MECHANICAL PROPERTIES OF HOLLOW AND SOLID WHEAT STEMS

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ABSTRACT

Harvesting wheat is carried out by cutting the stem and threshed. When the stem (straw) bends due to pest and weather, losses are incurred especially during harvesting. Solid stem wheat varieties have been bred to resist pest like wheat stem sawfly and lodging. Solid stem varieties may lead to higher straw strength and energy which consequently impacts harvesting and collection. Also, farmers are faced with the challenge of increased cost of transporting the straw outside the farm due to their high volume. Previous research investigations have been done on increasing the straw bulk density and have led to producing more dense straws (double-compressed bales, pellets, cube, and briquette) but the cost of processing them and their physical quality is still a challenge. There has been a report that it takes low capital producing bale than other dense products. This means that if the bulk density of bales can be further increased through compression, it will be more economical using the wheat straw in a dense bale form.

The research project investigated the mechanical properties of stems of twelve varieties of wheat (solid and hollow stem) at different moisture levels and internode positions. Aside from the compression test that was carried out on single moisture (14% w.b), samples were conditioned to three moisture content levels (14, 18, and 22% w.b) before testing was carried out. Shearing, cutting, tensile, and compression tests were done using different tools mounted on the Instron^{TM} universal tester while the texture analyzer and a three point tool were used for bending test. The shear box apparatus was employed in determining the coefficient of internal friction. The stem diameters were determined by individually imaging the stems to be tested. Compression and relaxation models were fitted to the compression test data to determine their applicability to wheat straw compression and relaxation experimental data, respectively.

Different orientations of fibers were obtained across varieties for studies on stem imaging with varying stem areas. Data analysis revealed that moisture had significant effect on coefficient of internal friction while moisture and internode position had positive correlation on shearing, cutting, and tensile strength as well as shearing and cutting energy but a negative effect on bending strength and modulus of elasticity for all varieties ($P < 0.05$). The coefficient of internal friction ranged from 0.095-0.669. Average shearing, tensile, and cutting strength varied between 4.9-23.0 MPa, 14.3- 114.7 MPa, and 1.4- 10.2 MPa, respectively, while the average shearing and cutting energy ranged from 62.4-270.0 mJ and 27.0-133.3 mJ, respectively. Mean bending strength and modulus of elasticity varied between 43.9-4.2 MPa and 3.5-0.1 GPa, respectively. Different trends were found across varieties when the mechanical properties were compared with respect to the internode position. Solid stem varieties had much lower shearing, cutting, and tensile strength than hollow stem wheat varieties while there was no difference between both stem types in relation to coefficient of internal friction, shearing, and cutting energy as well as bending strength and modulus of elasticity.

The compression and relaxation models fitted accurately to the compression and relaxation test data, respectively, for all wheat varieties. The k_4 values obtained from fitting the Peleg and Moreyra model to the relaxation data were greater than one ($k_4 > 1$). Average percentage relaxation and asymptotic modulus range from 38.6 to 42.4% and 10.57 to 11.49 MPa, respectively, with no difference between the average percentage relaxation and asymptotic modulus of solid and hollow stem varieties. Models developed relating moisture content to shearing strength and energy, cutting strength and energy, bending strength, modulus of elasticity, and coefficient of internal friction, respectively, had varying R^2 values.

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DEDICATION

I would like to dedicate this thesis to my loving wife and family who believe in me and kept me constantly in their prayers.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS

a, b = Kawakita-Ludde model constants

a_1, a_2, k_1 and k_2 = Cooper-Eaton model constant

A = Cross-section area of the specimen at the point of failure (mm^2)

A_a= Cross sectional area of cylinder (m^2)

B = 15% of average, the value of allowable variation

B_1, B_2 = Power model constant

b_c = Porosity index

C = Degree of volume reduction or engineering strain

C_E= Cutting energy (mJ)

C_o = Cohesion (kPa),

d = Inner diameter of the hollow stem (mm)

D_f = Fiber diameter (mm) = ($2R_f$)

Df = Degrees of freedom

E = Modulus of elasticity (GPa)

Ɛ = Strain

E_A = Asymptotic modulus (MPa)

f, *h* = Pitt and Gebremedhin model constant

F(t) = Relaxation force at time t (kN)

F_0 = Initial relaxation force (kN)

F_b = Bending force (N)

F_e= Final relaxation force (kN)

F_S = Shear force at failure (N)

F_c = Maximum cutting force (N)

F_t = Maximum tension force (N)

I_b = Second moment of the area (mm^4)

k_3, k_4, = Peleg and Moreyra constant

K_o = Initial bulk modulus

l = Distance between the two metal supports (mm)

M = Mass of the specimen (g)

MC = Moisture content (% wb)

m_f = Final mass of the sample (g)

m_i = Initial mass of the sample (g)

M_w = Wet basis moisture content (decimal value)

N = Number of replicates (sample size)

N1 = First internode

N2 = Second internode

N3 = Third internode

P = Applied pressure (MPa)

r_a = Axis of the cross section (outer radius) (mm)

R_{ap} = Percentage average relaxation (%)

R_f = Radius from neutral axis of stem to the most distant load carrying fiber (mm)

RH = Relative humidity (%)

S_E = Shearing energy (mJ)

t = Time (s)

t = Stem thickness (mm)

t_1 = Value of student's t for two sided limit at 95% probability level and infinite degrees of freedom, 1.96 (for population)

T = Temperature (^oC)

ν = Estimate of coefficient of variation, CV

V = Volume of compact at pressure P (m^3)

V_0 = Volume of compact at zero pressure (m^3)

V_S = Void-free solid material volume (m^3)

β = Dry matter density (kg m^{-3})

β_0 = Compact dry matter density (kg m^{-3})

δ = Deflection at the specimen centre (mm)

μ = Coefficient of internal friction (decimal)

ρ = Particle densities (kg m^{-3})

ρ_o = Initial material density

σ_b = Bending strength (MPa)

σ_c = Cutting strength of the specimen (MPa)

σ_t = Tensile strength of the specimen (MPa)

τ_S = Shearing strength (MPa)

CHAPTER ONE

INTRODUCTION AND OBJECTIVES

1.1 Introduction

Wheat (*Triticum spp)* is a cereal grain that is cultivated in most part of the world. Canada stands as the fifth largest producer of wheat in 2010 with production of about 27 million tonnes (Agriculture Corner 2015). Canada's major contributions come from Alberta, Saskatchewan, and Manitoba provinces (Canadian Encyclopedia 2012). Saskatchewan alone produces more than 45% of the wheat grown in Canada (Canadian Encyclopedia 2013). Wheat generally comes in various types based on their growing period and usage; durum wheat, hard red winter wheat, hard white wheat, hard red spring, soft red winter wheat, and soft white wheat (Canadian Grain Commission 2015).

Table 1.1 World top ten wheat producers 2009/10 (Million tons) (Agriculture Corner 2015)

Rank	Countries	(Million Tons)
1	China	115
2	India	81
3	Russia	62
4	USA	60
5	Canada	27
6	Pakistan	24
7	Australia	22
8	Ukraine	21
9	Kazakhstan	17
10	Argentina	11

Despite the wide variety of wheat that is available, all wheat plants are primarily composed of the grain, straw, and chaff (Figure 1.1). The straw is the residual part of the plant after the grain and chaff have been removed (Tehmina and Umarah 2012). It makes more than half of the wheat plant (Ruiz et al. 2012) and predominantly contains 33-40% cellulose, 20-25% hemicelluloses, and 15-20% lignin, as well as 4% ash (McKendry 2002). Wheat straw has many usage ranging from livestock bedding, fodder to basket making (Tehmina and Umarah 2012) as well as an energy source (biofuel) (Ruiz et al. 2012).

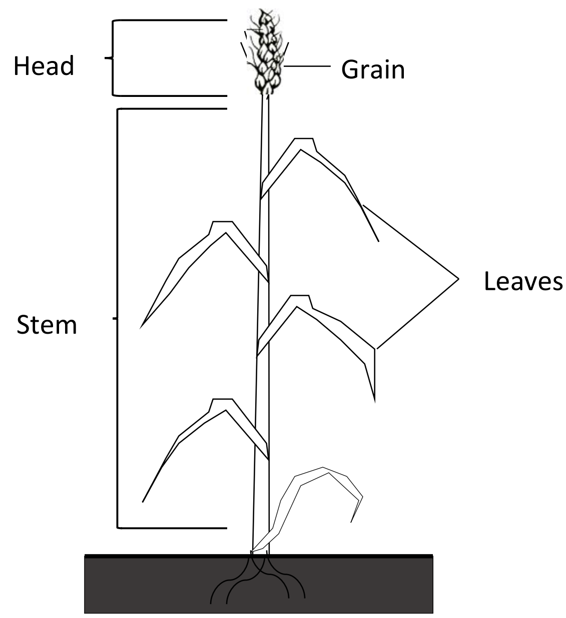


Fig. 1.1 Diagram of the various parts of the wheat plant (*Triticum spp*).

Source: http://science.howstuffworks.com/life/botany/wheat-info1.htm

The utilization of wheat straw and other biomass as feedstock for biofuel (ethanol) production originated from the decline in the energy reserve of other source of energy (fossil fuel) and the demand for more environment friendly energy (Demirbas et al. 2007). Conversion of wheat straw to biofuel requires a multistage supply chain just like any other agricultural residue used for similar purposes. These stages range from harvesting and storage to paricle size reduction and subsequent conversion, and fermentation to ethanol (Kahr et al. 2013). During harvesting, the straws are left in the field to dry after which they are gathered to baled form for easy handling and storage (Nader and Robinson 2010). Size reduction is achieved with the aid of a hammer mill or other milling machine where the straws are ground to the desired size. The purpose of size reduction and other pre-treatment like steam explosion, radiation, and ammonia freeze explosion is to increase the inner contact area and breakdown the structure of the materials for further treatment and conversion (Gonzalez et al. 1986). Hydrolysis liberates the cellulose and hemicellulose of the straw to simple sugar using either enzymes or chemicals (Palmqvist and

Hahn-Hagerdal 2000; Carvalheiro et al. 2008). Chemical hydrolysis involves the use of concentrated acid such as hydrochloric or sulphuric acid to liberate the lignocellulosic matrix (Gonzalez et al. 1986) but in the case of enzymatic hydrolysis, enzymes are used for the same purpose (Palmqvist and Hahn-Hagerdal 2000). Fermentation converts the sugar produced during hydrolysis to ethanol in the presence of yeast or bacteria. For this project, the focus is on the properties related to harvesting, handling, and storage of the wheat straw.

