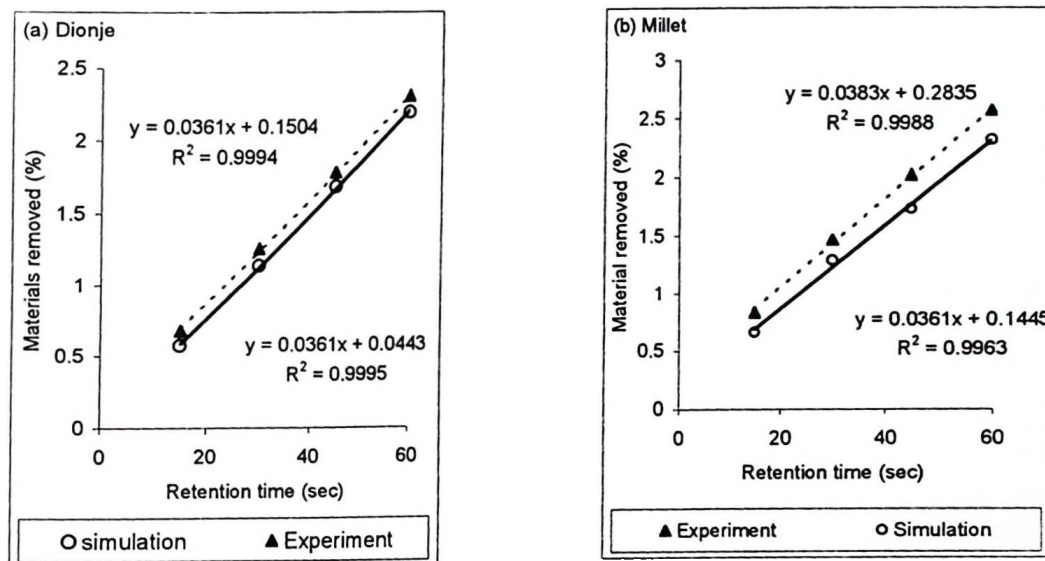


Figure 5.7 Effect of retention time on the amount of materials removed from sorghum (Dionje) and millet (IM) after 60 seconds in the experiment and simulation

However, as the retention time in the dehuller increased, the difference between the rate of material removal predicted by the simulation and the experiment increased for both sorghum and millet as shown in figure 5.8(a) and (b). The mean difference between simulated and experimental results after 240 seconds retention was 0.5% for sorghum and 0.4% for millet.

Statistical analysis (t-test) showed that the difference between material removed predicted by the model and experimental results was not significant ($P < 0.05$) for short retention time (60 seconds) but was significant ($P < 0.05$) for long time retention period (240 seconds).

The difference could be explained by the fact that, the longer the grain is retain in the dehuller, the higher the chance of kernel breakage occurring, thus leading to some of the broken particles being lost in the bran fraction and hence the increase in the rate of material removal in the experiment. This explanation is supported by experimental evidence from literature that kernel breakage is positively correlated with retention time in the dehuller (Deshpande, 1981). On the other hand the model assume that no grain is broken during the dehulling process and only the materials removed are shear off.

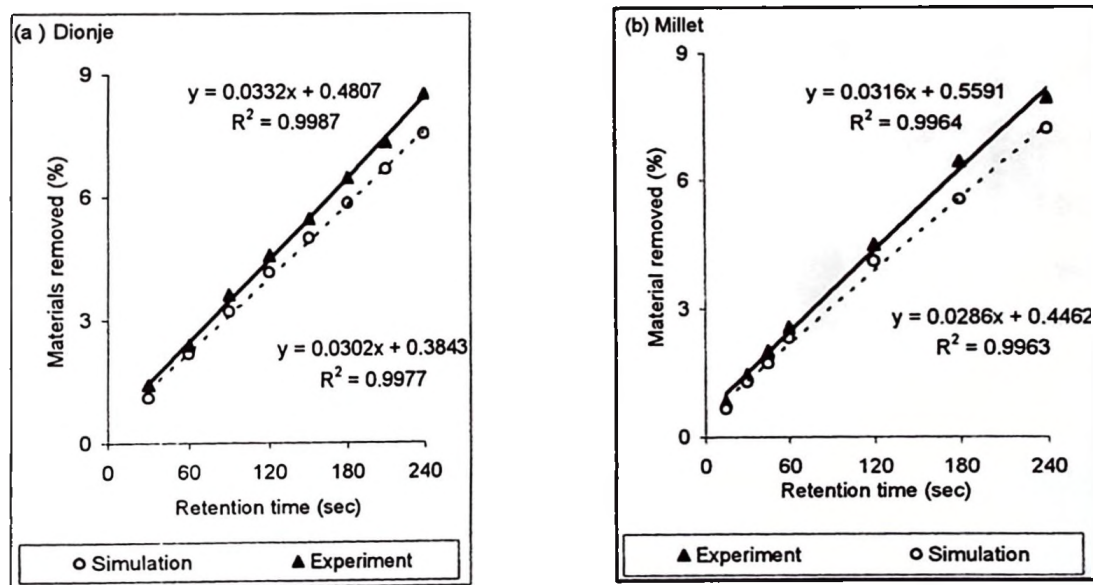


Figure 5.8 Effect of retention time on the amount of materials removed from sorghum (Dionje) and millet (IM) after 240 seconds in the experiment and simulation

The relationship between the material removed (%) and retention time for the experiment and simulation could be represented by the following empirical equation:

$$Y_{removed} = at + b \quad (5.66)$$

where, $Y_{removed}$ is the material removed (%), a and b are constants and t is the retention time in the dehuller (sec). The values of the constants and the respective R^2 values for short and long retention times are given in Table 5.4 for both sorghum and millet.

Table 5.4. Values for the constants and R^2 for the relationship between retention time and material removed (equation 5.66)

Grain type	Retention Time (sec)	Experiment			Simulation		
		a	b	R^2	a	b	R^2
Dionje	60	0.04	0.15	0.999	0.04	0.04	0.999
	240	0.03	0.48	0.998	0.03	0.38	0.998
Millet	60	0.04	0.28	0.999	0.04	0.14	0.996
	240	0.03	0.56	0.996	0.03	0.45	0.996

5.5.2.3 The influence of grain properties and machine operating variables on the rate of material removal from the grain sample.

Apart from direct comparison between experimental and simulation results, the model was used to simulate the effect of different grain properties and mill parameters on the rate of material removal from the grain sample. These included, grain strength properties, the roughness of the dehulling disk, and the speed of rotation of the dehulling disk.

5.2.3.1 Effect of grain strength properties

The effect of grain strength or kernel hardness on the rate of material removal from the grain was simulated by varying the modulus of rigidity of the grain, the higher the modulus of rigidity the harder the grain and vice versa. The rate of material removal from the grain decreased with increase in the modulus of rigidity (or hardness) of the grain as indicated in figure 5.9 (a) and (b) for sorghum and millet respectively. The model predicted that, the softer the grain the more the amount of materials which will be removed as bran from the grain sample for a given retention time in the dehuller. These results are in good agreement with experimental results reported in literature that for the same retention time in the dehuller, more materials were lost as bran from soft grain than in hard grain (Reichert *et al.*, 1988).

The relationship between the grain modulus of rigidity or hardness and the rate of material removal from the grain as illustrated in figure 5.9 (a) and (b) and could be represented by the following empirical equations for sorghum and millet respectively:

$$\ln(S_{removed}) = 2.9 - 0.002G_s \quad (R^2 = 0.994) \quad (5.67a).$$

and

$$\ln(M_{removed}) = 1.9 - 0.001G_s \quad (R^2 = 0.994) \quad (5.67b).$$

where, $S_{removed}$ and $M_{removed}$ is the material removed per second (%) from sorghum and millet respectively, and G_s is modulus of rigidity of the grain (MPa)

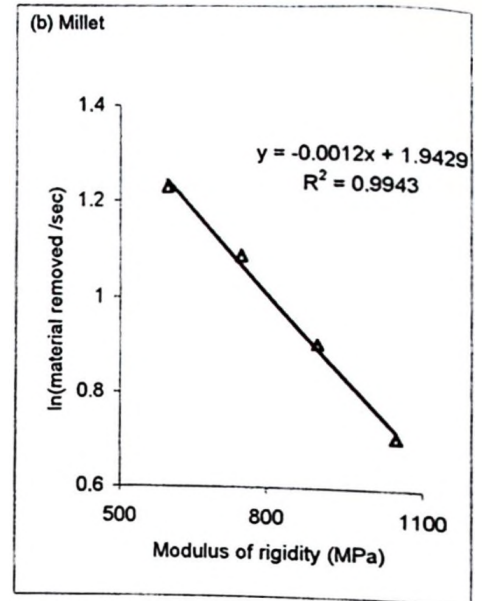
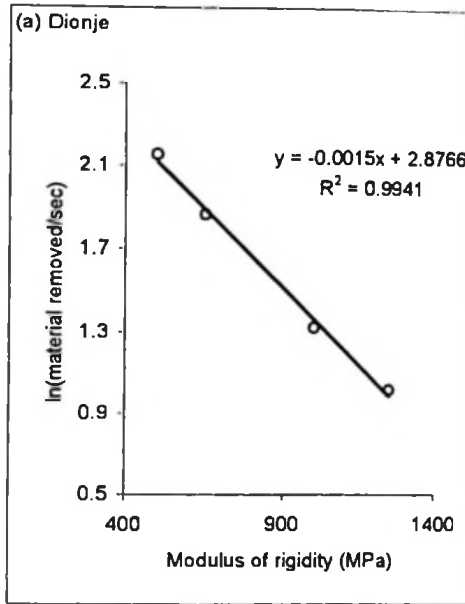


Figure 5.9 Effect of modulus of rigidity on the rate of material removed after 60 seconds retention as predicted by the model

5.5.3.2 Effect of time step and damping constant on material removed

The effect of time step and damping ratio on the amount of material removed was investigated by varying the time step and damping constant using different values of *frac* and damping ratios. The results are given in figures 5.10(a) and 5.10(b) for time step and damping ratio respectively. In both cases there was no significant difference in materials removed from the grain sample by varying *frac* from 1.0 to 0.1, or varying damping ratio from 0.1 to 0.5. Therefore the largest possible time step calculated in the program (equation 5.33) with a *frac* value of 1.0 and damping ratio of 0.3 (sorghum) and 0.25 (millet) for grain/ wall collision was used throughout the simulation.

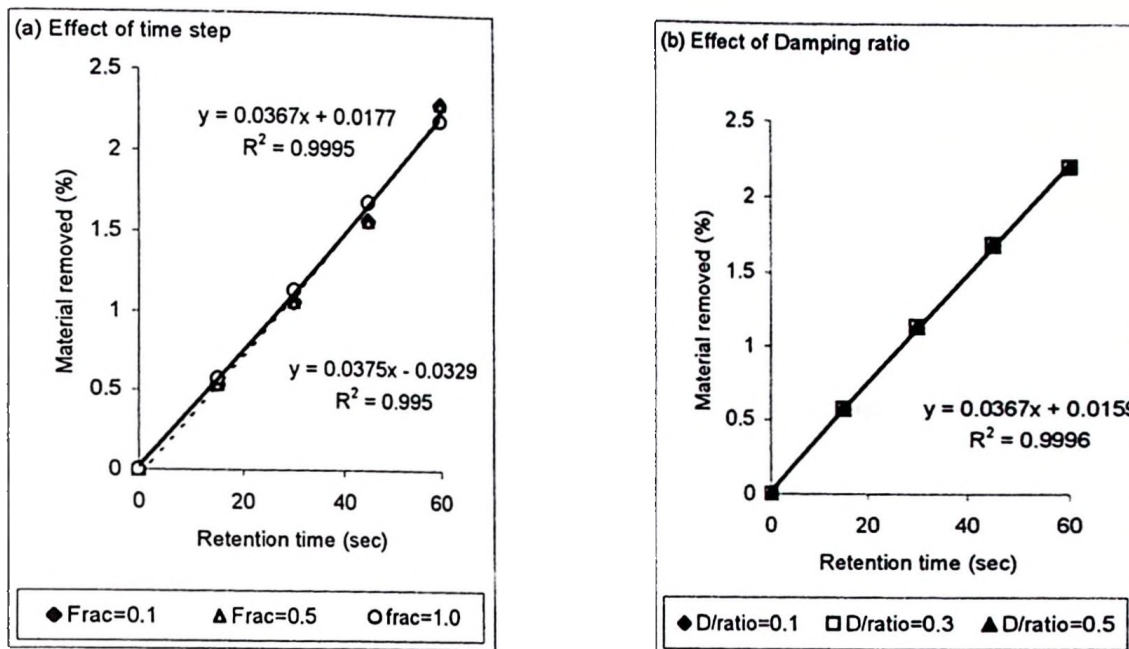


Figure 5.10 Effect of time step and damping ratio on the amount of material removed after 60 seconds retention in the dehuller

5.5.3.3 Effect of dehulling disk speed

The effect of speed of rotation of the dehulling disk on the rate of material removal was studied by varying the disk speed from 500 rpm to 2000 rpm for a retention time of 60 seconds. The results as predicted by the model are summarised in figure 5.11(a) and (b) for sorghum and millet respectively. The rate of removal of materials from both sorghum and millet increased with increase in disk rotation speed from 500 rpm, reaching a peak between 1500-rpm (157 rad/sec) and 2000 rpm. For speed of revolution above 1500 rpm there was no significant increase in the rate of material removal from the grain for both sorghum and millet. This might have been caused by the fact that, as the speed of rotation of the disk increased above 1500 rpm, the particles spend more time suspended in air than in contact with the dehulling disk thus causing the number of contacts between grain and the dehulling disk to decrease. Figure 5.12(a) and (b) shows the relationship between number of contacts between grain particles and dehulling disk for sorghum and millet as the disk speed increase from 500 rpm to 2000 rpm. The results show that there was no significant increase in the number of

contacts as the speed of rotation increased from 1000 rpm to 2000 rpm. The mean number of contacts between grain particles and the dehulling disc was 20, 22 and 21 for sorghum and 25, 27, 26 for millet at 1000, 1500 and 2000 rpm respectively, indicating that there was on average more contacts between grain particles and the dehulling disk at 1500 rpm than at 2000 rpm.