Wheat harvesting is carried out by cutting the stem. Wheat's stem experience lodging (bending of the stem towards the ground) due to the attack by wheat stem sawfly (*Cephus cinctus*) (Jim and Scott 2013) and weather (strong winds and heavy precipitation) (Crook and Ennos 1996) thereby reducing the yield. To tackle this problem, new varieties such as the dwarf species (Ottman 2011) and solid stem wheat have been introduced (Jim and Scott 2013). While the solid stem variety is said to reduce the harmful effect of wheat stem sawfly, it may lead to higher stem strength and consequently, higher energy requirement and harvesting cost.

Another challenge faced during the postharvest handling of wheat straw is due to its natural physical state, namely, high moisture content and volume which makes it challenging to handle, transport, and store (Sokhansanj et al. 2002). As such, for wheat straw to be profitable as a feedstock, the cost of handling, transporting, and storage of the straw needs to be reduced (Adapa et al. 2009). This can be achieved through densification. Previous research has led to the production of denser straws (double-compressed bales, pellets, cube, and briquette) but the cost of processing them and their physical quality is still a challenge (Mupondwa et al. 2012). To cope with these challenges and understand the optimum operational parameters to minimize cost and energy consumption of harvesting and postharvest processes of wheat and its straw, it is necessary to have knowledge of the physical properties as well the mechanical properties of the material (Tavakoli et al. 2008).

The mechanical properties that are necessary for designing equipment for harvesting and postharvest operations of wheat straw are cutting, shearing, bending, compressive, and tensile strength, modulus of elasticity and coefficient of internal friction. The physical properties of the plant are also important when considering these mechanical properties (Tavakoli et al. 2009b). Some of the physical properties include stem moisture content, diameter and bulk density.

Table 1.2 Density of biomass for selected densification technologies (Clarke and Preto, 2011).

Form of biomass	Shape and size characteristics	Density (kg m^{-3})	Energy density (GJ m^{-3})
Traditional method			
Baled biomass	Large round, Soft core 1.2 x 1.2, 1.2 x 1.5, 1.5 x 1.2, 1.8 x 1.5 m (4 x 4, 4 x 5, 5 x 4, 6 x 5 ft) diameter x width	160–190	2.8–3.4
	Large round, Hard core 1.2 x 1.2, 1.2 x 1.5, 1.5 x 1.2, 1.8 x 1.5 m (4 x 4, 4 x 5, 5 x 4, 6 x 5 ft) diameter x width	190–240	3.4–4.5
	Large/Mid-size square 0.6 x 0.9 x 2.4 m (2 x 3 x 8 ft) 0.9 x 1.2 x 2.4 m (3 x 4 x 8 ft)	210–255	3.7–4.7
Non-traditional method			
Ground biomass (i.e., hammermill)	1.5 mm (0.06 in.) pack fill with tapping	200	3.6
Briquettes	32 mm (1.3 in.) diameter x 25 mm (1 in.) thick	350	6.4
Cubes	33 mm (1.3 in.) x 33 mm (1.3 in.) cross section	400	7.3
Pucks	75 mm (3 in.) diameter x 12 mm (0.5 in.) thick	480–640	8.6–12.0
Pellets	6.24 mm (0.2 in.) diameter	550–700	9.8–14.0
Torrefied pellets	6.24 mm (0.2 in.) diameter	800	15.0
Bio-oil	liquid	1,200	20
Note: Loose biomass has a density of 60–80 kg m^{-3}			

1.2 Objectives of the Research

The main objective of this research is to determine the mechanical properties of wheat stem from solid and hollow stem varieties for similarities and differences so that these data could be used in the design of equipment to improve harvesting and handling of straw. The specific objectives are as follows:

1. to investigate the effect of moisture content, internode position, and stem type (solid and hollow) and their interactions on the internal friction, shearing, cutting, bending, tensile, and compression properties of wheat stems;
2. to compare the mechanical properties of wheat straw from solid and hollow stem varieties; and
3. to develop statistical models that will predict the various mechanical properties as a function of the independent variables.

This work will help in selecting the design and operational parameters of wheat plant processing equipment and optimize the equipment, particularly its design based upon information on its properties. The research work will also aid in reducing losses due to lodging as well as increase the potential for lowering the cost incurred during harvesting, handling, and storage of the wheat straw.

1.3 Organization of the Thesis

Chapter 1 introduces the subject matter and the objectives of the research. The review of literature on the effect of moisture on coefficient of internal friction of wheat straws, the effect of moisture and internode position on the other mechanical properties (shearing strength and energy, cutting strength and energy, bending strength, and modulus of elasticity) of wheat stem, modelling, compression, and relaxation properties and models, respectively, are discussed in Chapter 2. Chapter 3 presents the materials and methods used in the research. Chapter 4 covers the general results and discussion of all mechanical properties studied. Chapter 5 concludes the thesis by summarizing the main observations based on the results discussed in preceding chapters. Recommendations for future studies are given in Chapter 6 alongside references and appendix.

CHAPTER TWO

REVIEW OF LITERATURE

The literature on the effect of wheat stems' physical properties on their mechanical properties, lodging, standability measurements, lodging prevention, densification of straw, relaxation, asymptotic modulus, and modelling and models fitting were reviewed and presented in this chapter.

2.1 Introduction

The mechanical properties that are essential for designing equipment for harvesting and postharvest operations of wheat are shearing, cutting, bending, tensile, and compressive strength, as well as modulus of elasticity and coefficient of internal friction. The physical properties of the plant are also important when considering these mechanical properties (Shaw and Tabil, 2006). Some of the physical properties of wheat stem include moisture content, stem height (length), and density. Depending on the weather conditions, cost of drying, and farmers' preference, harvesting is carried out at grain moisture content of 15 to 20% wb (Dennis 2014) and stem moisture of 10 to 20% wb (O'Dogherty et al. 1995). According to Kenny et al. (2014), wheat plant height varied between 0.60 to 0.85 m, with internodes at different intervals across the stem height separated by node (Figure 2.1). O'Dogherty et al. (1995) noted that the first internode diameter and wall cross-sectional area were lower in comparison to the fourth internode (measured from the head). Similar result was reported by Tavakoli et al. (2009b). They also noted that the diameters (inner and outer) increased as moisture content increased. The outer diameter of the first internode of wheat straw for example, ranged from 3.46 to 4.19 mm for moisture content between 10.24 and 22.61% wb, respectively.

Knowledge of the mechanical properties of wheat stem and how it is affected by these physical properties will provide vital information that can be utilized during harvesting of the crop and postharvest handling and storage of the straw. The literatures of these mechanical properties are highlighted in the succeeding sections.

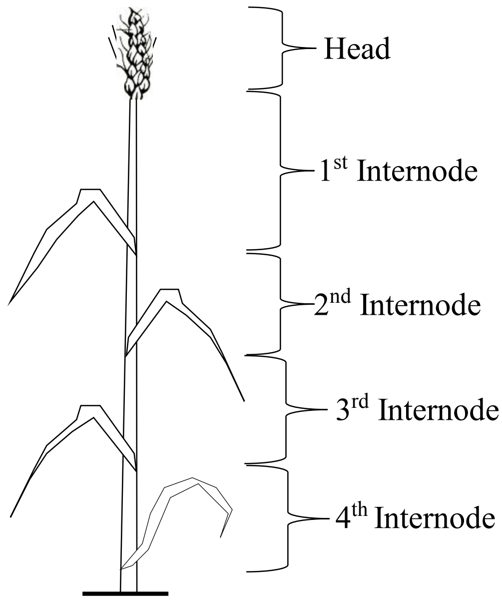


Fig. 2.1 Diagram of wheat stem identifying the internodes (redrawn from Tavakoli et al. 2009b)

2.2 Shearing properties of wheat stem

The study of the shearing properties of wheat stem is essential in determining parameters for harvesting machinery. The shearing properties show the correlation between the shear strength and the plant morphology which can be utilized in minimizing the required energy consumption of the machines (Liang and Guo 2011). According to Hoseinzadeh et al. (2009), wheat stem with lesser shear strength required lesser energy consumption for cutting than stem with higher shear strength.

2.2.1 Effect of moisture content on shearing properties

The moisture content of wheat plant varies with its root system and availability of water in the soil (Kramer 2015). O'Dogherty et al. (1995) work on the effect of moisture content on the shearing strength of wheat straws revealed that the shearing strength of wheat straw had a positive correlation with moisture content. Mean shearing strength values of the third internode was between 5.46 and 6.51 MPa for moisture content range of 8.2 and 22.0% wb. Esehaghbeygi et al. (2009) reported that the average shearing stress increased from 3.25 to 3.86 MPa for moisture content range between 15 and 45% wb. Tavakoli et al. (2009c) research on barley straw indicated that as the moisture content varied from 10 to 20% wb, the mean shearing stress and shearing energy at the second internode increased from 4.84 to 5.25 MPa and 92.46 to 121.25 mJ, respectively. Kushwaha et al. (1983) noted that the effect of moisture on shearing strength was only significant at lower straw moisture content (6 - 15% wb) but at higher moisture content (> 15% wb), the shearing strength was not significantly affected by the moisture content. They added that the optimum moisture content for cutting wheat straw was between 8 to 10% wb. Hematian (2013) reported that the reason for the increase in shearing strength and shearing energy was as a result of the increase in the elastic properties of the plant caused by the increase in moisture content.

2.2.2 Effect of internode position on shearing properties

Tavakoli et al. (2008) investigated the shearing strength and energy of wheat straw at different internode positions at a moisture content of 10.24% wb and 10 mm min^{-1} loading rate using a shear box (double shear). Analysis of the data revealed that the shearing strength and specific shearing energy increased from 6.81 to 7.12 MPa and 21.85 to 25.74 mJ mm^{-2}, respectively, from the first to the third internode, with measurements taken from the ear. Esehaghbeygi et al. (2009) reported significant increase in the shearing stress (3.80-3.35 MPa) in relation to the cutting height (100-300 mm) measured from the bottom. Chandio et al. (2013) noted similar trend of the shearing strength and specific shearing energy across the internodes when comparing the mechanical properties of rice and wheat straw. On the contrary, O'Dogherty et al. (1995) reported that the effect of the internode position on the shear strength of wheat straw was not consistent, although, they acknowledged significant effect of internode position with respect to the shearing strength. The lack of trend may be due to variations in the moisture content across the straw height under study which also has significant effect on the shearing strength.