The relationship between the disk speed (radians/sec) and the rate of material removal (%) from the grain sample as shown in figure 5.11 could be represented by the following polynomial equations for sorghum and millet respectively:

$$S_{removed} = 7E-09r^3 - 5E-06r^2 + 0.0013r + 1.22 \quad (R^2=1) \quad (5.68a)$$

$$M_{removed} = -1E-08r^3 + 4E-06r^2 - 0.002r + 0.85 \quad (R^2=1) \quad (5.68b)$$

Where, $S_{removed}$ and $M_{removed}$ are the material removed per second for sorghum and millet respectively, and r is the disk rotation speed (rad/sec)

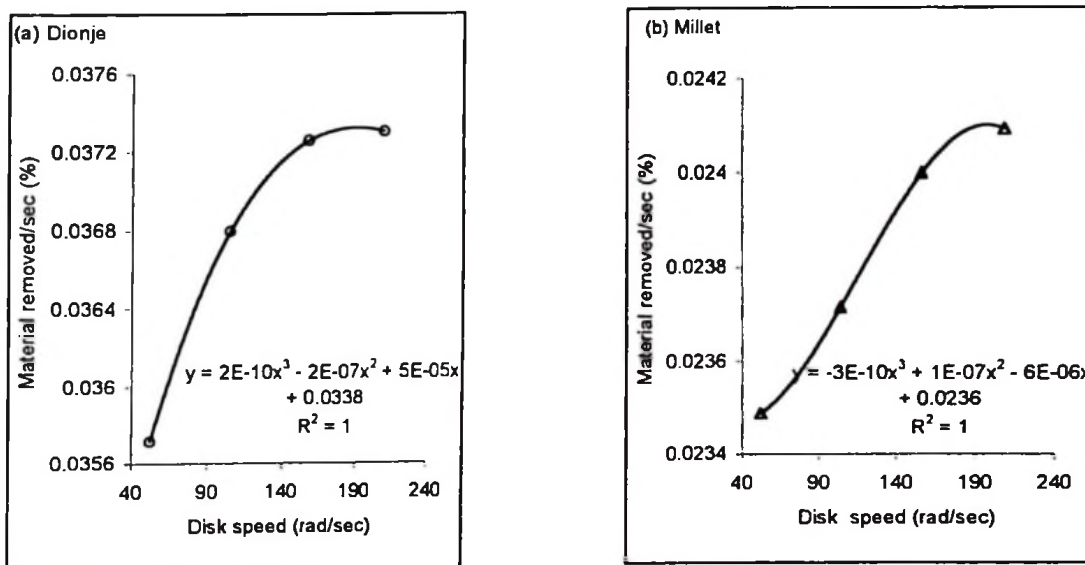


Figure 5.11. The effect of dehulling disk speed on the rate of material removal as predicted by the model

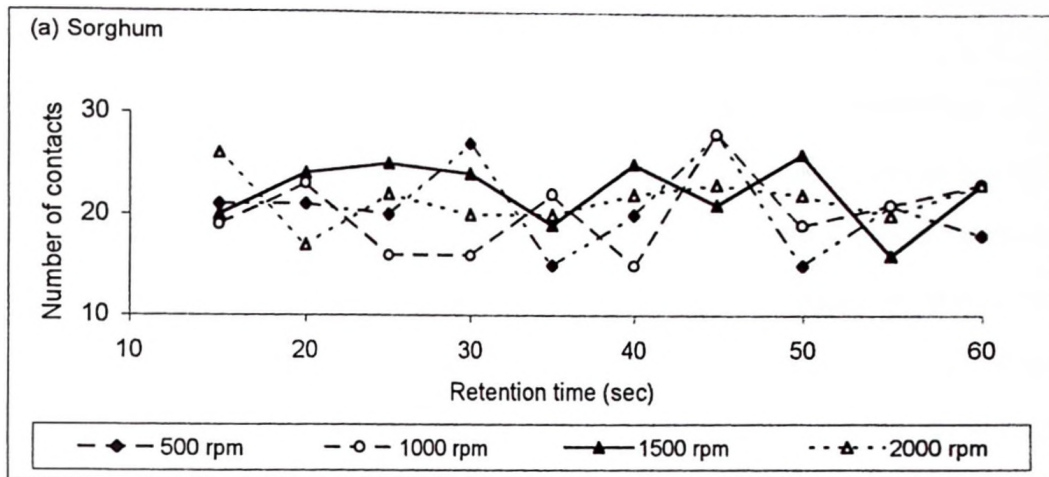


Figure 5.12(a) Effect of dehulling disk rotational speed on the number of contacts between grain particles and the dehulling disk for Dionje

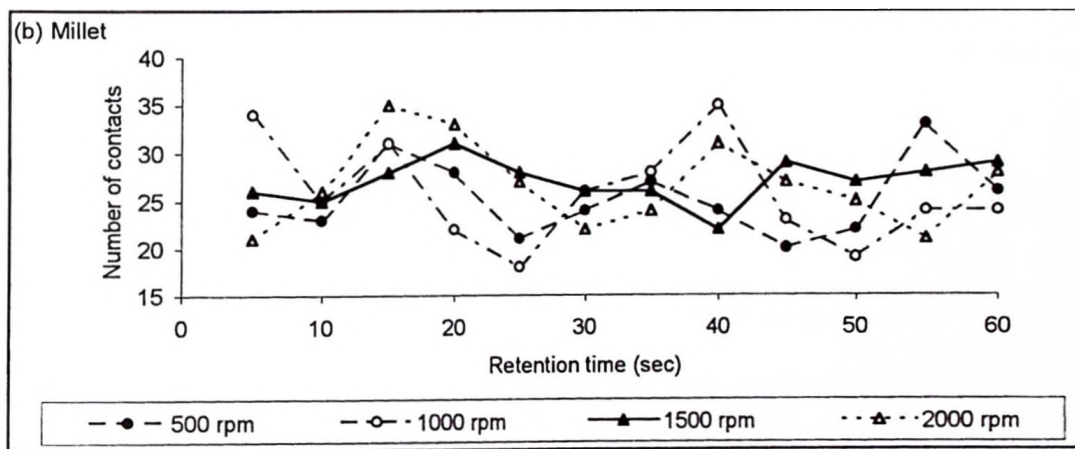


Figure 5.12(b). Effect of disk speed on the number of contacts between grain particles and the dehulling disk for millet.

5.5.3.3 Effect of the dehulling disk roughness

The effect of the dehulling disk roughness was simulated by varying the coefficient of friction between the grain and the dehulling disk. Figure 5.13 summarise the results of the effect of varying the coefficient of friction between grain particles and the dehulling disk on the rate of material removal from the grain sample for 60 seconds retention time. The rate of material removal increased with increase in friction coefficient between grain and dehulling disk for both sorghum and millet. These results agreed well with experimental results from literature. Deshpande (1981) found that, all other factors being similar, the rougher the abrasive disk the greater the amount of materials removed from the grain sample for a given retention time.

The relationship between the coefficient of friction between disk and grain particles and the rate of material removal from the grain could be represented by the following equation:

$$\ln(S_{removed}) = 4.7\mu + 0.6 \quad (R^2=0.999) \quad (5.69a)$$

$$\ln(M_{removed}) = 10.1\mu - 2.7 \quad (R^2=0.988) \quad (5.69b)$$

Where, $S_{removed}$ and $M_{removed}$ is material removed per second for sorghum and millet respectively, and μ is the coefficient of friction between grain and the dehulling disk

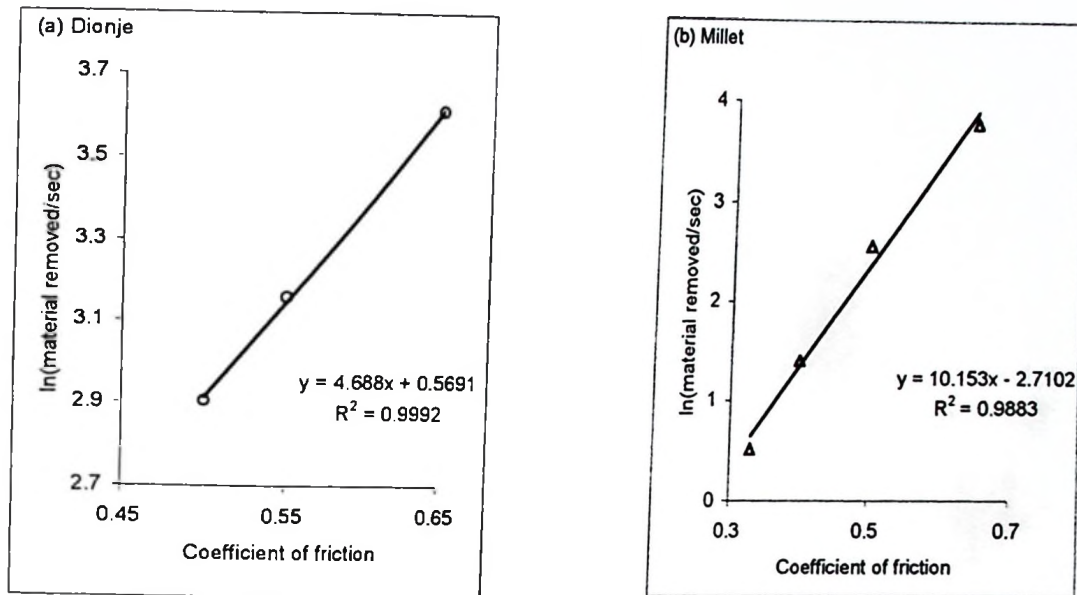


Figure 5.13. The effect of dehulling disk roughness on the rate of material removed as predicted by the simulation for 60 seconds retention.

5.5.3 Summary and conclusions

The dehulling process inside a tangential dehulling device (TADD) was successfully simulated using a 3-D DEM program based on CONBAL 3-4. The program was able to simulate the movement of the grain particles inside the mill from which important parameters such as the velocity, displacement and force experienced by individual grain particles inside the mill could be obtained at any stage of the process if required. Comparison between the effect of retention time in the dehuller on the rate of material removal as bran from the grain sample was carried out and it was found that result from simulation and experiment were fairly well correlated. A number of simulation experiments relating different grain properties and mill parameters to the rate of material removal from the grain were also carried out using the model. The results predicted by the model agreed well with results from literature.

This is the first time that the dynamic events taking place inside the dehulling mill have been successfully simulated by considering individual grain particle velocity, contact force and displacement. This made it possible to study the effect of changing different mill parameters such as rotational speed of the dehulling disk, retention time in the mill, the roughness of the dehulling disk, or grain properties such as grain hardness, on rate of material removal from the grain sample without performing the actual experiments. This means that in future carrying such simulations will save time, money and labour from performing such lengthy experiments in laboratory. Also practically any information required such as frequency, distribution and intensity of forces and impacts of grain kernel inside the mill could be obtained from the simulation. Such information, given the harsh conditions existing inside the dehulling mill and current capability of experimental methods available, would be difficult if not impossible to obtain. The results shown here, although in no way exhaustive, are quite fundamental in nature and point towards a possible new methods for studying the dehulling process in much more detail than is currently possible. This model could therefore be useful for further study and improvement of existing dehulling mills or in design of new ones for higher dehulling efficiency and lower losses.

CHAPTER SIX

DEVELOPMENT OF A PROTOTYPE DEHULLER FOR TEMPERED SORGHUM AND MILLET

6.1 Introduction

The dehulling process for sorghum and millet is accomplished either traditionally by hand pounding of tempered grain using pestle and mortar or mechanically using abrasive type dehullers. The effects of hand pounding are very different from those of abrasive dehulling (Munck *et al.*, 1982). In hand pounding the pestle causes mechanical shock, which generates strong interactive forces between the grain particles as well as between grain and the equipment. Due to tempering which helps in reducing the seed coat adhesion strength, large flakes of hull materials are detached during pounding. On the other hand, abrasive dehulling utilises carborundum or emery coated disks and drums mounted on vertical or horizontal rotor to abrade the outer layers of the dry grain, thereby producing fine bran particles.

The traditional hand pounding method is a slow and laborious process; hence the urgent need to develop efficient mechanical processing methods which could reduce the hardship and drudgery involved in this process. Mechanical abrasive dehulling is much faster and less tedious than the traditional method, however, it causes excessive losses of endosperm in the bran fraction through kernel breakage. This is especially serious in the case of soft grain varieties mainly due to the fact that for sorghum and millet, the seed coat is tightly attached to the endosperm and to remove it by abrasion a large compressive force is required. This can result in breakage of the grain kernels even before the seed coat is removed. The nature of abrasive dehulling is such that materials are removed from all over the broken particles irrespective of whether there is a seed coat or not, as fines which get mixed with the bran making it impossible to separate. This lead to high loss of endosperm, poor dehulling

efficiency and low quality end product. On the other hand, traditional dehulling initially produces coarse endosperm particles, which dwindle during the successive cycles of dehulling, but most of the broken endosperm can still be recovered during the winnowing stage hence losses are much lower. Also in traditional dehulling it is possible to control the dehulling conditions depending on the grain mechanical properties.

Sorghum and millet could be dehulled with less loss and at a much higher dehulling efficiency than is possible with current mechanical dehullers if proper pre-treatment procedures and dehulling equipment could be developed. It was shown in chapter four of this thesis that simple pre-treatments such as tempering used in the traditional dehulling system could greatly facilitate the removal of the seed coat from the endosperm. Incorporation of some of pre-treatments commonly used in traditional dehulling system in mechanical dehulling system could therefore make it possible to use only a fraction of the force required to remove the seed coat from the dry untreated grain. This could lead to less breakage of grain during the dehulling process and hence lower losses, also faster and complete seed coat removal from the endosperm could be achieved leading to improved dehulling efficiency and saving on the energy cost.

However, so far it has not been possible to successfully incorporate these simple pre-treatment principles in mechanical dehulling systems for the following reasons:

- (i) Combination of moisture and fine bran produced during the abrasive dehulling process tends to clog or block the sieve systems commonly used in these dehullers, depressing both capacity and efficiency.
- (ii) The abrasive effect of the dehulling disks or stones used in these machines diminishes with addition of water. Deposition of a layer of fine wet bran on the surface of the disks as dehulling progresses also lead to low dehulling capacity and efficiency.
- (iii) Many of the grinding stones and disks used in these dehullers are made by pressing stone materials together using adhesive materials which are dissolved by water, therefore presence of moisture damages the disks.

Attempts have been made to develop dehullers for tempered sorghum grain but with little success so far. Weineckle *et al.* (1965) developed an experimental unit for dehulling and degerming tempered sorghum grain. Their dehuller consisted of a 6-inch diameter stainless steel compact wire brush rotating within a 7-inch diameter perforated cylinder. The grain was introduced into the cylinder and remained there until it was small enough to pass through the perforations on the cylinder wall together with the hull and the germ. Dehulling was accomplished by the brushing action on the grain, which took place between the brush and the screen. The hull and the germ were later separated from the dehulled grain by aspiration and floatation in a sodium nitrate solution, respectively. The grain was tempered to moisture content of 18-19% prior to dehulling. The problem with such a dehuller design was that the fine moist bran produced during the process, accumulated within the compact wire brush and clogged it. Also with time, the wet bran led to blockage of the perforations on the cylinder screen reducing both throughput and dehulling efficiency. Freeman *et al.* (1969) also described a method for peeling sorghum grain for starch manufacture by wet milling techniques. However, the reduction in starch yield associated with their method prevented the acceptance of the process on a commercial basis (Shoup *et al.*, 1970).

The objective of this chapter was to design and build a prototype dehuller for dehulling of tempered grain which could overcome the problems encountered by the previous designs or current mechanical dehullers. Successful development of an efficient small scale dehuller for tempered grain will eliminate much of the daily drudgery that is currently associated with traditional processing of sorghum and millet and also will increase the acceptability of sorghum and millet products and hence stimulate increased production of these grains. Tempering technology is well established throughout the sorghum and millet producing areas, therefore the introduction of such dehullers will be complimenting the indigenous technology and hence will have a higher chance of being adopted than other types of dehullers so far introduced in these areas.

6.2 Design considerations

Apart from low dehulling efficiency, other problems facing the introduction of mechanical dehullers in the rural areas include: the high cost of the dehullers, lack of locally available spare parts and the requirement of trained technicians for servicing the dehullers. In order to develop a sustainable and efficient dehuller suitable for both rural and urban areas in the developing countries, these problems must also be considered. Therefore the following design considerations were taken into account during the design stage of the prototype dehuller.

- (1) The dehuller should be able to dehull tempered grain effectively (high seed coat removal and lower losses) without the clogging problems experienced by current mechanical dehullers or previous designs. To achieve this requirement a dehuller with a different kind of dehulling surface, which is not affected by water or moist grain was required.
- (2) The dehuller should be simple in design and construction, easy to operate and maintain without necessarily requiring highly trained personnel.
- (3) Grain to grain friction and abrasion between grain and the dehulling surface should be the main dehulling principle
- (4) The dehuller should be reasonably cheap but durable. Also spare parts should be locally available and at reasonable (affordable) price.
- (5) It should be possible to modify the dehuller in future such that it can be manually operated by hand cranking or foot pedal using cheap locally available materials and parts

6.3 Construction of the dehuller

The constructional drawings of the dehuller are shown in figures 6.1 to 6.7. The main part of the dehuller consist of the dehuller drum, which is made from a 200 mm long and 100 mm inside diameter plastic pipe (the drum could also be made from a 5-mm mild steel cylinder). Fixed to the inner surface of the drum is a new type of a dehulling surface, which is made from

a 3 mm thick mild steel sheet rolled into a cylinder and has 1.5 - 2.0 mm protrusions on its inner surface. These protrusions act as a rough abrasive surface to the grain kernels in contact with the drum surface when the dehuller is in operation, they also help to increase the interlocking within the grain mass for the grain layers near the drum surface, thus increasing the dehulling efficiency. To develop these protrusions a round wooden block was fitted inside the cylinder and the cylinder was punched from the outside using a punch at a regular spacing. To ensure regular spacing of the protrusions a grid paper (2.5×2.5 mm) was glued to the outer surface of the cylinder and the protrusion were made following the grid pattern. The centre to centre spacing between rows and columns of the protrusions was 2.5 mm. This dehulling surface is moisture proof, durable and is easy to remove and replace in case the protrusions are worn out.

The drum is fixed to the supporting frame and a drive shaft 20 mm in diameter ran through the axis of the drum carrying two mild steel impellers bolted on each side of the shaft (figure 6.4). A flexible stainless-steel wire brush is fixed at the end of each impeller such that it just touches the drum surface when the impeller is rotating within the drum. The drive shaft is mounted on horizontal bearings and fixed to a pulley driven through a v-belt by a 0.3 kW electric motor coupled to a variable speed drive unit (figure 6.1). The wire brush was made thin and flexible to avoid caking by the wet fine bran from the grain, a problem experienced when using a densely packed wire brush. In this case it is easy for the materials to drop off as the brush moves around the drum. The main task of the impellers is to move the grain around inside the drum, while the task of the wire brush is to brush off any materials, which get stuck to the dehuller surface during the dehulling process. For loading and unloading grain in the dehuller, an inlet hopper is provided on top of the drum and an outlet at the rear end drum cover.

6.4 Dehulling mechanism of the prototype dehuller

The dehulling process (the removal of the seed coat from the endosperm) in this prototype dehuller is accomplished mainly through the abrasion between grain and grain and between

grain and the rough dehuller drum surface. The jostling and rubbing of individual grain particles against each other and against the dehuller surface as the grain is moved around inside the dehuller by the impellers helped to create the friction necessary to remove the already loosened seed coat from the grain. The grain was retained in the dehuller for a period of time required to remove approximately 10% of the grain sample by weight, which is equivalent to the mean seed coat content of the grain varieties used. Preliminary experiments showed that a retention period of 5 minutes was necessary to achieve this extraction level. It was also found that to achieve best results, the dehuller needed to be filled to at least two thirds of the dehuller volume so as to develop enough pressure within the grain mass as it is moved around by the impellers, since the major contributor to the dehulling action is the grain to grain friction. Also to ensure good mixing of the grain during the dehulling process, the dehuller should not be filled to more than $\frac{3}{4}$ of the drum volume. An impeller speed of between 300-350 rpm was found sufficient for the dehulling operation.

Most parts of the prototype are cheap and easily available in most developing countries. The construction of the prototype is also simple and could be carried out even in small village workshops without necessarily requiring highly trained technicians. A secondary objective was the possibility of future modification of the prototype so that it can be manually operated using either pedal power or handle cranking. A rotational speed of 300-350 rpm can easily be achieved using a system of bicycle chains and sprockets. These parts are easily available in both rural and urban areas of developing countries and are within the financial capabilities of most small scale farmers. Such a modification would be very appropriate for those remote areas where there is no electricity and farmers cannot afford engine driven dehullers.

A modified version of impeller without wire brush was also developed and tested (figure 6.5). The use of this impeller type cut down even further the number of parts, which needs frequent replacement in the prototype dehuller making it very appropriate for remote areas where maintenance technicians may be unavailable. The removal of the wire brush also makes the cleaning of the dehuller much easier and thus improved the hygienic condition of the prototype dehuller substantially. Figure 6.6 shows the cross-section of the dehuller drum for the modified

version of the prototype, and figure 6.7 show the front view of the improved prototype. Proper tempering and conditioning of the grain minimised the possibility of material sticking to the sides of the dehuller. Also during the dehulling process a lot of heat is produced, due to friction between the grain particles and between grain particles and the dehuller surface, this reduce the moisture content of the grain mass and thus reducing further the chance of materials sticking to the sides of the dehuller and hence eliminated the need for a cleaning brush.