2.2.3 Effect of cutting angle on the shearing properties

Esehaghbeygi et al. (2009) experiment on the effect of knife angle on the shearing stress of wheat stem revealed that the shearing stress decreased from 3.92 to 3.36 MPa as the knife angle increased from 0^o to 30^o. Hoseinzadeh et al. (2009) studied the effect of bevel angle on shearing energy of wheat stem using the pendulum method. Data analysis indicated that the shearing energy increased from 0.71 to 0.77 MJ mm^{-2} for bevel angle between 25 and 35^o.

Kushwaha et al. (1983) compared the shear strength of 30^o blade and 90^o blade. They reported lower shear strength when using 30^o blade in comparison with 90^o blade indicating that more energy was required when cutting the wheat straw with 90^o blade. Gene (2009) suggested a blade angle lower than 45^o. This means that the more the angle gets closer to the vertical, the higher the shearing stress and energy.

2.2.4 Effect of cutting blade on the shearing properties

Esehaghbeygi et al. (2009) reported that the shearing stress of wheat stem was higher when using serrated edge knife than when using a smooth knife. They concluded that with a serrated knife, friction was higher in comparison to a smooth knife hence, the increased shearing stress. Hematian et al. (2013) compared the effect of nano-coated knife and regular knife on the shearing strength of sugarcane stem at different moisture content and speed. They noted that the nano-coated knife had a lower shearing strength and specific shearing energy in comparison to the regular (sickle) knife. Their work also revealed that lower shear strength and energy is achieved when the surface of the knife is smooth compared to when it is rough. The lowering of the shearing strength is a result of reduced friction between the knife surfaces and the cut plant.

2.2.5 Effect of internode position on cutting properties

Alizadeh et al. (2011) used a pendulum impact type of machine to determine the effect of internodes on the cutting energy of rice stem. They noted lower cutting energy at the second internode in comparison to the third internode. Chandio et al. (2013) reported that the cutting force of wheat straw increased from the first internode (13.58 N) to the third internode (15.34 N) at loading rate of 15 mm min^{-1}. They concluded that cutting the straw at the first internode required lesser energy than at other internodes. Kehayov et al. (2004) observed similar trend in their investigation on the cut height of wheat harvest. They noted that increasing the cut height towards the plant head reduced the cutting energy and fuel consumed during harvesting.

2.3 Lodging in wheat plant

Lodging is a major challenge encountered by farmers. It is the permanent bending of the plant stem from its upright position. There are two types of lodging; stem and root lodging. Stem lodging involve bending of the stem towards the ground while root lodging is due to inability of the root system to keep the plant upright (Kratochvil 2008). From the agronomic point of view, lodging occurs as a result of nutrient imbalance in the plant, diseases, environmental, and morphological factors (Lovell 2012). Lodging has a great impact on harvest yield and quality. Lodging tolerance or standability is the ability of the plant to resist lodging. Johnson et al. (2008) reported at the North American Alfafa Improvement Conference (NAAIC) a standard for determining plant standability. Stems that made angle greater than 45^o with respect to the ground were considered to have lodging tolerance (standability). Farmlands were rated based on the percentage of erect stems (lodging tolerance) within the area (Table 2.1).

Table 2.1 NAAIC rating for lodging tolerance (Johnson et al. 2008).

Rating	**Conditions**
9 = Resistant	91 to 100% erect stems
7 = Resistant	71 to 90% erect stems
5 = Moderately resistant	51 to 70% erect stems
3 = Moderately resistant	31 to 50% erect stems
1 = Susceptible	11 to 30% erect stems
0 = Susceptible	0 to 10% erect stems

Measurements to determine lodging tolerance are mostly taken around bud to mid-bloom stage (Johnson et al. 2008). They reported two methods used in carrying out these measurements and subsequent rating; 1) spaced plants trial and 2) solid seeded plots. In the spaced plant method, rating was done based on the percentage of erect stems within plant rows while in the solid seeded plots method, plots were rated based on percentage of erect stem within the plot.

Different methods have been adopted to tackle lodging. Some of them include soil quality improvement, good management practice (HCGA 2005) cultivation of dwarf varieties, and introduction of lodging-resistant varieties (Prairie Grains 2005). Hasnath and Jahan (2013) investigated the lodging resistance of different genotypes of hard wheat. They noted that some genotypes (Pradiv, Akbar, Gourav, and Shatabdi) had higher lodging resistance than others (Bijoy, Sufi, Shourav, Barkat, Prativa, and Balaka,). Kong et al. (2013) reported that the solid stem wheat genotypes are more resistant than the hollow stemmed genotypes. The difference was because the solid stemmed wheat having more mechanical support tissues as well as a wider stem wall. On the other hand, Crook and Ennos (1994) work on the lodging resistance of four winter wheat cultivars revealed that the lodging resistance was independent of stiffness of the stem but rather was related to the height of the stem. They recommended shorter stem plants with widespread coronal roots as a remedy to lodging.

2.4 Bending properties

From the anatomical point of view**,** Evans et al. (2007) reported that the sclerenchyma cells were responsible for resisting the bending stress of stem. They noted that these cells appear predominantly near the outside of stems where bending stresses are highest. Crook and Ennons (1996) compared the bending strength of two grown wheat (frame supported and free standing). They realized that the free standing wheat stem had more strength and lodging resistance than the frame supported although not much difference. The bending property, in summary is a function of the physical and biological properties (Persson 1987; Tavakoli et al. 2009a). A closer look into some of these variables will give us a better understanding in determining the strength of the stem.

2.4.1 Effect of moisture content on bending strength

Esehaghbeygi et al. (2009) research on wheat stem indicated that moisture content have significant effect on the bending stress of wheat stem. The bending stress decreased from 26.77 to 17.74 MPa for 15 to 45% wb increase in the moisture content. Alireza et al. (2012) worked on modeling of the some mechanical properties of barley straw using fuzzy logic. Results revealed that the bending stress of barley straw decreased as the moisture content increased. Tavokoli et al. (2009a) obtained similar trend while investigating the bending characteristics of barley stem. They reported a decrease in bending stress from 9.91 to 6.98 MPa for moisture content range of 10 to 20% wb, They concluded that the decrease in bending stress caused by increase in moisture content of the barley straw was a result of the reduction in the brittleness of the straw.

2.4.2 Effect of internode position on bending properties

The physical properties of wheat stem vary from the head to the root (Tavakoli et al 2009b). According to Crook and Ennos (1994), the height of the plant is related to lodging. Tavokoli et al. (2008) worked on the bending stress and modulus of elasticity of wheat at different internode position using the three-point bending test. Test results showed that the bending stress and modulus of elasticity experienced a significant decrease from the first to the third internode with values ranging from 19.31 to 13.70 MPa and 1.82 to 0.98 GPa, respectively. Esehaghbeygi et al. (2009) studied the bending properties of wheat stem using a cantilever at different cut heights (100, 200, and 300 mm). The bending stress and modulus of elasticity were reported to decrease from 21.14 to 17.85 MPa and 3.81 to 3.12 GPa, respectively. Tavakoli et al. (2009a) obtained similar trend when studying the bending characteristics of barley stem at different internode position. The literature revealed that the resistant of the stem to lodging decreases from the plant head to the root.

2.5 Tensile strength of wheat straw

Another mechanical property that is essential in the design of harvesting and postharvest machinery of wheat plant is the tensile strength. The tensile strength indicates the minimum force required to pull the stem apart. From an anatomic point of view, the force the biomass stem can withstand is determined by the lignin content of the stem (Christopher et al. 2005). Higher lignin content means higher stem strength. The physical properties also play an important role in the magnitude of the tensile strength. Galedar et al. (2009) noted that the tensile strength increased with increased stem area. More insights into how the physical properties affect the tensile strength will give us a better knowledge in designing cost-effective equipment.

2.5.1 Effect of moisture content on tensile strength

O'Dogherty et al. (1995) investigated the effect of some physical properties on the tensile strength of wheat straw. No consistent trend was observed with mean tensile strength varying from 22.7 and 31.2 MPa for moisture content range of 8 to 22% wb. Limpiti (1980) reported tensile strength range of 32.5 and 37.8 MPa for moisture range between 10 and 65% wb. Kronbergs (2000) determined the tensile strength of wheat stalk at 10% wb moisture content using a tensile testing machine with rubber jaw. He noted that the ultimate tensile strength was 118.7 ± 8.63 MPa.

2.5.2 Effect of internode position on tensile strength

The tensile strength increased with increased stem area (Galedar et al. 2009). As reported by Tavakoli et al. (2009b), wheat stem diameters and subsequently area increases from the head to the root indicating that the tensile strength increases from the first to third internode. O'Dogherty et al. (1995) reported an increase in the tensile strength of wheat straw from the first to the second internode and a corresponding decrease toward the fourth internode with mean values between 21.2 to 28.4 MPa. Galedar et al. (2009) reported that the relationship between moisture content and tensile strength of alfafa stem was exponential. They noted that the increased tension across the stem length was as a result of increase in lignin content**.**

2.6 Compression of wheat straw

The natural physical state of straw (low bulk density) makes it very challenging to handle, store, and transport (Sokhansanj et al. 2002). Depending on the type of biomass, the bulk density varies between 50 and 130 kg m^{-3} (Sokhansanj and Turhollow 2004). In other for the wheat straw to be profitable as a feedstock, the cost of handling, transporting, and storage of the straw needs to be reduced (Adapa et al. 2009). This can be achieved through densification.

Different densification technology have been adopted, some of which are baling, cubing, and pelleting (Clarke and Preto 2011). The method of production and its bulk density differentiate one densification technology from the other. Baling involves the use of a machine (baler) to gather the straws together. The bales come in round and square shape with density ranging from 160-255 kg m^{-3} (Clarke and Preto 2011). Pellets are made using a ring die or a piston where finely ground biomass material are compressed and pushed out of cylindrical dies. Cubes involve the same process like pellet except for lower final density (~ 400 kg m^{-3}) and larger biomass particle size (Clarke and Preto 2011).

Mupondwa et al. (2012) reported that it takes huge capital to break-even when producing pellet than bale. Sokhansanj and Turhollow (2004) noted that the delivery cost for bales was US$60.15/ dry Mg (54.57/ dry ton) while that of cubes was US$80.22/ dry Mg (72.77/ dry ton), respectively, indicating that the operational cost of the bale as well as the bulk density was low in comparison to other dense product. If the bulk density of bales can be further increased through compression, it will be more economical using the wheat straw in a dense bale form. Talebi et al. (2011) reported that compression properties of timothy hay are affected by many factors. A better knowledge of these factors will help optimize compression equipment and processes that can tackle the challenges encountered in handling, transporting, and storage of wheat straw.

2.6.1 Effect of moisture content on compression (compact density)

Agricultural materials generally undergo deformation during compression. The material may either return to its original state if it has not exceeded its elastic limit (elastic deformation) or maintained its deformed state (plastic deformation). According to Kenny et al. (2014), moisture plays an important role during compression of biological materials. Sokhansanj et al. (2002) noted that higher moisture bales produced heavier and denser bales. Talebi et al. (2011) work on compression and relaxation properties of timothy hay was also in agreement. Rehkugler and Buchele (1969) explained that for high moisture biomass, the moisture occupies the void spaces thereby increasing the mass and subsequently the density but in the case of low moisture biomass, air occupies the void and are dispersed during compression resulting in their lower compact density. Mangaraj and Kulkarni (2011) tested the performance of a baler (CLASS MARCANT-55, CLAAS Agricultural Machinery Pvt. Ltd, Faridabad, Haryana, India) and noted that the bulk density of the wheat straw bale was 102 kg m^{-3} at 8% wb moisture content. Kenny et al. (2014) reported that for a biological material undergoing recompression, the force required to compress the material decreases with respect to the previous force used in the previous compression. Gale and Neale (1996) developed a compression machine and evaluated the effect of moisture content on compressed straw (wafer) at 150 MPa. Their results indicated that straw with higher moisture content compressed more than straw with lower moisture content and relaxed more (two times greater) upon removal of the pressure. The reason is that the moisture acts as a binding agent during compression (Grover and Mishra 1996) but due to the weak van der Waals' forces created, the bale relaxed more upon removal of the pressure.

2.6.2 Relaxation and asymptotic modulus

Compression of biomass involves particle rearrangement, elastic and plastic deformation, and densification (Adapa 2009). Upon attaining the maximum or desired compressive pressure, the plunger is held at constant position (constant strain). The purpose of which is to prevent spring back effect (Mani et al. 2006a). During the hold time, the stress acting on the material decreases with time at constant strain, a phenomenon known as stress relaxation or simply relaxation (Talebi et al. 2011).

Relaxation is an important factor when considering compression of biomass. It gives an indication of physical changes experienced at constant strain and helps determine the un-relaxed stress sustained by the material (Shaw and Tabil, 2007). The un-relaxed stress or asymptotic modulus is what keeps the particles compact solid (Mani et al. 2006a). This means that the solidity of the compressed biomass increases with increase in asymptotic modulus (Talebi et al. 2011). Shaw and Tabil (2007) presented Peleg and Moreyra (1979) model (equation 2.1) for normalizing and linearizing relaxation data.

$$\frac{F_o.t}{F_o - F(t)} = k_3 + k_4.t \qquad (2.1)$$

where:

F(t) = Relaxation force at time t (kN)

t = Time (s)

k_3, k_4= Constants

The constant k_4 was reported as the solidity index of the compressed material and help determine the asymptotic modulus. It was reported that the k_4 value should be greater than one (k_4>1) for the material to be solid (Shaw and Tabil, 2007; Mani et al. 2006a; Talebi et al. 2011). Scoville and Peleg, (1981) proposed an equation for calculating asymptotic modulus (equation 2.2) which has been utilized by many researchers (Nussinovitch et al 1990; Lam et al. 2013; Kenny et al. 2014).

$$E_A = \frac{F_O}{A_a \varepsilon}\left(1 - \frac{1}{k_4}\right) \qquad (2.2)$$

where:

E_A = Asymptotic modulus (MPa)

F_0= Initial relaxation force (kN)

Ɛ= Strain

The asymptotic modulus is also affected by the compressive force such that increasing the compressive force acting on the biomass increases the asymptotic modulus (Talebi et al. 2011). Similar trend was reported by Mani et al. (2006a) in their study on the "effects of compressive force, moisture content, and particle size on the mechanical properties of biomass pellets from grasses". They compared the asymptotic modulus of four biomass grinds (wheat, barley, switchgrass, and corn stover) and discovered variability in the asymptotic modulus across the different biomass types with barley grind having the highest value. They recommended asymptotic modulus as the property of a material that can be used in characterizing biomass. Shaw and Tabil, (2005) studied the compressive characteristics of four biomass samples (flax shives, wheat straw, peat moss, and oat hulls) during pelleting at five compressive loads (1000, 2000, 3000, 4000, and 4400 N). They reported that different biomass had the highest and lowest asymptotic modulus, respectively, at each successive pre-set load. For example, at 1000 N, flax shives and oat hulls had the highest and lowest asymptotic modulus, respectively, while at 3000 N, peat moss and wheat straw had the highest and lowest values, respectively. These findings back Mani et al. (2006a) proposal that asymptotic modulus can be used in characterizing the compression behavior of different biomass.

2.6.3 Effect of moisture content on stability

Moisture content plays an important role in stabilizing compacted wheat straw (Smith et al. 1977). Mohsenin and Zasket (1976) studied the stress relaxation of unconsolidated agricultural materials under compression. Findings revealed that lower moisture content resulted in less expansion of the wafer. They also added that the longer holding time resulted in lesser expansion of the material upon removal of the pressure. Gale and Neale (1996) reported that bale under compaction experienced more compression at higher moisture content in comparison to low moisture bale.

2.6.4 Effect of moisture content on compression energy

Talebi et al. (2011) reported that the energy requirement for compressing high moisture hay was less than the energy requirement for low moisture hay when compressed to the same density. This inference is only possible at fair high moisture (Rehkugler and Buchele, 1969). They also reported that during compression, moisture is required to fill in the pore spaces between the material particles but when the moisture content of the material is very high, the volume is increased causing an increase in the energy requirement. Faborode, (1989) reported that the moisture content at which minimum compaction process energy is attained has effect on the quality of the compressed biomass. His work on barley straw revealed that it was hard to form wafers at moisture content above 22% wb while 22.2 MJ per dry tonne of barley straw was needed to form dense wafer.

2.7 Coefficient of internal friction of wheat straw

When materials in contact move relative to one another, there is resistant to motion along their contact surfaces. The resistance (friction) contributes and affects the amount of force and consequently energy required to cause motion or work (Mani et al 2006b). For materials such as straws undergoing compression, aside from the friction experienced between the straw and the surface of its container (wall friction), there is also straw-straw resistance (internal friction) relative to one another (Adapa et al. 2010). The ratio of the internal friction relative to the compressive force is called coefficient of internal friction. The coefficient of internal friction plays a significant role when designing handling and storage equipment for straws (Afzalinia and Roberge 2007; Ghorbani et al. 2011; Kibar et al. 2014). It gives information of the amount of lateral force generated during compression (Opoku et al. 2006). According to Shaw and Tabil, (2006), moisture content and particle size affect the coefficient of friction. Studies relating variation of moisture content to coefficient of internal friction of agricultural materials have been focused on grains, chopped forage, and straw grind as well as external friction. Laskowski (1999) studied how moisture content affects the coefficient of internal friction of cereal grain (wheat, barley, and rye). He noted a positive correlation of coefficient of friction with moisture content on all grains with exception of oat that experienced an initial increase from 10 to 14% wb and then decrease as the moisture increased to 18% wb. Brubaker and Pos (1965) noted that the contact surface (container) and moisture content had effect on the coefficient of friction of wheat grain. They reported increased (0.33-0.38) and decreased (0.19-0.12) values of the coefficient of friction of wheat grain against steel and Teflon surfaces, respectively, for moisture content range of 9.7-15.1% db. Sologubik (2013) reported a positive correlation of moisture content with coefficient of static friction of barley grain on three surfaces, namely; aluminum, plywood, and galvanized steel. Unuigbe et al. (2013) analyzed the frictional properties of Dika nut on galvanized steel at different moisture content. They noted that the coefficient of internal friction of Dika nut on galvanize steel surface increased from 0.52 to 0.90 for increased moisture content range of 8.25 and 18.98% db. Ghosh (1968) reported similar trend for parchment coffee on different construction material surfaces (no specific material was mentioned) Afzalinia and Roberge (2007) studied the coefficient of internal friction of alfalfa hay and barley straw using shear box apparatus at four cut lengths (10, 30, 60, and 90 mm) and 12% moisture content (wb). Their results revealed that the length of the biomass did not affect the coefficient of internal friction. Menzies (1975) studied the coefficient of friction of alfafa on stainless steel at high pressure. He noted that wall (external) friction decreased with increased moisture content. Similar observation was reported by Ghorbani et al. (2012) on the coefficient of internal friction of alfafa grind. They reported that increased moisture content (8-11% wb) resulted in decreased coefficient of internal friction (0.794-0.690) and increased cohesion (5.793-6.705 kPa).

2.8 Relationship between mechanical properties and physical properties of wheat straw

Models are used to interpret interaction among variables that exist within a system. In most cases, the independent variables are used to predict the dependent variable. Mechanical properties of biological material are dependent on their physical properties. This relationship is mostly presented in the form of equation for easy comparison.

2.8.1 Models of stem mechanical properties

Esehegbeyi et al. (2009) developed a trigonometric equation from experimental data that relate the bending strength and moisture content of wheat stalk. Tavakoli et al. (2009b) reported an exponential relationship between the bending strength and moisture content of wheat straw as presented in equation (2.3).