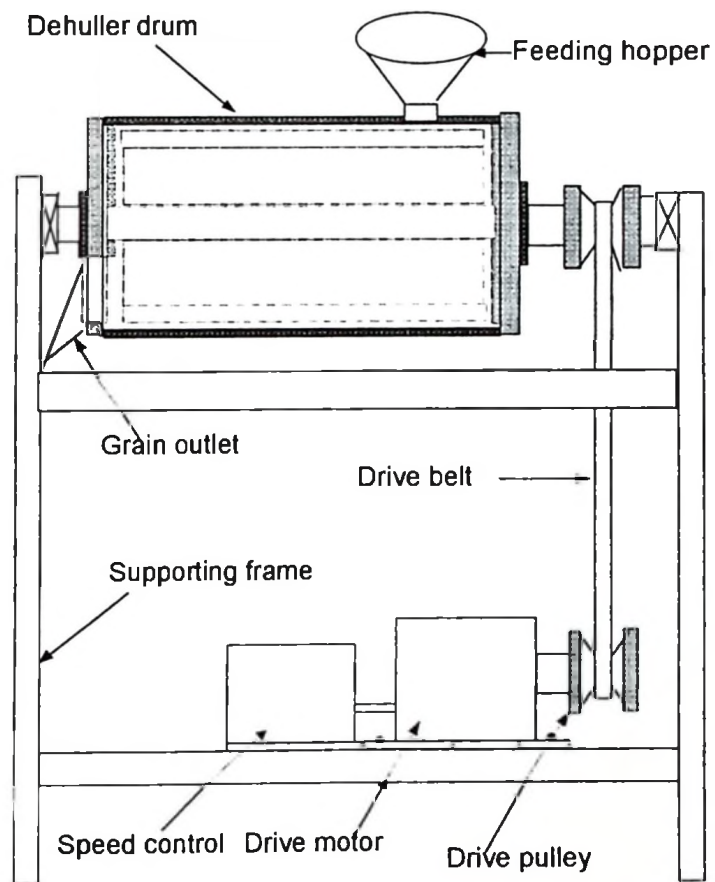


Figure 6.1 Front view of the prototype dehuller for tempered grain

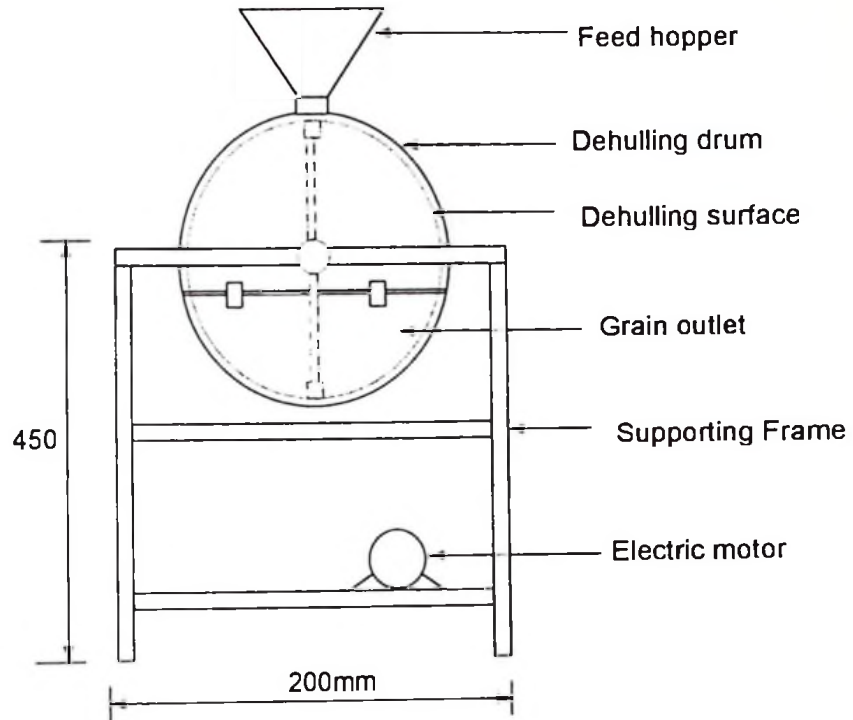


Figure 6.2 Side view of the dehuller

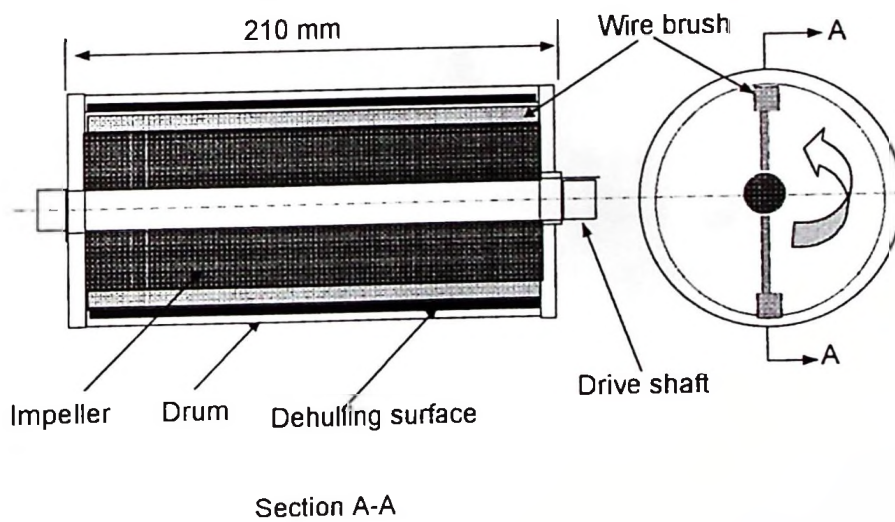


Fig 6.3 Cross-section of the dehulling drum

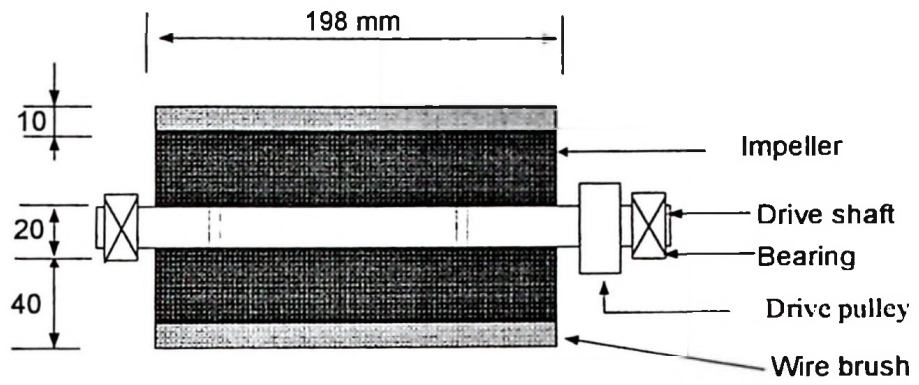


Figure 6.4 The impeller and brush assembly

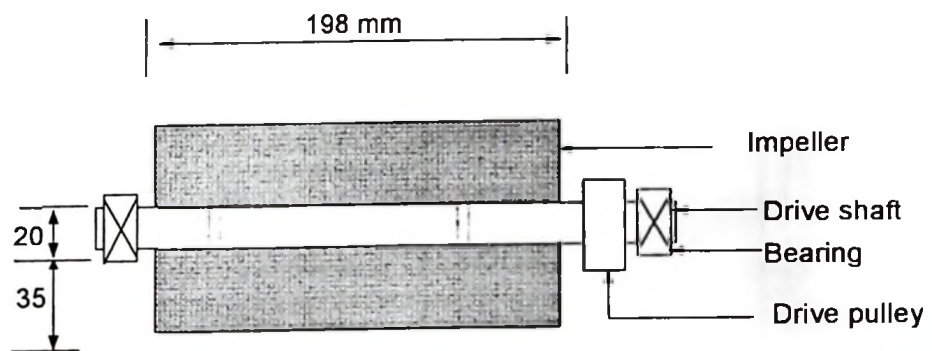


Figure 6.5 The impeller assembly without a brush

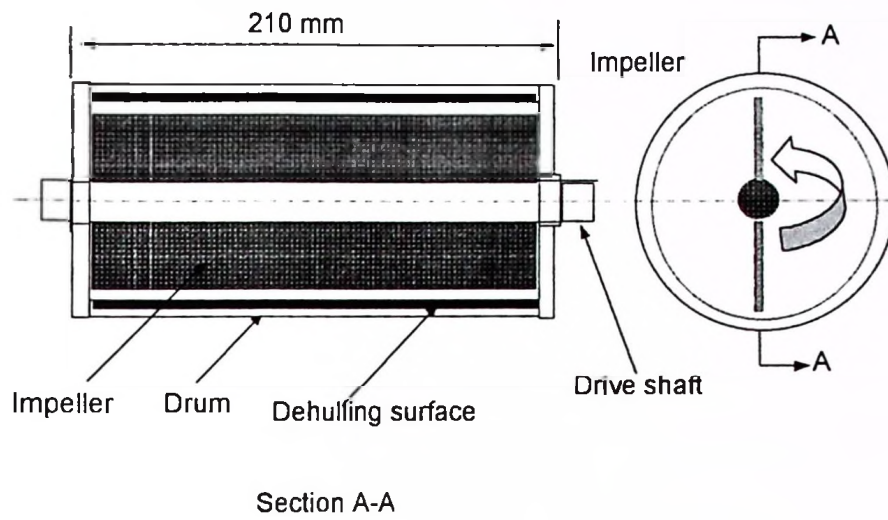


Figure 6.6 Cross-section of dehulling drum with impeller without a brush

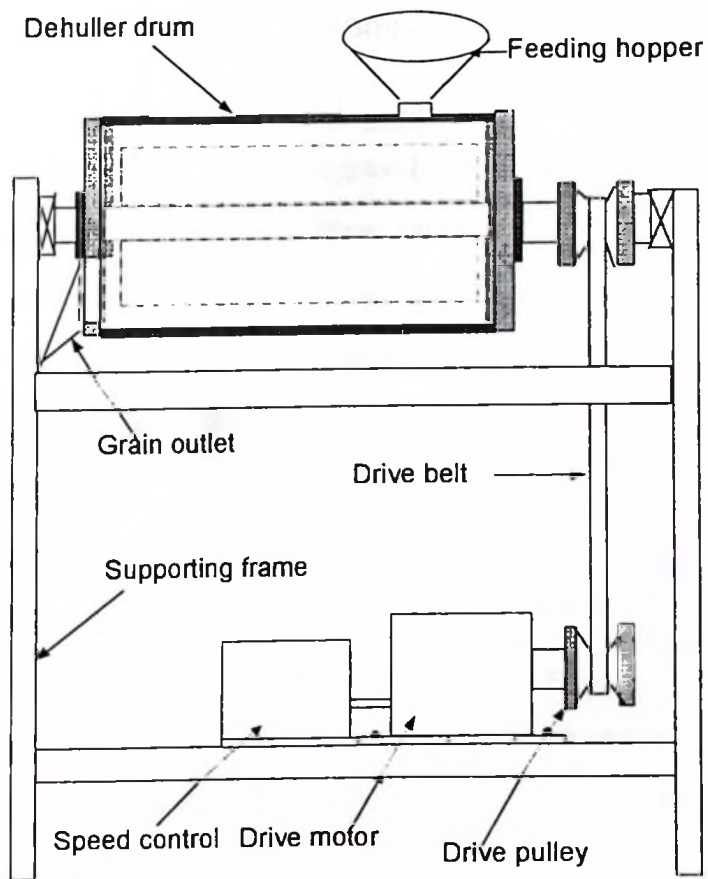


Figure 6.7 Front view of the final prototype design

6.5 Performance tests of the dehuller

6.5.1 Materials and methods

6.5.1.1 Materials

Two varieties of sorghum, Jumbo (soft) and Dionje (hard) were used to evaluate the dehulling performance of the dehuller. The initial moisture content of the grain was 12% (db).

6.5.1.2 Methods

6.5.1.2.1 Grain tempering and conditioning

The grain was tempered by soaking 350 g of grain (which is about two thirds of the dehuller drum volume) in tap water for 15 minutes. Fifteen minutes tempering duration used here was on the basis of the experimental findings from chapter three (section 3.6.3.4) and chapter four (section 4.3.5) that tempering the grain for 15 minutes or less does not affect the mechanical strength properties of the grain significantly but does reduce the seed coat-endosperm adhesion strength substantially. Soaking was followed by a rest period to allow the surface moisture to be absorbed into the grain, during which the grain was kept in a closed container and mixed occasionally. No attempt was made to hold a constant time for the surface moisture absorption between the different grain varieties used, rather an effort was made to ensure that all surface moisture was absorbed before the grain was introduced into the dehuller. The surface moisture absorption was considered complete when no moisture was left on the palm when a handful of grain was lightly squeezed. It is very important to make sure that all surface moisture is absorbed before the grain is fed into the dehuller to avoid introducing too much moisture in the dehuller, which might lead to clogging problems.

6.5.1.2.2 Dehulling tests

After all the surface moisture had been absorbed, the tempered grain was fed into the dehuller and dehulled at 350-rpm impeller rotational speed for five minutes. At this retention time the throughput of the prototype was approximately 3 kg per hour, allowing 2 minutes for emptying and filling the dehuller. After dehulling, the grain was removed from the dehuller air-dried and the bran was separated from the endosperm fraction by aspiration using a fan. The dehulled grain was weighed to determine the percent endosperm recovered, amount of bran produced and percent grain breakage.

6.5.1.2.3 Proximate analysis and flour colour determination

Samples of dehulled grain from the prototype and TADD together with hand peeled samples from each variety were taken and ground into flour for proximate analysis and flour colour evaluation. Proximate composition (protein, fat, ash and crude fibre) of the samples was determined according to the AACC standard methods (AACC, 1995). Flour colour measurements were carried out using the Kent-Jones and Martin colour grader. This colour grader measures the whiteness and brightness of a milled flour sample. The flour colour depends on the inherent whiteness of the grain endosperm, and the amount of bran contamination present in the sample. Although the colour grader was specific for wheat flour, the objective here was to compare the two dehulling system to find which one was able to remove most of the colour from the flour sample, especially from the coloured variety. The hand peeled sample was used as a standard for comparison as how close the two dehullers approached an ideal dehulling system (assuming that the flour grade of the hand peeled sample was the best flour grade which could be obtained from that particular grain variety).

The colour measuring procedure was as follows : Flour slurry was made by mixing 30 g of flour with 50 ml of water and stir for 45 seconds. The flour slurry was then poured in a glass cell, which was placed in the colour grader and the light reflected from the glass surface of the cell

was measured. The results of the test are usually given as flour colour grade units. The lower the value, the whiter the flour. For example, a standard wheat flour used for bread making has a colour grade value of between 2 and 5.

6.5. 2 Results and discussion

Table 6.1 shows the time taken by different grain varieties in absorbing the temper moisture and the amount of moisture absorbed during the tempering period. The hard variety - Dionje absorbed less moisture and took longer to absorb the surface moisture than Jumbo the soft variety. The total amount of moisture absorbed was 8.4% and 11.67% by weight for Dionje and Jumbo respectively (at 20⁰C and 70% RH). This amount of moisture raised the moisture content of the grain from 12% (db) to 21.4% and 25.1% (db) for Dionje and Jumbo respectively. From literature, the amount of water, which is usually added to the grain during traditional dehulling, as quoted by Carr *et al.* (1982) is 20-25% by weight. This amount of water will be too much for the developed prototype, as it will take a long time for all the water to be absorbed, which could lead to significant softening of the grain resulting in high breakage during the dehulling process. The water-grain ratio should therefore be modified to the proportion obtained in this research in case of mechanical dehulling.

Table 6.1 Relationship between grain hardness and absorbed moisture

Grain variety	Soaking/tempering time (min)	Absorption time (min)	% moisture absorbed (w/w)	Final grain m.c (%db)
Dionje	15	45	8.4 ± 0.7	21.4
Jumbo	15	30	11.7 ± 0.8	25.1

The yield of dehulled grain after 5 minutes retention in the dehuller was 92% and 91.2% for Dionje and Jumbo respectively.

Table 6.2 present the proximate composition of milled fractions of grain dehulled using the prototype together with grain dehulled using the conventional abrasive dehulling method (TADD) and unde-hulled grain which in this case act as a control.

Table 6.2 Proximate composition of the dehulled grain

Proximate composition	Dehulling method	Grain variety	
		Dionje	Jumbo
Ash content (%)	Prototype	1.3	1.2
	Prototype II*	1.3	1.1
	TADD	1.5	1.5
	Undehulled (control)	1.6	1.5
Fat content (%)	Prototype	2.3	3.3
	Prototype II	2.3	3.4
	TADD	2.5	3.5
	Undehulled (control)	2.8	3.7
Crude fibre (%)	Prototype	2.4	3.5
	Prototype II	2.4	3.2
	TADD	3.3	4.1
	Undehulled (control)	3.9	5.8
Protein (N 6×25) (%)	Prototype	9.6	11.7
	Prototype II	9.8	12.6
	TADD	9.7	11.8
	Undehulled (control)	9.1	11.6
Colour Grade	Prototype	11.6	13.4
	TADD	11.7	16.6
	Hand peeled	6.7	12.5

*Prototype II - Prototype with impeller without a wire brush

There was a reduction in ash, fat and crude fibre content for the dehulled grain from both the prototype and TADD compared to the unde-hulled grain (control). The results also showed that grain dehulled by the prototype had less ash, fat, crude fibre and protein than grain dehulled by TADD for both grain varieties. This could be explained by the fact that adding water to the grain or tempering usually causes the germ to swell and pull away from the cementing layer making it easy to remove (Wall and Ross, 1970). Tempering may have caused the germ, which is high in ash, fats and protein to be easily detached from the endosperm and hence removed during the dehulling process in the prototype whereas in dry dehulling process in the TADD the germ was retained on the endosperm. The lower fat content, however, is an advantage because it ensures longer shelf life and stability for the dehulled products. The lower crude fibre content of the dehulled grain from the prototype (2.4 % compared to 3.3% for Dionje and 3.5% compared to 4.1% for Jumbo) indicated that the prototype was more efficient than the TADD in removing the seed coat from the grain kernel during the dehulling process.

The dehulling efficiency of the prototype for the two varieties of sorghum was determined from the crude fibre reduction in the dehulled samples in comparison to hand dissected samples as described in section 4.2.2.5.3 of chapter 4. Using equation (4.8), the dehulling efficiency of Dionje was 89.8 % while for Jumbo was 93.2% indicating that grain with a thick seed coat (Jumbo) was more efficiently dehulled than grain with a thin seed coat (Dionje) in this system, which is also the case in traditional dehulling system (Kapasi-Kakama, 1977). Grain breakage was 1.2% and 2.3% for Dionje and Jumbo respectively which is much lower compared to abrasive system 2.6% and 3.8%. As in the traditional system, in the prototype, it was possible to recover most of the broken particles during the aspiration stage and hence leading to reduced actual loss.

Comparison of the results obtained using the prototype dehuller with previous results from chapter four (section 4.3.3.3) for untreated and hydrothermal treated grain dehulled in TADD showed that the prototype was able to achieve an improvement in dehulling efficiency of approximately 36.9% for Dionje and 30.3% for Jumbo over untreated grain dehulled in TADD

and 19.6% and 18.2% over hydrothermal pre-treated grain and dehulled in TADD for Dionje and Jumbo respectively. This indicates that there was a substantial improvement of the dehulling efficiency by dehulling tempered grain using the prototype compared to dehulling pre-treated or untreated grain in conventional tangential abrasive dehullers such as TADD.

The recovery levels from the prototype dehuller were also substantially higher compared to conventional abrasive dehuller. This was mainly due to the fact that less fines were produced during the dehulling process in the prototype than in TADD hence there was less loss of endosperm in the bran fraction. Lower breakage indicated that higher quality dehulled grain could be obtained using this system.

Flour colour grades were used to quantitatively compare the efficiency of the dehullers in colour reduction in the dehulled grain. Colour reduction is an important factor in consumer acceptability of products produced from sorghum, especially from coloured sorghum varieties. The results indicated that the prototype was more efficient in terms of colour removal than TADD for both varieties. This was especially evident for Jumbo, the coloured variety in which the colour grade of the flour from the prototype was 13.4 compared to the colour grade of 16.6 from TADD. The hand peeled grain flour grade was 12.5 which was the best colour grade which could be obtained from this variety, thus indicating that the prototype was very efficient in colour removal from the dehulled grain. For Dionje there was only a slight improvement in flour colour from the prototype (11.6) compared to (11.7) from TADD.

Comparison of the dehulling performance of the prototype using an impeller with a wire brush attachment and one without wire brush attachment (Prototype II, Table 6.2) indicated that there was no significant difference between the two designs as far as the dehulling efficiency of Dionje was concerned as indicated by the same crude fibre reduction levels in the dehulled grain. However, for Jumbo there was a higher reduction in crude fibre in the dehulled grain when using the impeller without wire brush, indicating that it was more efficient in seed coat removal. Protein content of the dehulled grain was higher than in the original design for both Dionje and Jumbo. Grain yield was 91.8% and 90.2% for Dionje and Jumbo respectively. From

hygienic point of view and frequency of part replacement, the modified version of the impeller (without wire brush) will be more favourable for the prototype.

6.6 Summary and conclusions

A new mechanical dehulling system for sorghum and millet combining basic principles from both traditional and mechanical dehulling systems was developed. A dehulling surface not affected by moisture was incorporated into the dehuller making possible the dehulling of moist grain without the clogging problem or damage usually associated with moist grain in conventional abrasive dehullers. The performance of the dehuller was tested using two varieties of sorghum. The results obtained indicated that it was possible to obtain high recovery levels and higher dehulling efficiency using this prototype dehuller than conventional abrasive dehullers. A yield of 92% for Dionje and 91.2% for Jumbo was obtained at a dehulling efficiency of 89.8 and 93.2% for Dionje and Jumbo respectively.

Comparison of the results obtained from this prototype with results obtained from untreated and hydrothermal pre-treated grain indicated that an average of 36.9% and 30.3% improvement in dehulling efficiency over untreated grain and 19.6% and 18.2% improvement over hydrothermal pre-treated grain and dehulled in TADD was achieved for Dionje and Jumbo respectively. This further confirms the conclusions drawn in chapter 4 that maximum benefits from different pre-treatments can only be achieved by processing the grain while still moist. This also shows the need to develop dehullers capable of processing pre-treated grain and the need to include more pre-treatments in the mechanical dehulling system. On the basis of relative efficiencies in terms of colour removal, crude fibre reduction, kernel breakage and recovery levels achieved, the prototype was more efficient than TADD. Other considerations such as low maintenance requirements and simplicity also favour the prototype over the present abrasive systems for village scale dehuller.

CHAPTER SEVEN

CONCLUSIONS AND RECOMMENDATIONS FOR FURTHER STUDIES

7.1 Conclusions

The ultimate objective of the research presented in this thesis was to investigate ways of enhancing the acceptability of sorghum and millet as human food through improvement of their dehulling efficiency and quality. To achieve this objective it was necessary to study different grain properties related to the dehulling process and how these properties are influenced by different conditions likely to be encountered during the dehulling process. Different pre-treatment methods, which have been found to be useful in the traditional dehulling methods, such as tempering and steam treatment were studied, modified and incorporated in the mechanical dehulling system. Alkali dehulling of sorghum and millet using different concentrations of alkali was studied at different retention periods. A prototype dehuller for tempered grain incorporating dehulling principles from both traditional and mechanical systems was developed and tested. Finally a numerical model for dehulling of sorghum and millet based on discrete element method was developed, this model could be used to study the dehulling process in more detail than it has been possible so far using the current experimental methods. From these studies the following conclusions could be drawn:

Mechanical properties of single sorghum and millet kernels were highly influenced by both grain and process conditions such as the grain moisture content, temperature and loading. The mean values of all the mechanical properties of sorghum and millet grain, with exception of ultimate strain, decreased as moisture content of the grain increased from 12 to 25% (db) and temperature from 20 to 50°C. Among the two factors, moisture content had a greater influence on the mechanical properties of the grain than temperature within the range covered in this study. This indicated that control of the moisture content of the grain to be dehulled was an important factor to be considered during the dehulling of sorghum and millet.

Functional relationship between grain properties, moisture content and temperature were established for sorghum and millet within 12 to 25% moisture content (db) range and 20 to 50°C temperature range. The proposed simple functional relationships could have numerous applications for moisture and temperature dependent strength related research of sorghum and millet.

Grain kernel orientation during loading strongly influenced the strength properties of the grain. The compressive strength of the grain kernel, irrespective of kernel moisture content depended on whether the kernel was loaded while on the side or flat loading position, thus indicating that sorghum grain kernel is anisotropic with respect to mechanical strength properties. This means that in evaluating grain properties for design purposes all possible kernel orientations likely to be encountered should be considered if accurate and reliable data is to be obtained.

Hydrothermal treatments in form of tempering and steaming followed by drying to original moisture content using either ambient air (20°C) or hot air at 60°C, improved the dehulling efficiency of sorghum and millet in a conventional abrasive dehuller by up to 10% and 20% for sorghum and millet respectively in terms of seed coat removal and by 14 and 13% in terms of crude fibre reduction in the dehulled grain compared to untreated grain. This indicated that the dehulling efficiency of current abrasive dehullers could be improved by incorporation of simple pre-treatment stage to the grain before dehulling

Short duration tempering of grain for 15 minutes or less followed by a rest period to allow surface moisture to be absorbed reduced the seed coat adhesion strength substantially without affecting the kernel strength significantly. This showed that short duration grain tempering could allow less force to be used in the removal of the seed coat from the grain kernel during the dehulling process, thus leading to a substantial reduction in amount of breakage and loss likely to occur during the dehulling process. However, the effect of seed coat adhesion reduction was reversed as the grain dried up. This means, to obtain maximum benefit from the

seed coat loosening effect brought about by tempering or other hydrothermal treatment, the grain should be dehulled while still moist, thus indicating the urgent need for the development of mechanical dehullers capable of dehulling moist grain if pre-treatments like tempering or steam treatment are to be utilised beneficially in the mechanical dehulling systems.

Alkali dehulling using aqueous solution of sodium hydroxide was found to be very effective for both sorghum and millet resulting in higher recovery rates (>90%) of high quality seed coat free endosperm than it is possible with any of the current conventional dehulling methods. There was also a high reduction of crude fibre from the dehull grain indicating that the process was very effective in removing the seed coat from the endosperm which was confirmed by the high dehulling efficiencies achieved (>90%). The high quality of dehulled grain produced by this dehulling method could make possible the introduction new types of foods from sorghum and millet especially the use of whole-dehulled sorghum and millet grain as rice substitute. Such a product will be important in urban areas where rice culture is growing fast, to replace the imported rice, which is far more expensive than sorghum or millet. Whole-grain dehulled sorghum and millet products are also much cheaper and more stable than flour products because they do not require further processing and have a much longer shelf life.

Moisture absorption characteristic of sorghum and millet during soaking in water within 20 – 50°C temperature range, indicated that moisture absorption in sorghum and millet was highly influenced by the temperature of the soaking water. The moisture absorption data was fitted to Fickian diffusion model and Peleg's model. From the Fickian diffusion model the moisture diffusion coefficient was found to vary from 4.65×10^{-8} to $1.93 \times 10^{-7} \text{ m}^2 \cdot \text{h}^{-1}$ for sorghum (Dionje) and from 8.29×10^{-8} to $3.15 \times 10^{-7} \text{ m}^2 \cdot \text{h}^{-1}$ for millet as the temperature increased from 20°C to 50°C. The activation energy for the soaking process was found to be 39.60 kJ.mol⁻¹ and 34.89 kJ.mol⁻¹ for sorghum (Dionje) and millet (IM) respectively. Comparison of the two models showed that Peleg model gave a better fit to the experimental data than the Fickian diffusion model, especially for the initial soaking period. By Combining the Arrhenius and Peleg's equations a model for prediction of moisture absorption and tempering duration in sorghum and millet at different temperatures within 20–50°C temperature range was

developed. This model can be used to accurately predict the required tempering duration instead of the current trial and error method.

A three dimensional computer code based on the computer program CONBALL 3.4 was developed to simulate the dehulling process of sorghum and millet in a Tangential Abrasive Dehulling Device (TADD). The simulation results were compared with experimental results and good agreement between simulation and experimental results was obtained. The program was also used to investigate the influence of different grain and mill parameters on the performance of the dehuller. Results correlate well with results from literature. This means that the use of numerical simulations will save time, money and labour for performing such experiments in laboratory. The model could be used as a tool for the study of the abrasive dehulling process in more detail than it has been possible so far using the current available experimental methods and also to acquire information which was impossible or difficult to obtain using the current methods.

Based on the experimental results on grain properties and the use of pre-treatments, a prototype dehuller for dehulling of tempered grain was developed incorporating a dehulling surface which is not affected by moisture or clogging problems associated with current mechanical dehullers. The use of short tempering duration (15 minutes) together with ensuring that all the temper moisture content was absorbed into the grain before the grain was introduced into the dehuller eliminated the clogging problem. The dehuller was able to achieve higher dehulling efficiency and recovery levels compared to conventional abrasive dehuller even with pre-treatments. The quality of the produced grain was also much higher as indicated by low kernel breakage and superior colour grade of the flour obtained from grain dehulled in this prototype compared to conventional mechanical dehuller. This showed that it is possible to increase the yield and dehulling efficiency of sorghum and millet substantially by use of appropriate dehulling equipment in combination with controlled pre-treatment procedures and therefore call for more effort in development of dehulling equipment which can incorporate more of the pre-treatments currently used in the traditional dehulling system.

In summary, this research has shown that, improvement in the dehulling efficiency of sorghum and millet can be achieved through a combination of innovative new processing techniques (mechanical and chemical) and traditional local knowledge that can utilise the sorghum and millet varieties currently available to produce high quality flour and other products at an acceptable extraction rate (>80%). Successful development of simple but efficient small and large scale dehullers or chemical processes that can produce and supply stable high quality sorghum and millet products to both the rural and urban consumers will enhance consumer acceptability of sorghum and millet foods. These improved dehulling processes will also circumvent some of undesirable features of sorghum and millet and eliminate much of the daily drudgery that is currently associated with post-harvest technology of sorghum and millet. The availability of high quality flour will encourage new developments in sorghum and millet food products, leading to technologies that look far beyond the current traditional uses of sorghum and millet to more diverse applications that offer greater economic, nutritional and technological advantages, such as in flour composted with wheat for bread and biscuits, as rice substitute (dehulled whole grain), break-fast cereals and for industry as brewer's grits. Such a development will check the tendency of shifting from sorghum and millet to other grains and encourage more production of these grains. Greater production and utilisation of sorghum and millet will also result in better national and household food security because these crops are more tolerant to drought and poor soil conditions existing in these areas. The dependency on imported grain will also diminish reducing the great burden of draining in the national hard currency cash flow caused by importing wheat, rice and maize thus allowing more money to be spent on other developmental problems.

7.2 Recommendations for future work

(1) Scaling up the prototype to commercial production size.

- There is a need to scale up the designed prototype to commercial production size for both village and urban use. Studies conducted to evaluate the success of previously introduced dehullers in Tanzania has shown that the size of the dehuller is an important factor for its

success. In villages, farmers prefer to process grain in small batches of between 5 - 10 kg at a time. Therefore an ideal capacity for a motorised dehuller for village use should have a capacity to dehull 5 kg of grain at a time, giving a dehulling capacity of 0.5 tons per day (assuming an 8 hour working day). In urban areas people prefer to process bigger batches at a time and the population is much higher than in villages, therefore a dehuller capable of dehulling 10-20 kg per batch will be ideal.

- As sorghum and millet are produced in remote rural areas where electricity might be a problem, there is a need to look into the possibility of developing small hand or pedal operated dehullers for use in the rural areas. Such manual operated processing equipment has proved popular in post-harvest processing of other grains such as in groundnut and bean threshing (Lazaro, 1997). For manual operated dehullers, a dehuller capacity of 1-2 kg per batch will be an ideal size. A larger batch size might result in operational problems due to power required to operate the dehuller. Since the manual dehuller will be used mainly for individual household use the small sample size will not present a problem as grain can be processed whenever need arises. Apart from reducing the drudgery involved in traditional dehulling in the villages, the introduction of manual operated mechanical dehullers will also make the task of dehulling to be a shared responsibility for the whole family rather than falling to women alone as at present.
- Problems likely to be encountered:
 - (i) The prohibitive cost of acquiring a dehuller. This has been cited as one of the reasons for the slow rate of diffusion of dehulling technology in Tanzania (Uliwa, 1993). A typical village size dehuller (batch size 5 kg) will cost approximately 600 pounds about 750,000 Tanzanian shillings (Appendix D1). This is a prohibitive investment for rural people. There is a need for the government to support and encourage the introduction of this technology through a credit support system to entrepreneurs wishing to invest in the dehulling business.
 - (ii) There is a general lack of entrepreneurial skills at village level to undertake business ventures. The government should introduce opportunities for acquiring necessary entrepreneurial skills through seminars, workshops and short courses for people interested in undertaking business ventures in the villages.

(iii) Greater government support is needed to popularise and create awareness of the mechanical dehulling technology in both urban and rural areas by use of different mass media and visual aids such as radio, television, films and posters.

(2) Further research is required on nutritional implications of chemical processing methods, such as the use of alkali dehulling on sorghum and millet, and the possibilities of application of this method on industrial scale. This could be a significant factor in extending the use of the soft high tannin brown sorghum for food and the introduction of attractive sorghum foods such as sorghum rice in the urban areas.

(3) Other principles of traditional dehulling, such as impact dehulling to loosen the hulls from the grain, need to be researched as an alternative to abrasive dehulling.

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APPENDICES

Appendix A1 Physical properties of sorghum and millet at different moisture contents

Grain variety	m.c (%d.b.)	L (mm)	W (mm)	T (mm)	G.M.D (mm)	Sphericity (%)	S/area (mm ²)	1000 g/w (g)	K/density (kg/m ³)	B/density (kg/m ³)	Porosity (%)
Dionje	12	5.05	3.80	2.40	3.57	71.00	40.30	30.10	1240	684.7	44.8
	15	5.07	3.84	2.41	3.62	71.37	41.14	30.80	1260	678.5	47.8
	20	5.13	3.90	2.44	3.67	71.70	42.36	32.10	1304	669.2	49.1
Jumbo	25	5.14	3.94	2.49	3.71	72.11	43.00	33.50	1370	661.4	52.9
	12	5.21	4.16	2.51	3.83	72.80	45.97	33.47	1070	619.7	41.9
	15	5.26	4.24	2.58	3.86	73.39	46.92	34.13	1140	611.5	42.3
Millet (IM)	20	5.32	4.30	2.65	3.93	73.80	48.53	35.53	1160	601.2	44.2
	25	5.36	4.34	2.66	3.95	73.85	49.19	36.97	1220	592.8	51.4
	12	3.88	2.84	2.44	2.99	77.20	28.23	14.37	1110	688.1	34.5
Millet (IM)	15	3.90	2.86	2.47	3.02	77.59	28.75	15.03	1150	674.5	35.9
	20	3.92	2.90	2.54	3.07	78.18	29.61	15.73	1170	755.3	44.0
	25	3.96	2.92	2.57	3.09	78.39	30.18	16.47	1230	636.0	48.3

Each data point is an average of 10 replications.

GMD = Geometric mean diameter, L = Length, W = Width, T = Thickness

Appendix A2. Fitted constants for the relationship between grain dimensions and moisture content using equation (3.24)

Grain Variety	Dimension (mm)	a	b*10 ³	R ²
(a) Sorghum				
(i) Dionje	L	4.96	7.7	0.98
	W	3.68	12.9	0.99
	T	2.30	6.7	0.99
(ii) Jumbo	L	5.07	11.9	0.93
	W	4.02	13.3	0.94
	T	2.40	11.4	0.97
(b) Millet				
(i)IM	L	3.80	6.2	0.98
	W	2.80	6.0	0.97
	T	2.30	10.1	0.97

**Appendix A3. Fitted constants for the relationship between grain physical properties
and moisture content using equation (3.24)**

Grain variety	Grain property	a	b*10 ³	R ²
Dionje	D _{GM}	3.4	10	0.99
	S _{area}	37.8	200	0.98
	φ	70.1	80	0.99
	W ₁₀₀₀	26.9	260	0.99
	ρ	1059.0	12400	0.98
	ρ _b	706.1	-1800	0.99
	ε	35.7	650	0.98
Jumbo	D _{GM}	3.7	10	0.95
	S _{area}	43.1	200	0.98
	φ	71.8	90	0.99
	W ₁₀₀₀	30.1	102	0.98
	ρ	940.1	11200	0.98
	ρ _b	642.7	-2050	0.99
	ε	34.2	690	0.98
Millet (IM)	D _{GM}	2.9	8	0.96
	S _{area}	26.5	150	0.99
	φ	76.2	90	0.97
	W ₁₀₀₀	12.6	160	0.99
	ρ	1051.1	8470	0.99
	ρ _b	734.5	-3900	0.99
	ε	29.6	740	0.99

**Appendix A4 Effect of loading position and moisture content on mechanical properties
of sorghum**

Grain v variety	Moisture content (%db)	Flat loading		Side loading		Average MOD (MPa)	Strain at B/point (%)	Stress at B/point (MPa)
		MOD (MPa)	Std-dev (MPa)	MOD (MPa)	Std-dev (MPa)			
Dionje	12	1554.3	382.69	746.69	492.26	1150.51	10.62	270.23
	15	737.12	110.75	499.55	144.01	618.34	12.9	109.78
	20	659.36	105.63	248.53	57.99	453.95	13.74	73.26
	25	427.14	83.52	121.77	37.63	274.46	15.53	50.72
Mbagala	12	1491.89	537.99	615.27	414.87	1053.58	10.94	128.67
	15	933.85	125.45	433.57	107.28	683.71	12.36	103.20
	20	591.81	68.19	336.53	131.99	464.17	13.87	70.71
	25	298.95	64.94	129.66	60.34	214.31	16.64	35.31
Pato	12	1154.38	406.88	643.04	370.85	898.71	8.7	157.07
	15	705.80	66.96	424.30	175.64	565.05	10.56	67.19
	20	470.51	91.15	336.76	121.04	403.64	12.19	57.59
	25	277.91	48.37	139.82	26.70	208.87	14.26	35.76
Tegemeo	12	1140.83	425.80	824.67	454.37	982.75	9.2	156.13
	15	657.92	79.53	485.09	188.28	571.51	11.8	70.31
	20	495.37	70.30	230.26	90.64	362.82	12.90	55.24
	25	350.75	41.30	70.76	21.77	210.76	13.52	33.85
WS	12	1298.53	270.13	1208.65	442.22	1253.59	18.4	242.10
	15	1008.36	376.49	559.5	67.42	783.93	25.91	228.80
	20	560.26	100.29	396.82	86.05	478.54	29.32	161.94
	25	320.20	88.40	201.62	65.92	260.91	30.25	63.85
RS	12	1093.16	296.14	940.22	317.59	1016.64	10.47	118.00
	15	1018.48	155.77	519.98	194.66	769.23	8.33	85.05
	20	393.62	95.81	218.93	88.42	306.28	13.44	52.94
	25	213.70	71.36	103.99	29.27	158.85	15.04	35.74
Varietal mean	12	1288.84	386.61	829.76	415.36	1059.3	11.39	178.70
	15	843.59	152.49	487.00	146.22	665.29	13.64	110.72
	20	528.49	88.56	294.64	96.02	411.56	15.91	78.61
	25	314.78	66.32	127.94	40.27	221.36	17.54	42.54

Appendix A5 Effect of moisture content on mechanical properties of millet.