N1: $$\sigma_{b1} = 31.19e^{-0.04MC} \quad (R^2 = 0.97) \tag{2.3a}$$

N2: $$\sigma_{b2} = 21.14e^{-0.03MC} \quad (R^2 = 0.93) \tag{2.3b}$$

N3: $$\sigma_{b3} = 19.21e^{-0.03MC} \quad (R^2 = 0.93) \tag{2.3c}$$

Source: Tavakoli et al. (2009b)

Similar relationship with moisture content was presented by Galedar et al. (2009) for the tensile strength of alfalfa. Alireza et al. (2012) evaluated the shear strength of wheat stem using fuzzy logic model with independent variables as moisture, stem height, and cutting angle. Comparing the model with their experimental test results gave a minimum accuracy of 91%. Other shearing strength models developed indicated an exponential relationship with R^2 value ranging from 80 to 99 % (Tavakoli et al. 2009b; Kushwaha et al. 1983) although Esehegbeyi et al. (2009) reported a quadratic relationship with R^2 value of 96 % for wheat stem on the contrary. Laskowski (1999) developed a similar model relating moisture content to coefficient of internal friction for wheat grain (Table 2.2).

Table 2.2 Models of some mechanical property and their corresponding R^2 values.

Researcher	**Mechanical test**	**Material**	**Models**
Tavakoli et al. (2009b)	Bending strength	Wheat straw	$\sigma_b = 4.77e^{0.039MC}$ (R^2 = 0.99)
Galedar et al. (2009)	Tensile strength	Alfafa stem	$\sigma_t = 35.230e^{0.01MC}$ (R^2 = 0.97)
Esehegbeyi et al. (2009)	Shearing strength	Wheat stem	$\tau_s = 3.95 + 0.002MC - 0.003MC^2$ (R^2 = 0.97)
Shahbaz and Galedar (2012)	Shearing energy	Safflower stalk	$S_E = 126.00 + 17.84MC$ (R^2 = 0.997)
Tavakoli et al. (2009b)	Specific shearing energy	Wheat straw	$E_s = 7.157 + 2.074MC - 0.037MC^2$ (R^2 = 0.991)
Hoseinzadeh et al (2009)	Specific shearing energy	Wheat stem	$E_s = 0.9 + 0.29\cos(0.07MC + 2.11)$ (R^2 = 0.99)
Laskowski (1999)	Coefficient of internal friction	Wheat grain	$\mu = 0.0025MC^2 + 0.00927MC - 0.008$ (R^2 = 0.84)

- Reference stems internode: second internode
- μ = Coefficient of internal friction
- MC = Moisture content (% wb)
- σ_b = Bending strength
- σ_t = Tensile strength
- τ = Shear strength
- S_E= Shearing energy
- E_s= Specific shearing energy

Models used in predicting the energy required for cutting and shearing of biomass in relation to moisture content indicated different relationship by previous researchers. For example, for the relationship between shearing energy and moisture content, Tavakoli et al. (2009b) presented a quadratic relationship while Shahbazi et al (2011) and Hoseinzadeh et al (2009) proposed a linear and trigonometric relationship, respectively (Table 2.2).

2.8.2 Fitting compression and relaxation models to data

Densification of straw and other agricultural biomass is necessary to enable reduction in the cost of transportation, handling, and storage (Adapa et al. 2009). There is a correlation between the density of the biomass and the pressure applied during compression (Afzalinia and Roberge 2013). The density was noted to increase as the applied pressure increased (Talebi et al. 2011). Different models have been developed relating compression density (volume) with pressure (Adapa et al. 2009; Kenny et al 2014; Mani et al. 2006a). Comoglu (2007) mentioned two reasons for fitting compression models to experimental data: 1) to linearize the plots for easy comparison of data; and 2) to predict the pressure required to attain the desired density. Afzalinia and Roberge (2013) developed and validated an empirical model relating bale density and pressure exerted by the plunger in a large cubic baler using data generated during alfalfa and barley straw bailing. The R^2 values obtained by fitting the model to alfalfa and barley straw compression data were 0.89 and 0.94, respectively. Kenny et al. (2014) compared two compression models (Maxwell and Faborode) using experimental data generated during the compression test of wheat straw and hay. They noted that the Faborode model conformed more to the compression test than the Maxwell model.

Faborode-O’Callaghan’s model is given as:

$$P = \frac{K_o}{b_c}\left[e^{b_c\left(\frac{\rho}{\rho_o}-1\right)} - 1\right] \tag{2.5}$$

where

ρ_o = Initial material density,

ρ = Final or instantaneous material density,

K_o = Initial bulk modulus

b_c = Porosity index (Kenny et al. 2014)

Adapa et al. (2009) studied the compression characteristics of ground biomass (barley, canola, oat, and wheat straw) using five (5) different models (Jones, Heckel, Cooper-Eaton, Kawakita-Ludde, and Panelli-Filho). They noted that among all the models fitted to the compression data, the Kawakita-Ludde model had the best fit across all biomass studied (R^2=0.99). The Jones and the Cooper-Eaton models had low R^2 values while the Heckel and the Panelli-Filho models did not fit exactly with the compression test data. Mani et al. (2004) analyzed the fitness of three compaction models (Heckel, Cooper-Eaton, and Kawakita-Lüdde) on the compaction data of switchgrass grinds, corn stover, wheat and barley straws, and They noted that the Heckel model could not explain the trend in the compression data of the biomass grinds while the Kawakita-Lüdde and Cooper-Eaton models had a great fitting with the pressure-density data for all biomass grind samples. Talebi et al. (2011) investigated the applicability of five different models (Walker, Kawakita-Lüdde, Cooper-Eaton, Jones, Pitt-Gebremedhin, and Faborode-O'Callaghan's) in relation to compression characteristics of different qualities of timothy hay. Findings revealed that the Pitt-Gebremedhin and Faborode-O'Callaghan's models fitted accurately to the compression data generated during the hay compression test, although there was some shortcomings with respect to Pitt-Gebremedhin model as the model constant did not correlate with the experimental variables. The Walker, Kawakita-Lüdde, and Cooper-Eaton models had R^2 values between 0.90, 0.99 and 0.72, respectively, while the Jones model did not fit properly in the compression data.

Kawakita-Ludde model is given as:

$$\frac{P}{C} = \frac{1}{ab} + \frac{P}{a} \tag{2.6a}$$

where

P = Applied pressure

a and b = Kawakita-Ludde model constants related to characteristic of the powder

C = Degree of volume reduction or engineering strain given as:

$$C = \frac{V_O - V}{V_O} \tag{2.6b}$$

where

V = Volume of compact at pressure P (m^3)

V_0 = Volume of compact at zero pressure (m^3),

(Mani et al. 2004; Adapa et al. 2009; Talebi et al. 2011)

Cooper-Eaton model is given as:

$$\frac{V_O - V}{V_O - V_s} = a_1 e^{-\frac{k_1}{P}} + a_2 e^{-\frac{k_2}{P}} \quad (2.7)$$

where

V_S = Void-free solid material volume (m^3)

a_1, a_2, k_1 and k_2 = Cooper-Eaton model constants

(Mani et al. 2004; Adapa et al. 2009; Talebi et al. 2011)

Pitt-Gebremedhin model is given as:

$$P = h[e^{f(\beta - \beta_o)} - 1] \quad (2.8)$$

where

β= Dry matter density, kg m^{-3}

β_0 = Compact dry matter density, kg m^{-3}

f, *h* = Constants.

(Source: Talebi et al. 2011)

Models have also been fitted to relaxation data to predict relaxation and subsequently the un-relaxed stress or asymptotic modulus. Kenny et al. (2014) compared the applicability of two relaxation models (Peleg and Maxwell) by fitting them to the experimental data of wheat straw and hay compacted test. They reported that Peleg model fitted well (R^2>0.8) unlike Maxwell relaxation model that did not fit properly (R^2<0.8). Talebi et al. (2011) investigation on the relaxation characteristics of timothy hay produced a linear equation relating asymptotic modulus with applied pressure. Comparison of the equation with experimental data indicated a higher fitness (R^2=0.90). Mani et al. (2006a) noted similar relationship between the asymptotic modulus and applied pressure of four biomass grinds (R^2>0.95).

Peleg and Moreyra model is given as:

$$\frac{F_o.t}{F_o - F(t)} = k_3 + k_4.t \qquad (2.9)$$

where

F_0= Initial relaxation force (kN)

F(t)= Relaxation force at time t (kN)

t=Time (s)

k_3, k_4, = Constants

(Kenny et al. 2014; Mani et al. 2006a; Talebi et al. 2011)

2.9 Summary

The literature survey showed that increase in moisture content lead to an in increase in the shearing, compressive, cutting and tensile strength but decreased in bending strength of wheat stem. Moving from first to the third internode measured from the head resulted in increased shearing, compressive, cutting, and tensile strength but decreased bending strength. Although, there were some studies that observed no consistent trend (O'Dogherty et al. 1995). The survey also revealed that there is no detailed comparison between the mechanical properties of solid and hollow stem varieties of the wheat. Models fitted to compression and relaxation data showed varying degree of applicability and limitations to biomass compaction and relaxation data.

CHAPTER THREE

MATERIALS AND METHODS

The experimental methodology is divided into five sections. The first section comprised of sample procurement and preparation. The second and third section involved the methodology used in carrying out the physical properties test (moisture content, diameter) as well as mechanical properties test (coefficient of internal friction, cutting, shearing, bending, compressive, and tensile strength) while the fourth and fifth section consisted of statistical analysis and modelling respectively.

3.1 Sample procurement and preparation

3.1.1 Sample procurement

The twelve varieties of wheat stem used for this study were provided by Semi-arid Prairie Agricultural Research Centre of Agriculture (SPARC), Agri-Food Canada in Swift Current, SK (grown within the research centre at 50º17' N, 107º45'W). RAW AgVentures (Maymont, SK) provided wheat straw bales for pretrial use in compression and relaxation test. Collected at harvest time, the stem samples were stored at 30% relative humidity and 4^{o}C to maintain the harvest conditions (Figure 3.1). Details of these wheat varieties are presented in Table 3.1 which comprised of only three solid stem varieties (BW807, Lillian, and DT818) with the remaining as conventional hollow stem varieties.

3.1.2 Sample preparation

Except for samples used in tensile test which was cut to 80 mm length, the rest of the sample were cut to 50 mm length from each variety and internode were prepared for individual mechanical tests (Figure 3.2). These samples were stored in controlled climate condition (4^{o}C and 30% relative humidity (RH) for a minimum of 72 h) after preparation for further tests (Figure 3.3).

Table 3.1 Wheat varieties used in the tests with brief botanical and physical information collected in cropping year 2012 and 2013.