Grain variety	Moisture content (%db)	Average E_{MOD} (MPa)	Strain at B.P (%)	Stress at B.P (MPa)	Energy at B.P (mJ)
Okoa	12	1198.48	10.50	144.25	9.764
	15	568.32	10.87	62.86	8.44
	20	310.69	12.47	38.25	7.38
	25	149.40	15.07	19.53	5.20
Uwele	12	1048.30	23.18	253.03	30.22
	15	546.27	26.28	121.62	15.25
	20	380.04	27.01	106.80	14.11
	25	178.90	35.80	56.09	13.97
IM	12	1225.58	12.20	161.30	9.85
	15	731.35	14.64	126.07	7.42
	20	381.69	15.62	59.59	6.74
	25	288.05	17.10	58.98	6.40
ILM	12	1206.67	22.44	262.19	17.49
	15	610.63	23.19	113.90	14.97
	20	468.96	24.19	90.77	11.39
	25	241.98	25.36	66.86	9.72
Varietal mean	12	1169.76	17.08	205.19	16.83
	15	614.14	18.75	106.11	11.52
	20	385.35	19.82	73.85	9.91
	25	214.58	23.33	50.37	8.82

**Appendix A6. Fitted constants for the relationship between grain mechanical properties
and moisture content using equation (3.25)**

Grain variety	Mechanical property	a	b	R ²
Dionje	E _{mod}	8.1	-0.10	0.97
	ε	2.1	0.03	0.90
	σ	6.9	-0.13	0.95
	e	4.9	-0.8	0.99
	G _t	8.7	-0.10	0.98
	F	5.6	-0.05	0.96
	D	0.2	0.08	0.99
Jumbo	E _{mod}	8.8	-0.15	0.99
	ε	2.1	0.01	0.95
	σ	6.0	-0.12	0.99
	e	2.8	-0.05	0.94
	G _t	7.6	-0.08	0.97
	F	5.3	-0.07	0.99
	D	0.3	0.01	0.98
Millet (IM)	E _{mod}	8.3	-0.11	0.99
	ε	2.3	0.02	0.90
	σ	6.5	-0.11	0.98
	e	3.7	-0.07	0.98
	G _t	7.6	-0.06	0.96
	F	4.0	-0.04	0.97
	D	0.2	0.01	0.99

E_{mod} is the modulus of deformability, *ε* is the ultimate strain, *σ* is the ultimate stress, *e* is the energy to break point, *G_t* is the modulus of toughness, *F* is the force at break point and *D* is the deformation at break point.

**Appendix A7. Fitted constants for the relationship between grain mechanical properties
and temperature using equation (3.26)**

Grain variety	Mechanical property	a	b	R ²
Dionje	E_{mod}	7.68	-0.02	0.99
	σ	6.78	-0.04	0.91
	e	5.10	-0.04	0.98
	G_t	8.75	-0.04	0.98
Jumbo	E_{mod}	7.36	-0.02	0.98
	σ	5.19	-0.01	0.98
	e	3.32	-0.02	0.98
	G_t	7.20	-0.02	1.00
Millet	E_{mod}	7.46	-0.2	0.95
	σ	5.03	-0.02	0.87
	e	2.69	-0.01	0.94
	G_t	7.12	-0.01	0.99

E_{mod} is the modulus of deformability, σ is the ultimate stress, e is the energy absorbed up to break point, and G_t is the modulus of toughness.

**Appendix A8. Fitted constants for the relationship between grain mechanical properties
and tempering duration using equation (3.27)**

Grain variety	Grain property	a	b	R ²
Dionje	F	5.0	-0.003	0.91
	E	3.9	-0.005	0.95
	D	1.1	0.008	0.94
Jumbo	F	4.4	-0.010	0.98
	E	2.9	-0.006	0.97
	D	1.0	0.009	0.96
Millet (IM)	F	3.9	-0.008	0.96
	E	2.8	-0.018	0.97
	D	0.8	0.008	0.91

F is the force at break point, e is energy absorbed to break point, D is deformation at break point

Appendix B.

Appendix B1: Dehulling efficiency in terms of seed coat removed - Jumbo

Treatment	Duration (min)	D _{eff} (%)	Statistical analysis
Untreated (Control)	-	66.67	
Soaking / Ambient drying	15	71.16	***
	30	70.47	***
	60	69.56	**
Soaking / Oven drying	15	77.17	***
	30	77.20	***
	60	76.85	***
Steam / Ambient drying	5	70.90	***
	10	67.51	ns
	15	57.96	***
Steam /Oven drying	5	67.27	*
	10	67.25	ns
	15	68.35	*

Each data point is an average of 4 replications

*** Significant at P< 0.001, ** Significant at P< 0.01, * Significant at P< 0.05, ns Not significant

Appendix B2 Dehulling efficiency in terms of seed coat removed - Dionje

Treatment	Duration (min)	D _{eff} (%)	Statistical analysis
Untreated (control)	-	69.16	
Soaking / Ambient drying	15	74.45	***
	30	71.33	***
	60	77.52	***
Soaking / Oven drying	15	79.51	***
	30	74.95	***
	60	74.47	***
Steam / Ambient drying	5	73.03	***
	10	72.49	***
	15	70.89	***
Steam /Oven drying	5	64.85	***
	10	68.16	**
	15	63.19	***

Each data point is an average of 4 replications

*** Significant at P< 0.001, ** Significant at P< 0.01, * Significant at P< 0.05, ns Not significant

Appendix B3 Dehulling efficiency in terms of seed coat removed - IM millet

Treatment	Duration (min)	D _{eff} (%)	Statistical analysis
Untreated (Control)	-	64.35	
Soaking / Ambient drying	15	81.95	***
	30	80.29	***
	60	72.43	***
Soaking / Oven drying	15	81.80	***
	30	80.45	***
	60	76.58	***
Steam / Ambient drying	5	77.10	***
	10	80.82	***
	15	83.67	***
Steam /Oven drying	5	85.03	***
	10	84.17	***
	15	83.99	***

Each data point is an average of 4 replications

*** Significant at P< 0.001

Appendix B4 Dehulling efficiency in terms of crude fibre reduction - Jumbo

Treatment	Duration (min)	D _{eff} (%)	Statistical analysis
Untreated (Control)	-	60.52	
Soaking / Ambient drying	15	73.16	*
	30	73.96	*
	60	73.49	*
Soaking / oven drying	15	75.56	*
	30	74.67	*
	60	74.74	*
Steam / Ambient drying	5	64.02	ns
	10	69.31	*
	15	68.45	*
Steam /Oven drying	5	73.59	*
	10	66.58	*
	15	63.11	ns

Each data point is an average of 3 replications

* Significant at P< 0.05, ns Not significant

Appendix B5 Dehulling efficiency in terms of crude fibre reduction – Dionje

Treatment	Duration (min)	D _{eff} (%)	Statistical analysis
Untreated (Control)	-	54.96	
Soaking / Ambient drying	15	77.53	*
	30	81.5	**
	60	86.05	**
Soaking / oven drying	15	83.04	**
	30	83.95	**
	60	80.64	**
Steam / Ambient drying	5	67.32	*
	10	63.58	*
	15	64.61	*
Steam /Oven drying	5	62.58	ns
	10	63.63	*
	15	61.58	ns

Each data point is an average of 3 replications

*** Significant at P< 0.001, ** Significant at P< 0.01, * Significant at P< 0.05, ns Not significant

Appendix B6 Dehulling efficiency in terms of crude fibre reduction - IM millet

Treatment	Duration (min)	D _{eff} (%)	Statistical analysis
Untreated (Control)	-	77.88	
Soaking / Ambient drying	15	89.34	**
	30	92.36	**
	60	92.05	**
Soaking / oven drying	15	89.48	*
	30	89.45	**
	60	95.83	**
Steam / ambient drying	5	72.84	ns
	10	86.65	*
	15	81.85	*
Steam /Oven drying	5	88.43	*
	10	88.07	*
	15	91.09	**

Each data point is an average of 3 replications

** Significant at P< 0.01, * Significant at P< 0.05, ns not significant

Appendix B7 Proximate composition of dehulled grain - Jumbo

Treatment	Duration(min)	C/fibre (%)	Ash (%)	Oil (%)	Protein (%)
Untreated (Control)	-	4.04	1.49	3.77	11.17
Soaking / Ambient drying	15	3.57	1.47	3.71	12.69
	30	3.56	1.48	3.70	12.25
	60	3.54	1.34	3.81	12.63
Soaking / oven drying	15	3.41	1.39	3.76	12.50
	30	3.35	1.45	3.64	12.56
	60	3.34	1.42	3.71	12.37
Steam / Ambient drying	5	3.87	1.49	3.76	11.81
	10	3.71	1.46	3.68	11.87
	15	3.76	1.49	3.76	12.56
Steam /Oven drying	5	3.38	1.49	3.57	12.8
	10	3.82	1.46	3.68	12.63
	15	3.91	1.50	3.75	12.93

Appendix B8 Proximate composition of dehulled grain - Dionje

Treatment	Duration (min)	C/fibre (%)	Ash (%)	Oil (%)	Protein (%)
Untreated (Control)	-	3.30	1.76	2.52	8.87
Soaking / Ambient drying	15	2.69	1.50	2.77	9.0
	30	2.62	1.54	2.69	9.06
	60	2.54	1.55	2.71	8.93
Soaking / oven drying	15	2.25	1.61	2.65	9.06
	30	2.22	1.59	2.55	9.18
	60	2.31	1.63	2.57	9.12
Steam / Ambient drying	5	2.97	1.69	2.64	8.98
	10	3.26	1.68	2.77	9.18
	15	2.91	1.65	2.61	8.94
Steam /Oven drying	5	2.79	1.72	2.47	9.31
	10	3.04	1.71	2.45	9.43
	15	3.45	1.68	2.68	9.44

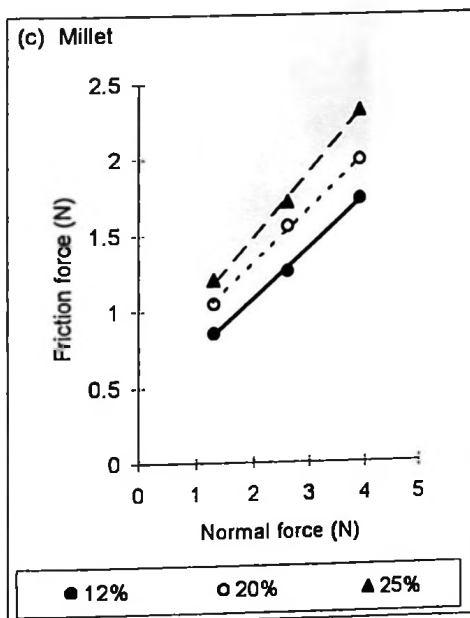
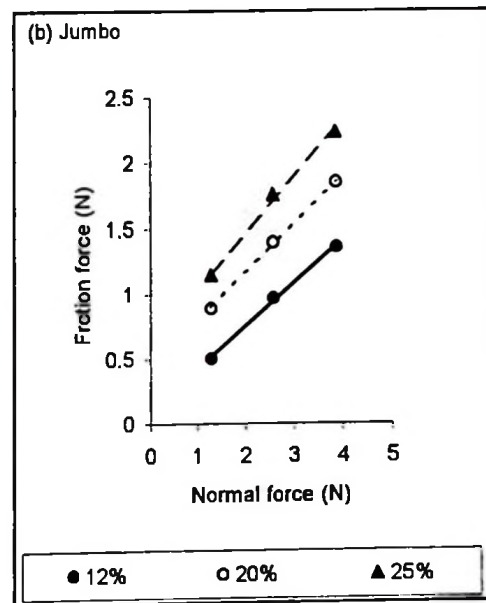
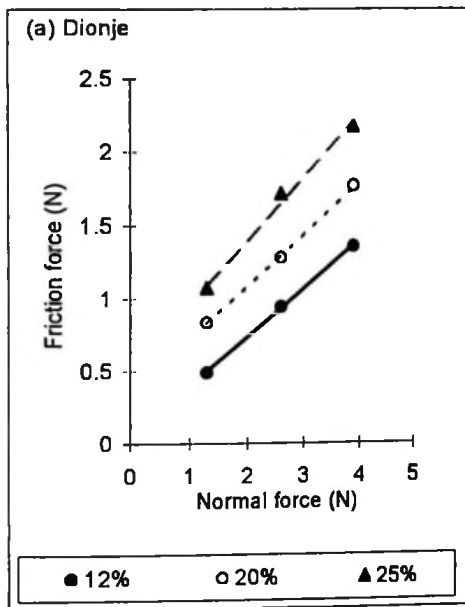
Appendix B9 Proximate composition of dehulled grain – IM millet

Treatment	Duration (min)	C/fibre (%)	Ash (%)	Oil (%)	Protein (%)
Untreated (Control)	-	3.03	1.56	3.67	10.43
Soaking / Ambient drying	15	3.15	1.03	3.72	10.5
	30	2.93	1.03	3.66	10.68
	60	2.84	1.05	3.64	10.68
Soaking / oven drying	15	2.95	1.01	3.46	10.81
	30	3.004	0.998	3.50	10.75
	60	2.74	0.997	3.61	10.69
Steam / Ambient drying	5	3.72	1.15	3.81	11.00
	10	3.05	1.17	3.76	10.94
	15	3.25	1.15	3.78	10.68
Steam /Oven drying	5	3.04	1.10	3.41	10.50
	10	3.08	1.06	3.66	10.62
	15	2.87	1.06	3.45	10.63

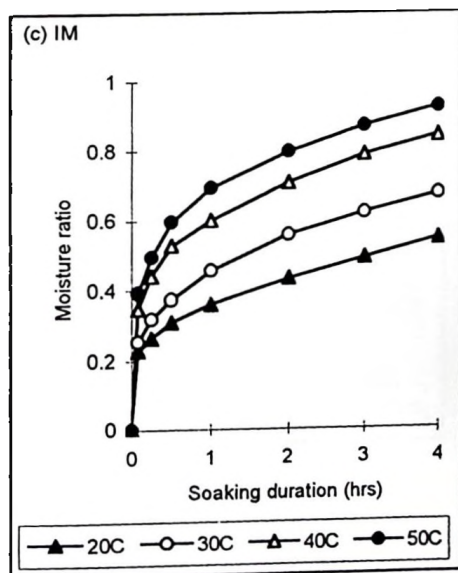
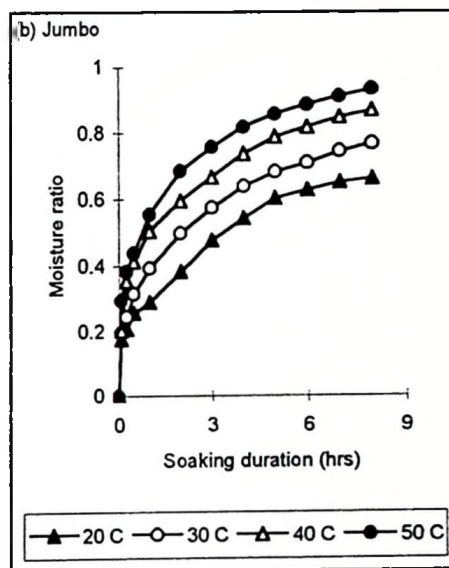
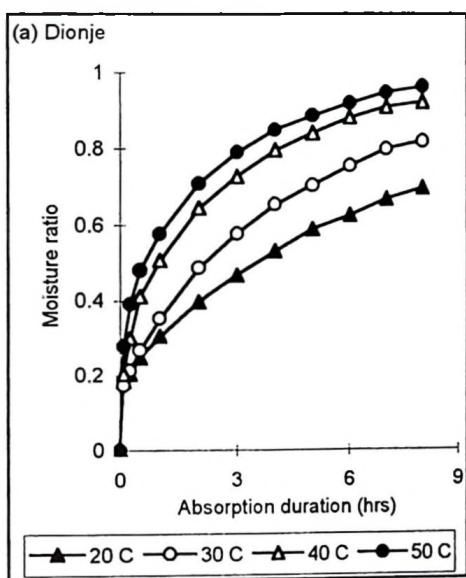
Appendix B10 Effect of tempering on seed coat adhesion strength.

Grain variety	Tempering duration (min)	Force to remove seed coat (N)	Total area removed (mm ²)	Force / unit area (MPa)
Dionje	0 (control)	13.1 ± 0.4	3.1 ± 0.4	4.2 ± 0.6
	15	1.7 ± 0.08	3.6 ± 0.6	0.5 ± 0.06
	30	0.9 ± 0.09	3.1 ± 0.8	0.3 ± 0.07
	60	0.6 ± 0.01	3.1 ± 0.4	0.2 ± 0.06
Jumbo	0 (control)	12.8 ± 0.5	2.8 ± 0.5	4.7 ± 0.8
	15	1.4 ± 0.4	3.3 ± 0.4	0.42 ± 0.1
	30	0.8 ± 0.08	2.0 ± 0.1	0.4 ± 0.06
	60	0.7 ± 0.03	2.3 ± 0.2	0.35 ± 0.5
Millet	0 (control)	13.9 ± 1.8	1.7 ± 0.4	8.3 ± 1.3
	15	1.6 ± 0.03	2.2 ± 0.3	0.73 ± 0.1
	30	0.97 ± 0.3	1.8 ± 0.3	0.56 ± 0.2
	60	0.5 ± 0.09	1.9 ± 0.2	0.28 ± 0.02

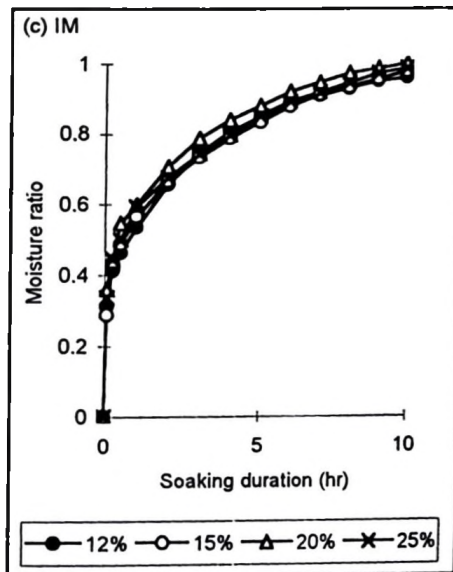
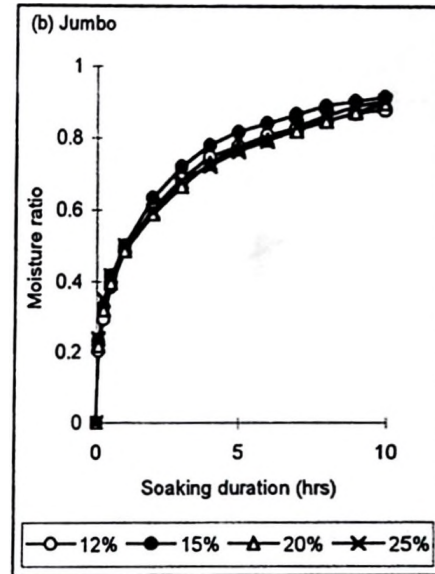
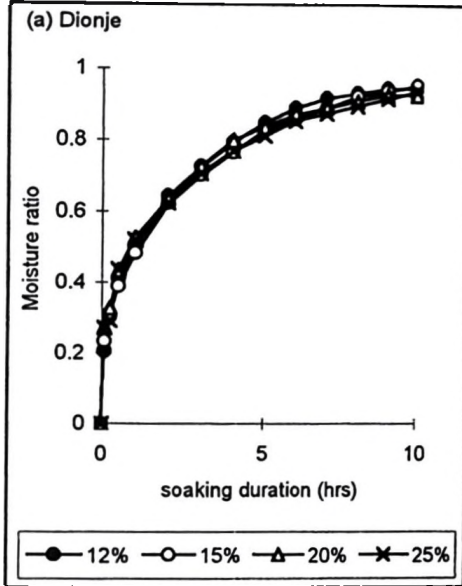
Appendix B11 Variation of friction force with normal force for sorghum and millet at different moisture contents



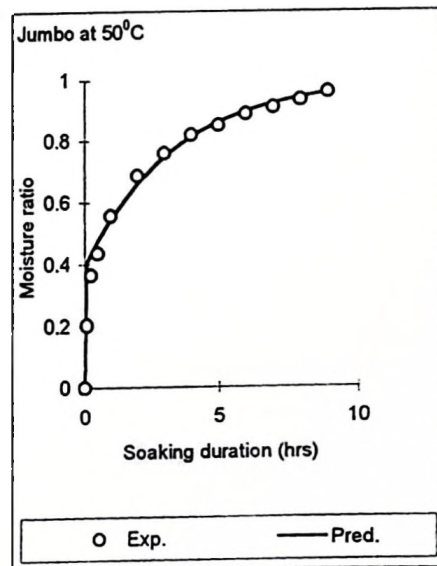
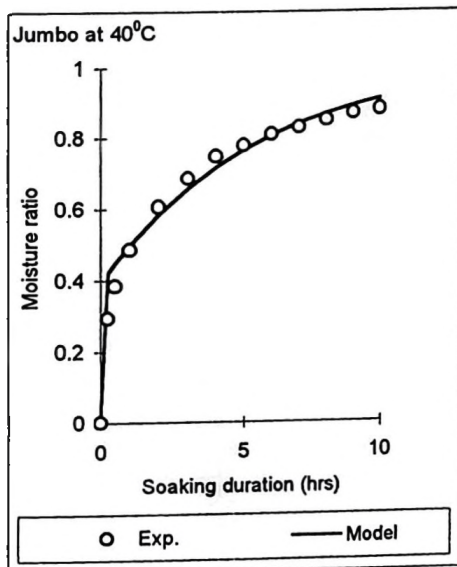
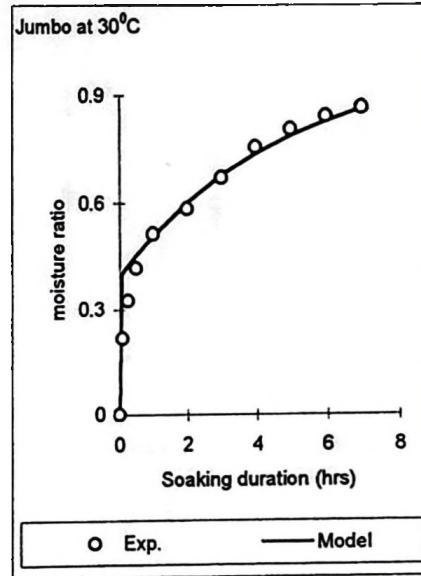
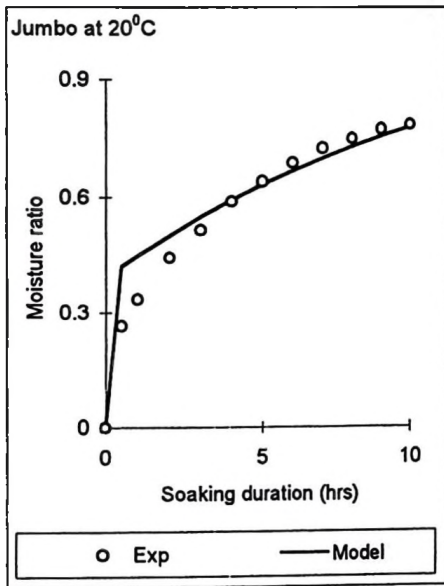
Appendix B12. Effect of temperature on moisture absorption characteristics of (a) Dionje (b) Jumbo and (c) IM millet



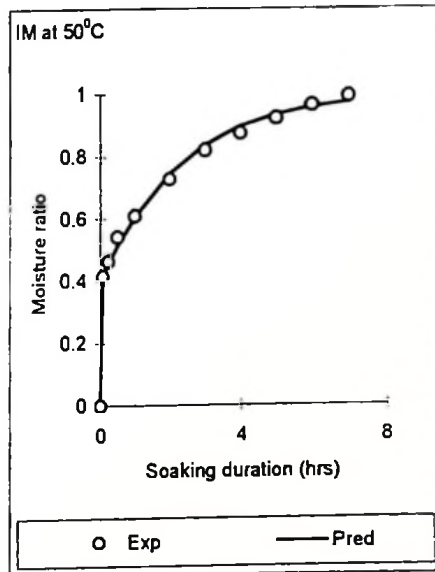
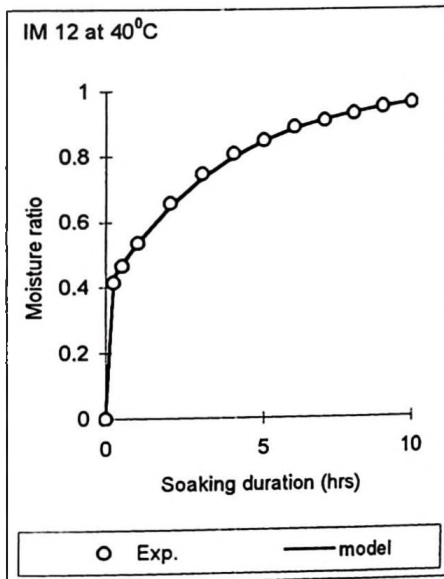
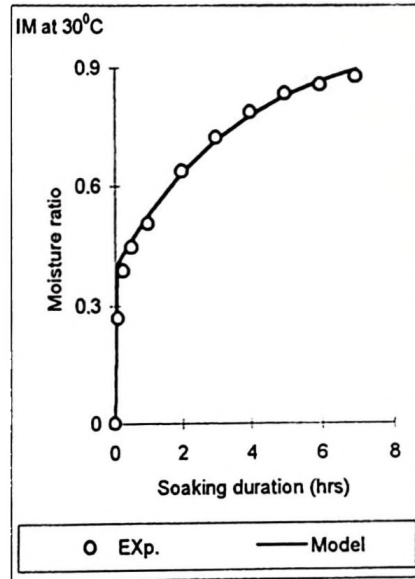
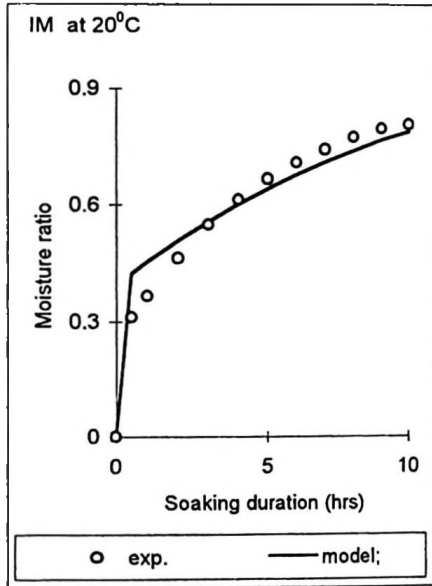
Appendix B13. Effect of grain initial moisture content on moisture absorption



Appendix B14 . Experimental moisture ratio with curve fitted using the Fickian diffusion model (Equation 4.11) for Jumbo



Appendix B15. Experimental moisture ratio with curve fitted using the Fickian diffusion model (Equation 4.11) for for IM

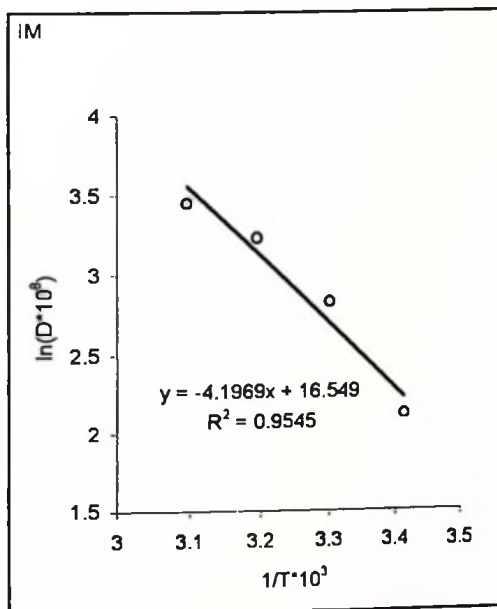
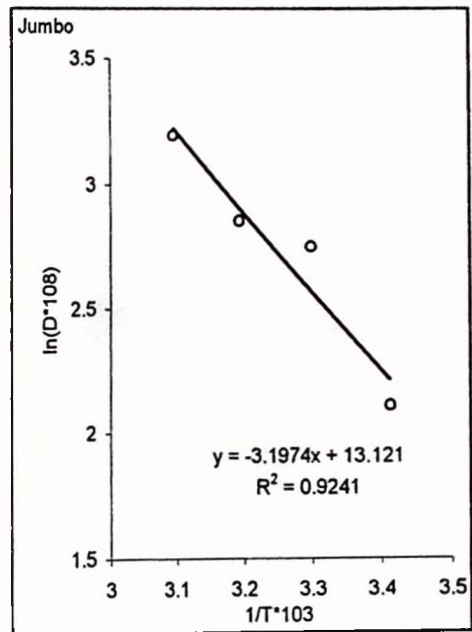
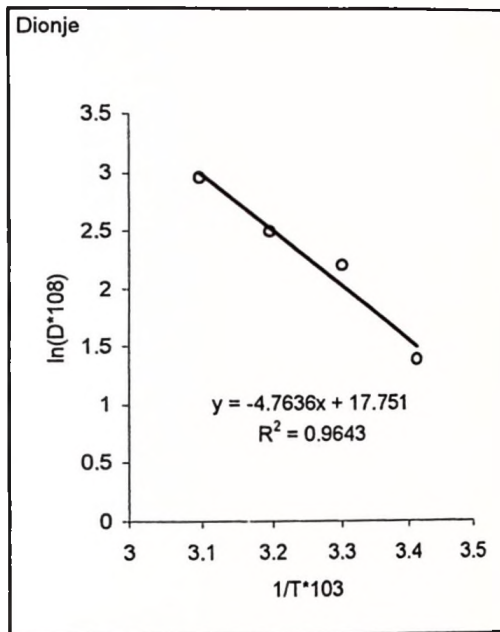