No.	Variety	Species	Stem sample collected	Solid
1	BW807*	*Triticum aestivum L.*	F17 (irrigated), Swift Current	YES
2	DT818*	*Triticum turgidum L. var. durum*	F17 (irrigated), Swift Current	YES
3	Lillian*	*Triticum aestivum L.*	F17 (irrigated), Swift Current	YES
4	Blackbird	*Triticum carthlicum*	F17 (irrigated), Swift Current	NO
5	Carberry	*Triticum aestivum L.*	F17 (irrigated), Swift Current	NO
6	Commander	*Triticum turgidum L. var. durum*	F17 (irrigated), Swift Current	NO (but thicker stem)
7	DT833	*Triticum turgidum L. var. durum*	F17 (irrigated), Swift Current	NO
8	HY1319	*Triticum aestivum L.*	F17 (irrigated), Swift Current	NO
9	Shaw	*Triticum aestivum L.*	F17 (irrigated), Swift Current	NO
10	Strongfield	*Triticum turgidum L. var. durum*	F17 (irrigated), Swift Current	NO
11	Transcend	*Triticum turgidum L. var. durum*	F17 (irrigated), Swift Current	NO
12	Unity	*Triticum aestivum L.*	F17 (irrigated), Swift Current	NO

Figure 3.1 Storage of wheat stem samples collected during harvest at Semi-arid Prairie Agricultural Research Centre of Agriculture (SPARC), Agriculture and Agri-Food Canada, Swift Current, SK.

Figure 3.2 Sample preparation showing cut samples for further moisture adjustment and subsequent testing.

Figure 3.3 Samples were placed inside glass vials with cap and stored in a controlled climatic storage (4^{o}C temperature and 30% relative humidity).

3.2 Moisture content

Moisture content is one of the physical properties considered when studying the mechanical properties of stems. The initial moisture content (% wb) of the wheat stems were determined by oven-drying 3 g samples at 103°C for 24 h according to ASABE standard S358.2 (ASABE, 2006). Reweighing was carried out using a precision balance (0.001 g) (Denver Instruments, Sartorious Corp. Bohemia, NY). To achieve the desired moisture content (14, 18, and 22% wb), samples were kept in an environmental chamber (Model SH-841, Espec Corp, Kita-ku, Osaka, Japan) for 72 h at 25˚C and corresponding relative humidity (Figure 3.4). Using the sorption isotherm for wheat straw reported by Duggal and Muir (1981), relative humidity of 78, 83, and 95%, respectively, gave the corresponding desired moisture content of 14, 18, and 22% wb, respectively.

Figure 3.4 Espec environmental chamber used for moisture adjustment of sample before testing.

The equation (3.1) used to determine the moisture content at storage and after conditioning of each samples is shown below:

$$M_w = \frac{m_i - m_f}{m_i} \tag{3.1}$$

where;

M_w = Moisture content of the sample (decimal value)

m_i = Initial mass of the sample (g)

m_f = Final mass of the sample (g)

(Tavakoli et al. 2009b; Alireza et al. 2012)

3.3 Mechanical properties

An understanding of mechanical properties of wheat stem provides vital information that can aid in the selection of design and operational parameters of equipment involving harvesting of grains and post-harvest handling and storage of the straw (Tavakoli et al. 2008). With this in mind, the following methods were used to determine these mechanical properties, namely, shearing strength and energy, cutting strength and energy, bending strength and modulus of elasticity, coefficient of internal friction, tensile strength, and compressive properties.

3.3.1 Shearing test

The shearing strength and shearing energy of the wheat stem samples were determined using a shear tool similar to those used by Chandio et al. (2013), Hematian et al. (2013), Shahbazi et al. (2011), and Zareiforoush et al. (2010) as shown in Fig 3.5. The shear tool comprised of a middle plate that slide freely between two fixed plates. Due to the varying diameters of the wheat stem samples (Tavakoli et al. 2008), eight (8) holes of different diameters ranging from 2.5 to 5 mm were drilled perpendicular to the sliding direction. The shear tool was mounted on a tension/compression testing machine (INSTRON 3366, Instron Corp., Norwood, MA). Shear force was applied at a loading rate of 300 mm min^{-1}.

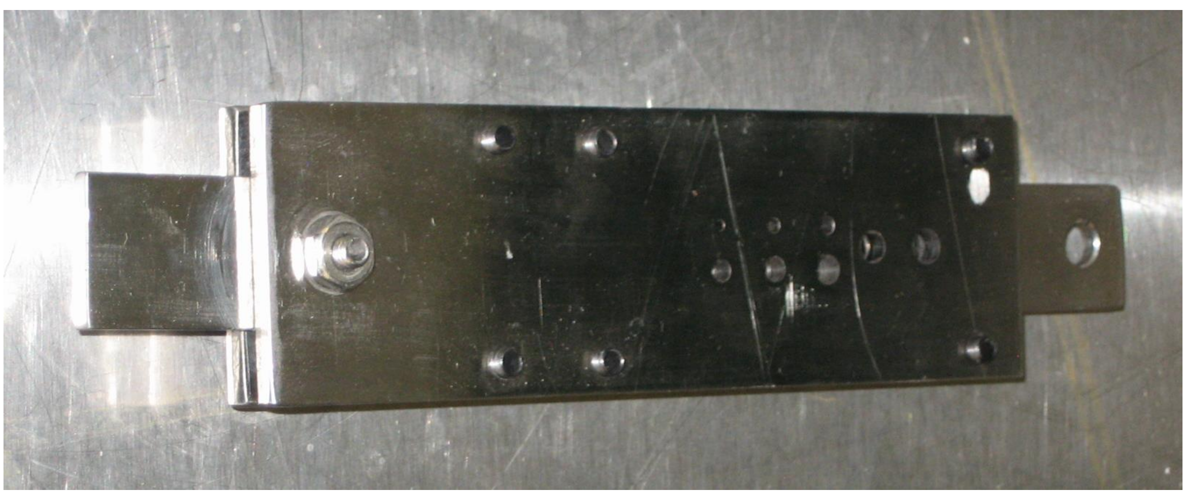


Figure 3.5 Shear tool used for shearing tests with sliding plate in the middle.

The shearing energy (mJ) of the stems was computed by integrating the area under the force– displacement curve plotted during the shear test (Shahbazi et al. 2011; Hematian et al. 2013) while shearing strength was computed using equation 3.2 below:

$$\tau_S = \frac{F_S}{2A_s} \tag{3.2}$$

where

τ_S = Shear strength (MPa)

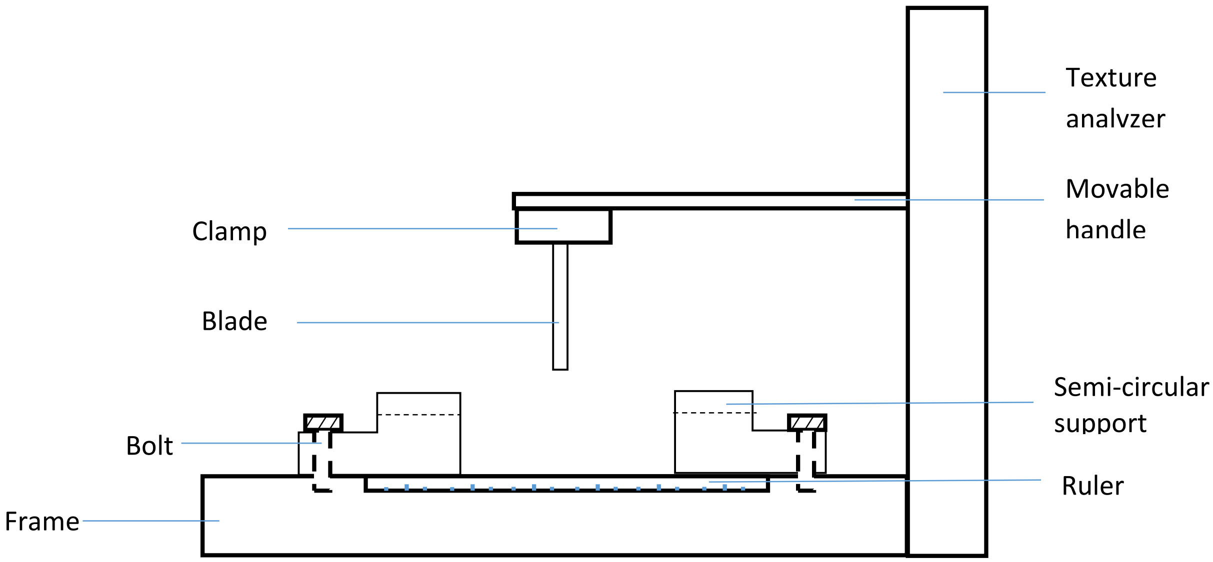
F_s = Shear force at failure (N)

A_s = Cross-section area of the stem at the shearing plane (mm^2).

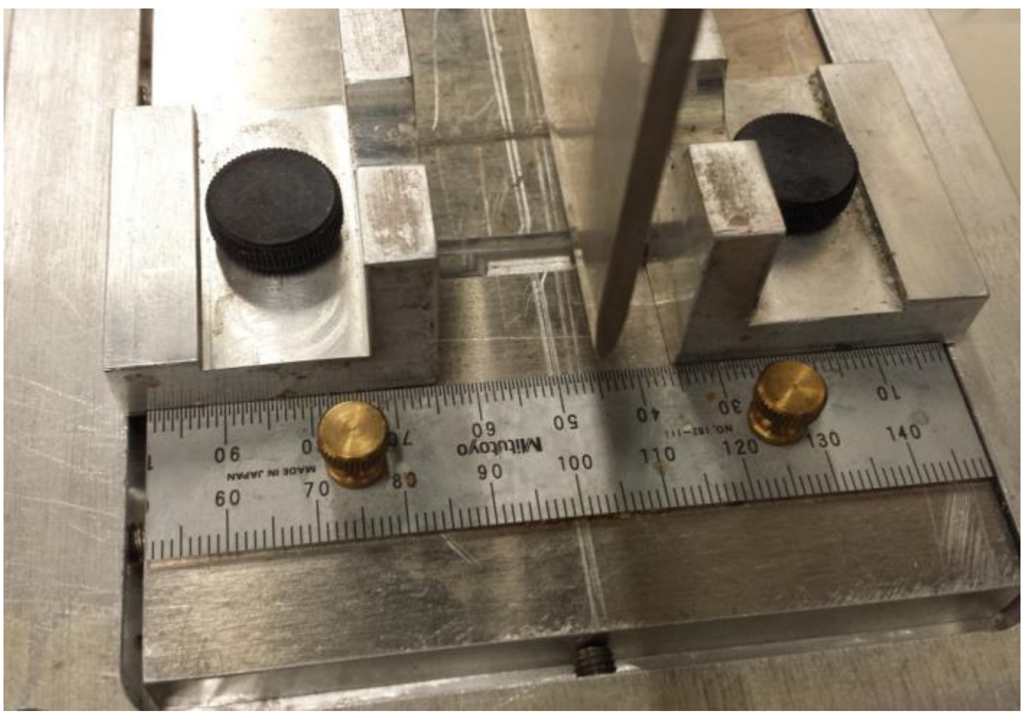
(Esehaghbeygi et al. 2009; Hoseinzadeh et al. 2009; Tavakoli et al. 2009b; Zareiforoush et al. 2010; Shahbazi et al. 2011; Hematian et al. 2013).