**Appendix B16 Diffusion coefficients of sorghum and millet at different temperatures
and initial moisture contents**

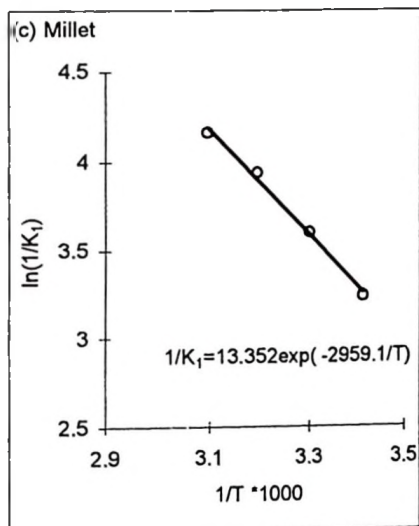
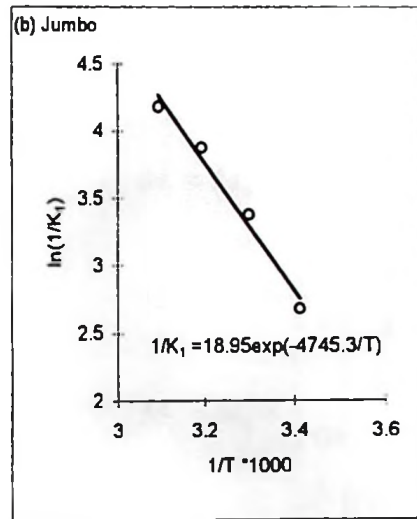
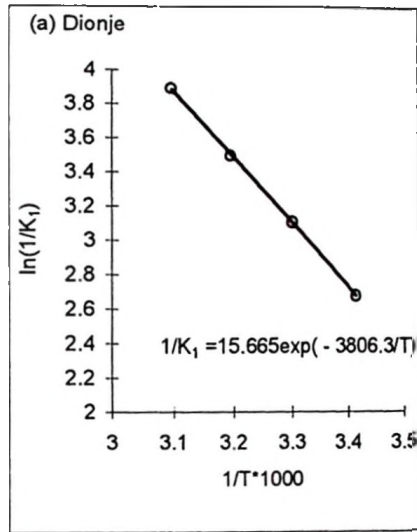
Grain variety	m.c (%db)	20 ⁰ C (D×10 ⁻⁸)	30 ⁰ C (D×10 ⁻⁷)	40 ⁰ C (D×10 ⁻⁷)	50 ⁰ C (D×10 ⁻⁷)
Dionje	12	4.65	1.11	1.22	1.93
	15	4.23	0.91	1.28	1.76
	20	4.88	0.87	1.78	2.45
	25	3.93	0.83	1.42	2.55
Jumbo	12	8.24	1.56	1.74	2.44
	15	7.18	1.53	1.85	2.18
	20	6.44	1.50	1.51	2.03
	25	5.47	1.51	1.58	1.82
Millet (IM)	12	8.29	1.69	2.52	3.15
	15	6.87	1.48	2.09	3.04
	20	7.21	1.54	2.10	2.69
	25	5.98	1.35	2.16	2.39

D is the diffusion coefficient (m² h⁻¹)

Appendix B 17 The effect of temperature on Diffusion coefficient of sorghum and millet



Appendix B18 Relationship between constant $1/K_1$ and temperature for sorghum and millet



Appendix B19. Prediction equations for water absorption characteristics of sorghum
and millet at different soaking temperatures.

Grain variety	Temperature (°C)	Predicted equation
(1) Sorghum		
(a) Dionje	20	$M_t = M_0 + \frac{100t}{6.68 + 2.29t}$
	30	$M_t = M_0 + \frac{100t}{4.49 + 2.29t}$
	40	$M_t = M_0 + \frac{100t}{3.04 + 2.29t}$
	50	$M_t = M_0 + \frac{100t}{2.05 + 2.29t}$
(b) Jumbo	20	$M_t = M_0 + \frac{100t}{6.84 + 1.92t}$
	30	$M_t = M_0 + \frac{100t}{3.41 + 1.92t}$
	40	$M_t = M_0 + \frac{100t}{2.07 + 1.92t}$
	50	$M_t = M_0 + \frac{100t}{1.53 + 1.92t}$
(2) Millet		
(a) IM	20	$M_t = M_0 + \frac{100t}{3.94 + 1.8t}$
	30	$M_t = M_0 + \frac{100t}{2.74 + 1.8t}$
	40	$M_t = M_0 + \frac{100t}{1.95 + 1.8t}$
	50	$M_t = M_0 + \frac{100t}{1.56 + 1.8t}$

APPENDIX C

Appendix C1: Particle and wall generation

Particle Generation.

Particles were generated systematically and placed side by side in the largest possible square box, which could be fitted within the circular working space. The length of sides of this square was equal to $R\sqrt{2}$ where R is the radius of the working space. The first particle to be generated was placed on one corner of the square working space a distance r equal to the radius of the particle from either vertical or horizontal walls. The rest of the particles were then systematically placed in the working space side by side in the x-y plane. After the first layer, the second layer of particles in the x-y plane was generated in the same way by moving up in the z-direction by an amount equal to 1.5 particle diameters. Figure 6a shows the generation of the particles. After generation the particles were consolidated by applying gravitational acceleration in the negative Z direction. The particle type and number to be generated are specified in the input file. For the present model only round particles with same diameter were generated.

Wall generation

Wall generation was effected by simply specifying the wall position usually the beginning, centre and end co-ordinates of the wall (and angle of inclination to one of the co-ordinate axes in case of inclined walls). Curved walls were created by specifying the co-ordinates of the mid point and the angle the wall subtend at the middle of the working space.

In the present case, two wall options are available; A total of three walls (one round and two flat) or a total of six walls. Four curved wall sections which form the dehulling cup sides and two flat walls which form the top cover and the bottom cover. The bottom cover acts as the dehulling disk when it was given a certain angular velocity.

Boxing of curved walls.

The working space created in the program was made of both flat and curved walls. For efficiency, the curved wall was split into 4 sections; each needed to be boxed in special manner. Figure. A1-1 shows the boxing procedure used for curved wall. In boxing a curved wall a line was drawn joining the starting point and the end point of the wall section, this line is boxed as usual by recording the entries into those boxes that are crossed by the line. Another

line is drawn parallel to the line joining the starting and the end points of the curved wall such that between these two lines the curved wall is sandwiched. This new line is also boxed. In this way the boxes which could possibly have entries for the curved wall are known (only between these two lines). To find if a particle is in potential contact with the curved wall a check is made to see if the particle is within these two lines.

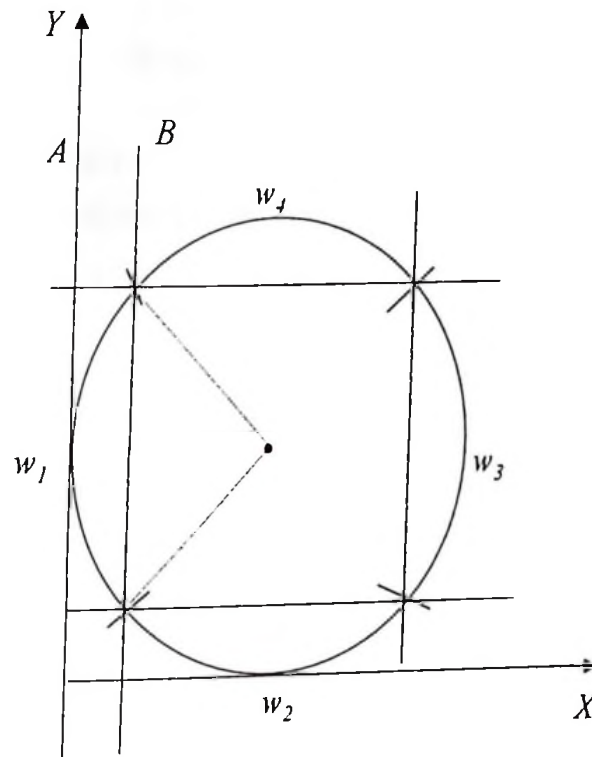


Figure C1-1 Boxing of a curved wall

APPENDIX C2: Contact Detection.

Particle-wall contact.

Particle-wall contact is of utmost importance to the problem in hand, as it is this interaction that provides the force required to shear off the seed coat or dehull the grain. The main idea behind quantification of a particle-wall interaction is to find, at any given instant of time, if the wall and the particle in question actually share a contact. To do this the direction cosine of the normal to the wall, the particle radius and the co-ordinates of its centre of mass have to be known. Having identified an actual contact, the co-ordinates of the point of contact are evaluated and used to check if the contact point lies within the extent of the wall in question.

The information generated at this point is used to evaluate the relative velocity of the particle, with respect to the wall and the elastic deformation at contact point, which are used to compute the force generated at the contact.

Two types of wall can be encountered during the dehulling process, Straight wall (bottom and top walls) and curved wall (side-wall). The contact between a particle and a straight wall W is shown in figure C2-1. The co-ordinates of the centre of the particle are (x_a, y_a) . Wall w is defined by the co-ordinates of the wall reference point (x_w, y_w) and angle θ_w with respect to the x-axis. D_1 and D_2 denote the distances between the particle centroid and wall reference point in direction parallel to the wall and perpendicular to the wall, respectively. From geometrical considerations D_1 and D_2 are given by

$$D_1 = (x_a - x_w)\cos\theta_w + (y_a - y_w)\sin\theta_w \quad (C2-1)$$

$$D_2 = (y_a - y_w)\cos\theta_w - (x_a - x_w)\sin\theta_w \quad (C2-2)$$

A contact is detected if

$$h_1 \leq D_1 \leq h_2 \quad \text{and} \quad 0 \leq D_2 \leq R \quad (C2-3)$$

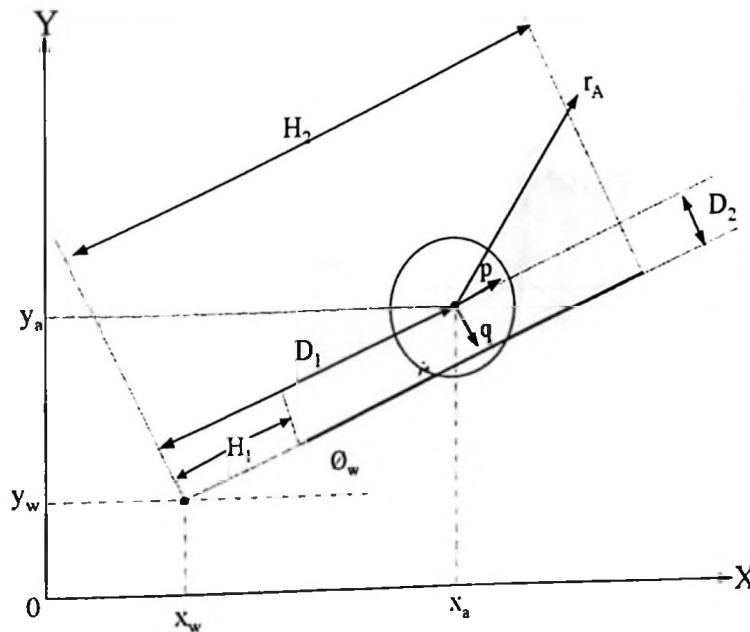


Figure C2-1 Contact between a particle and a flat wall

Contact between a particle and a curved wall.

Once a particle is found to be in potential contact with a curved wall, the following simple check can be made to find if a contact really exist. Figure C2-2 show a particle in contact with a curved wall. Let the co-ordinates of the centre of the particle of radius r_1 be (x_a, y_a) and the co-ordinates of the centre of the round wall of radius R_c be (x_b, y_b) then contact between the wall and the particle exist if there is an overlap between the wall and particle;

$$\text{Overlap} = (l+r_1)-R_c \quad (\text{C2-4})$$

Where

$$l = \sqrt{(x_b - x_a)^2 + (y_b - y_a)^2} \quad (\text{C2-5})$$

If overlap is positive i.e. $(l+r_1)-R_c > 0$ then contact exists between the particle and the wall.

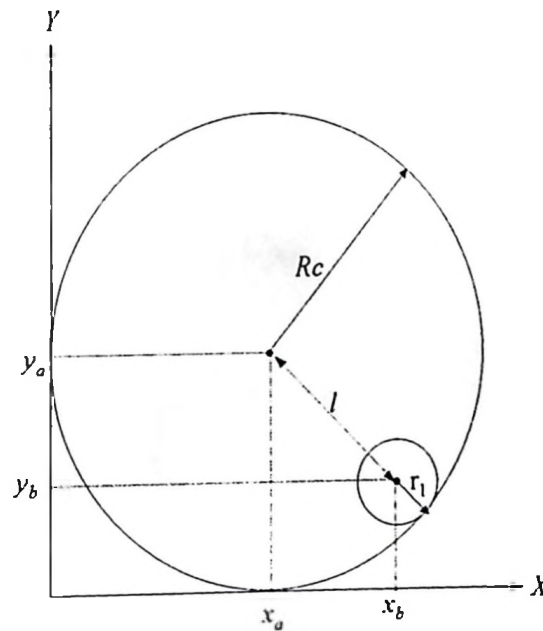


Figure C2-2 Contact between a particle and a curved wall

Particle-particle Contact detection:

The purpose of this operation is to identify those pairs of particles that have broken contacts and those, which have established new contacts. The search for new contact of particle A_1

Appendix C3 Determination of material stiffness

As mentioned earlier, in DEM formulation particle deformation is represented by a set of springs and dashpots at each contact. The spring stiffness recommended for use can be inferred from Hertz contact theory for elastic spheres in contact. Ng (1989) gave the following equation for determination of normal stiffness for identical spheres:

$$K_n = 2.a \left(\frac{G}{1-\nu} \right) \quad (C3-1)$$

Where G is shear modulus of the particles and a is the radius of contact area

Chang et al (1989) quoted the following non-linear relationship for calculation of the normal stiffness K_n for two spherical particles in contact with partial slip

$$K_n = \frac{2\pi G}{(1-\nu)[2 \ln(2r/A) - 1]} \quad (C3-2)$$

where,

$$\frac{1}{r} = \frac{1}{2} \left(\frac{1}{r_1} + \frac{1}{r_2} \right)$$

and

$$A = \left[\frac{2r(1-\nu)F_n}{\pi G} \right]^{\frac{1}{2}}$$

The tangential contact stiffness K_s is also related to particle's shear modulus. Its value lies between K_n and $\frac{2}{3}K_n$ for Poisson's ratios between 0 and 0.5 (Johnson 1985). Cundal and Strack (1979) also showed that the simulation results are not sensitive to changes in K_s within this range.

Appendix D

Appendix D1 Approximate cost for a village size motorised dehuller

Item	Approximate cost (£)
Motor (3hp)	200
Components (pulley, bearings, belts)	100
Dehuller drum and Impeller	100
Frame	100
Installation costs	100
Total	600

SPE
HD 9049
S59
L3