3.3.2 Bending test

The bending strength and modulus of elasticity of wheat stem were determined using a three point linkage bending apparatus similar to those described by Tavakoli et al. (2009a) and Zareiforoush et al. (2010). It comprised of two semi-circular supports placed 30 mm apart and rectangular blade of 2.5 mm radius of curvature attached to the Texture Analyzer (TAXT2, Texture Technologies Corp. Hamilton, MA). The supports are placed such that the rectangular blade is located half way their distance apart (Figure 3.6). To carry out the test, 50 mm specimen was placed horizontally on two semi-circular supports. Force was applied at the center of the specimen with the rectangular blade at a loading rate of 120 mm min^{-1}.



(a) Schematic diagram of the 3-point bending test tool. (Not to scale).



(b) Photograph of the three point bending test tool setup.

Figure 3.6 Three point test tool mounted on the texture analyzer for carrying out bending test.

The equations used by O' Dogherty et al. (1995), Tavakoli et al. (2009a), and Mostafavand and Kamgar (2010) were used to determine the maximum bending strength (equation 3.3a) and modulus of elasticity (equation 3.3b):

$$\sigma_b = \frac{F_b r_a l}{4I_b} \tag{3.3a}$$

$$E = \frac{F_b l^3}{48\delta I_b} \tag{3.3b}$$

where

σ_b = Bending strength (MPa)

E = Modulus of elasticity of the stem specimen (GPa)

δ = Deflection at the specimen centre (mm)

F_b = Bending force (N)

l = Distance between the two metal supports (mm)

r_a = Axis of the cross section (outer radius) (mm)

I_b = Second moment of the area (mm^4)

The calculation of second moment of area for the solid (equation 3.4a) and hollow (equation 3.4b) stem samples was carried out as follows (Shrivastava et al. 1994):

$$I_b = \frac{\pi}{64}(D_f^{\ 4}) \qquad \text{Circular solid stem} \tag{3.4a}$$

$$I_b = \frac{3\pi}{32}(D_f^{\ 3}t) \qquad \text{Circular hollow stem} \tag{3.4b}$$

where**:**

D_f = Fiber diameter (mm) = $2R_f$

R_f = Radius from neutral axis of stem to the most distant load carrying fiber (mm)

t= Stem thickness (mm)

3.3.3 Cutting test

A knife device, cutting support, and frame similar to that used by Sarauskis et al. (2013) were used to determine cutting strength and energy. Emery papers were glued on the cutting support to avoid slippage during cutting (Figure 3.7). Stem specimen of length 50 mm was placed on the cutting support perpendicular to the direction of cutting and held firmly on both ends of the support to avoid stem movement. Cutting force was applied at 60^o angle by a cutting knife fixed to the upper frame of the INSTRON 3366 universal testing machine. The crosshead speed was set at 500 mm min^{-1}.

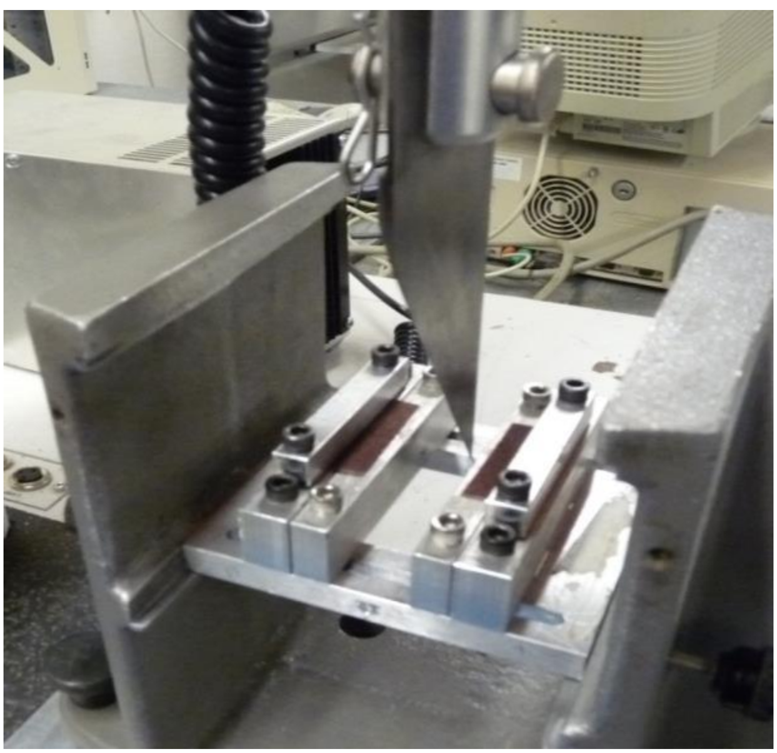


Figure 3.7 Cutting tool mounted on the Instron universal tester used for carrying out cutting test.

The cutting energy (mJ) was determined by integrating the force–displacement curve plotted during the cutting test while equation 3.5 was used to determine the cutting strength of the specimen:

$$\sigma_c = \frac{F_c}{A} \qquad (3.5)$$

where**:**

σ_c = Cutting strength of the specimen (MPa)

F_c = Maximum cutting force (N)

A = Cross-section area of the specimen at the point of failure (mm^2)

3.3.4 Tensile test

Hydraulic clamps mounted on the universal testing machine (INSTRON 3366, Instron Corp., Norwood, MA) was employed in carrying out the tensile test (Figure 3.8). Sample length of 80 mm (50 mm gauge length) was placed vertically and held in position with the aid of the clamps. To avoid slippage and failure of the specimen at the clamps sections during testing as reported by O'Dogherty et al. (1989), Galedar et al. (2009), and Kronbergs et al. (2000), 15 mm length steel rods equal to the internal (hollow stem) and an external diameter (solid stem) were inserted into both ends, respectively. Emery papers were also glued to the rubber placed on the clamps to avoid slippage. The test was carried out using a load cell of 1 kN on the Instron universal testing machine. Loading rate was set at 10 mm min^{-1} and readings of force-displacement were recorded until failure.

Figure 3.8 Hydraulic steel clamp with rubber fittings and emery paper glued for conducting tensile test.

The tensile strength was computed using the equation 3.6:

$$\sigma_t = \frac{F_t}{A} \tag{3.6}$$

where**:**

σ_t = Tensile strength of the specimen (MPa)

F_t = Maximum tension force (N)

A = Cross-section area of the specimen at the point of failure (mm^2)

3.3.5 Imaging of wheat stems

To avoid over- or underestimating the strength during computation of each mechanical properties studied (Srivastava et al. 1994), stem imaging of the transverse section of the stem was carried out using Wild Herbrugg stereoscope with magnification; 8x (Wild M3Z, Wild Heerburgg, Gais, Switzerland), Paxcam3 camera (Midwest Information Systems, Villa Park, IL) and Intralux 500 light source (Figure 3.9). To determine the inner and outer radius of the stems, the PAXcam Digital Imagine Software (PAX-it!, Version #7.8.1.1, Midwest Information Systems, Villa Park, IL) was employed.

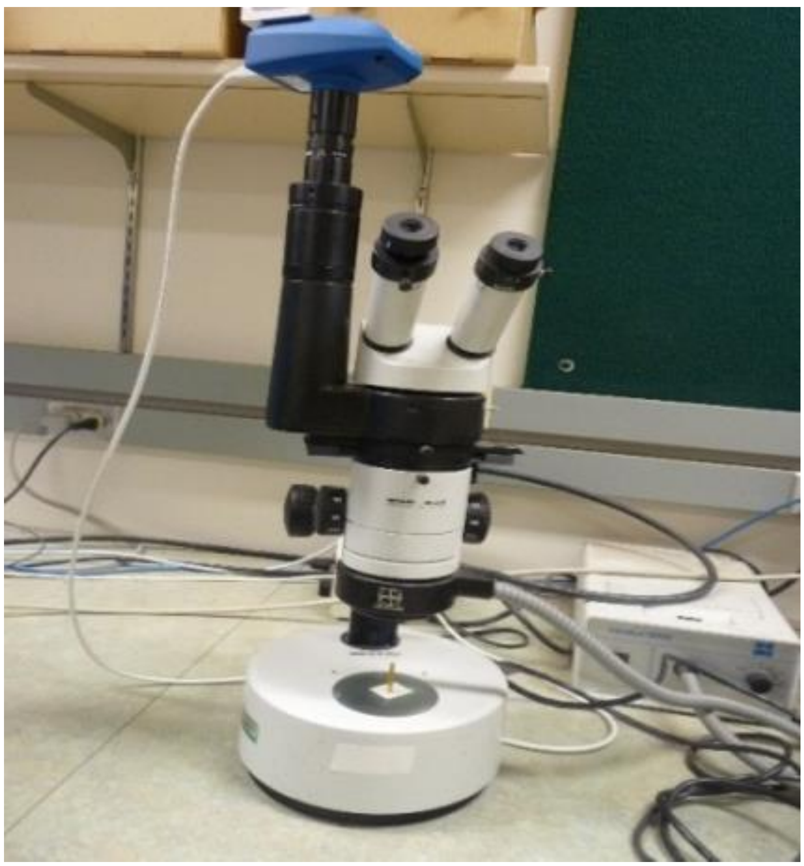


Figure 3.9 Wheat stem sample mounted on the Wild Herbrugg stereoscope during determination of stem diameter.

For each stem sample, six measurements of the inner and six outer diameters were taken. The outer diameter measurements were taken between fiber's centers as shown in Figure 3.10.

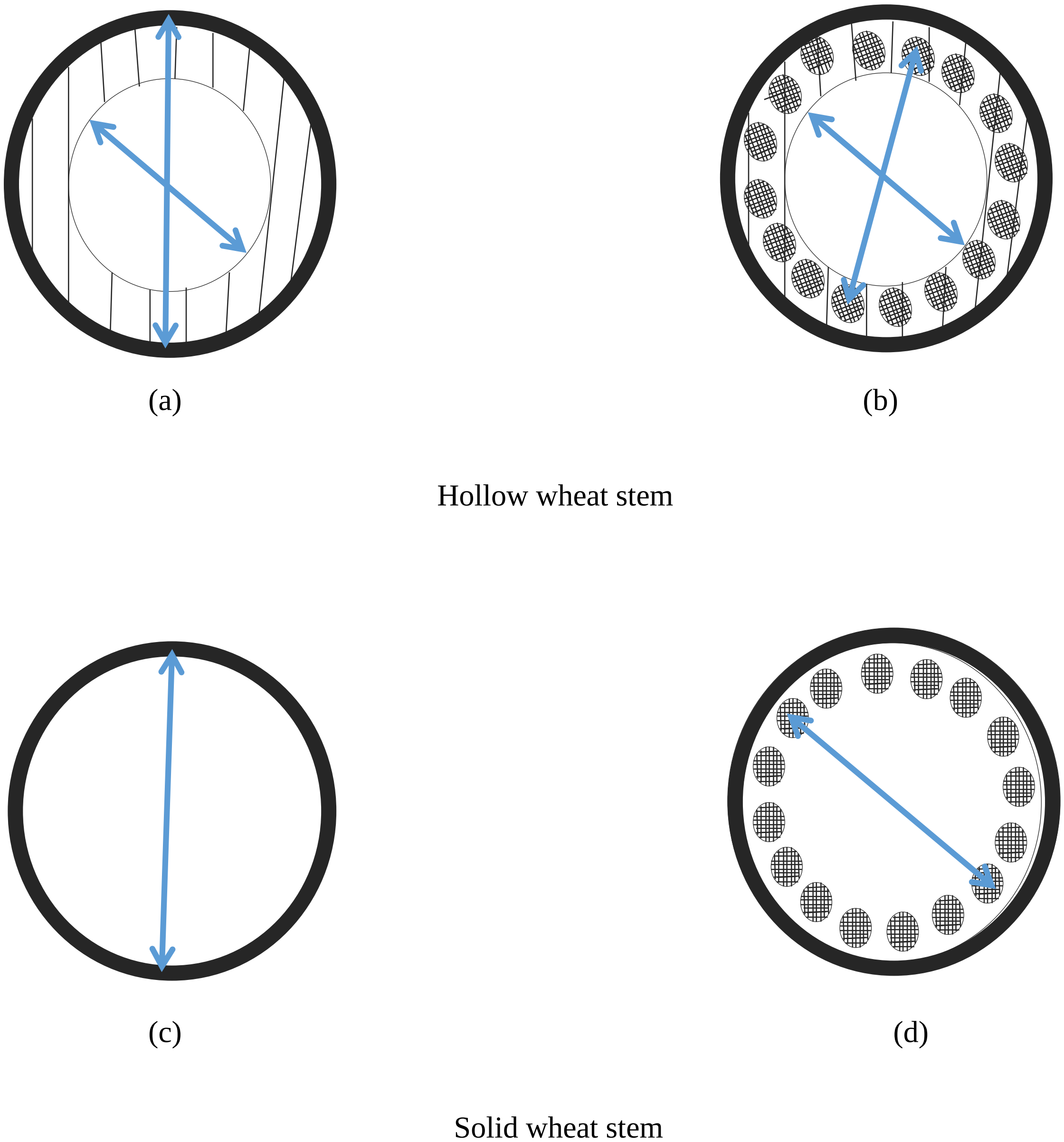


Figure 3.10 Stem imaging of hollow and solid wheat stem showing the distribution of fiber at the circumference of the stem (a and c) and within the stem (b and d) and indicating points for measuring the inner and outer diameters.

3.3.6 Determination of coefficient of internal friction

The coefficient of internal friction of the wheat straw samples was determined using a shear box apparatus in the laboratory similar to that used by Afzalinia and Roberge (2007). It comprised of a box for putting the test samples, different sizes of gears for adjusting the operating speed as well as horizontal and vertical load (Figure 3.11).

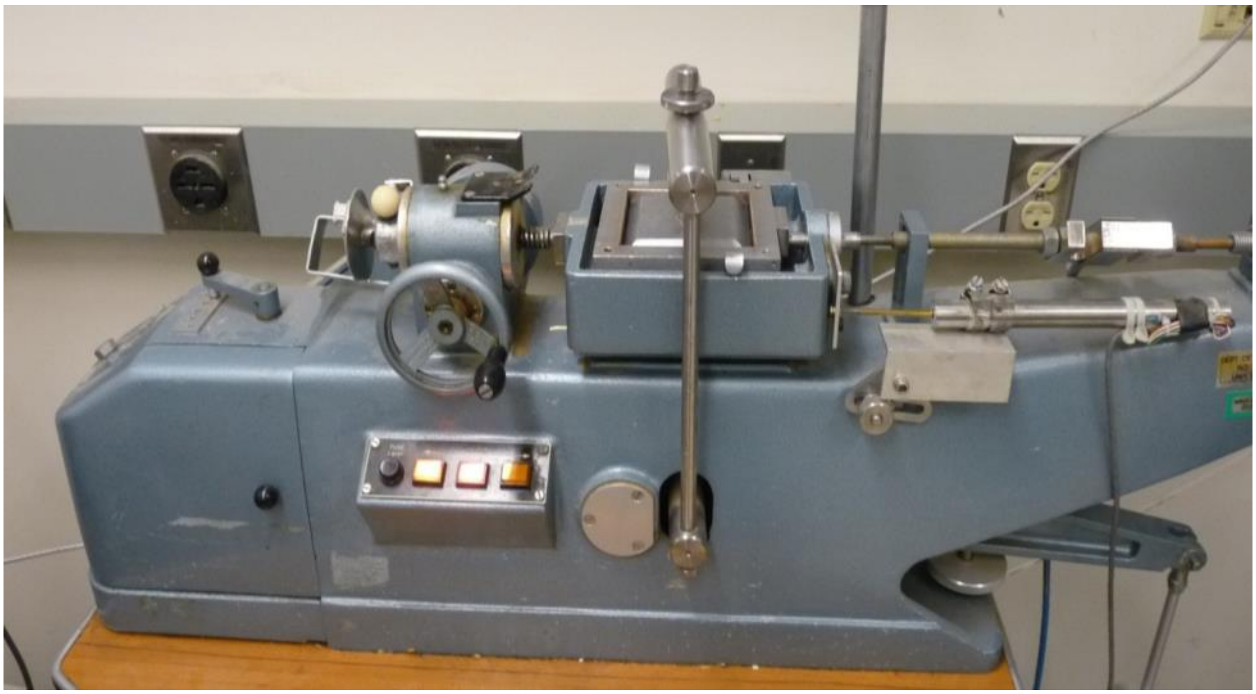


Figure 3.11 Shear box apparatus used for carrying out coefficient of internal friction test.

To perform the test, straw samples of 40 mm cut length were used. 25 to 40 g of each sample was measured, poured into the sample box, and covered. Normal force of 200, 600, and 1000 N, respectively, acted on each specimen at a shearing rate of 0.4 mm min^{-1}. Readings of horizontal force (shear force) and horizontal displacement were recorded on the computer connected to the shear box apparatus until when the readings reached a steady value. Graph of shear force (peak value) against normal force was plotted and the slope (μ, coefficient of internal friction) was determined based on equation 3.7:

$$\tau = C_o + \mu\sigma_n \tag{3.7}$$

where:

τ = Effective shear stress (kPa),

C_o = Cohesion (kPa),

μ = Coefficient of internal friction (decimal)

σ_n = Effective normal stress (kPa).

3.3.7 Compression test

To determine the compression properties of each variety of wheat straw, a similar fabricated metal cylindrical and plunger used by Sabbah and Gomaa (2008) was adopted with diameter and height of approximately 75 and 160 mm, respectively (Figure 3.12). The test was carried out at moisture content and compression load of 14% and 66.3 kN, respectively, with no replicate (as the samples were limited). The corresponding compression pressure was 15.7 MPa. This is the maximum pressure at which baling of biomass takes place (Tabil et al 2006; Talebi et al. 2011). The test sample of each variety was cut to length of 50 mm across the nodes. Thirty to 50 g was weighed using precision balance (accuracy of 0.01 g). Pressure was then applied on the specimen in the container through the plunger attached to the universal testing machine (INSTRON 600 DX, Groove City, PA) at a rate of 50 mm min^{-1} until the desired force (pressure) was attained. The position was held for 60 s and then released to check for any relaxation (pressure change with time) of the specimen. Force-time data during the entire compression test was recorded on the computer connected to the Instron machine. Compression models (equations 3.8 and 3.9) were used to analyze the compression behavior of the wheat straw to determine their applicability to the test data (Talebi et al. 2011).

Fig. 3.12 Cylinder and plunger mounted on the INSTRON 600 DX for compression testing.

The Power model (equation 3.8) was fitted to the compression data:

$$P = B_2(\rho^{B_1}) \tag{3.8}$$

The Pitt and Gebremedhin model (equation 3.9) was also fitted into the compression data:

$$P = h[e^{f(\beta-\beta_o)} - 1] \tag{3.9}$$

where:

P= Applied pressure (MPa)

ρ= Compact bulk density (kg/m^3)

β = Dry matter density (kg/m^3)

β_0 = Compact dry matter density (kg/m^3)

B_1, B_2, f, h = Constants

A typical pressure-time curve showing the stages (compression and relaxation) encountered during straw compression is shown in Figure 3.13. During the compression stage, pressure increases exponentially with time while the reverse (decay) is experienced during the relaxation stage.

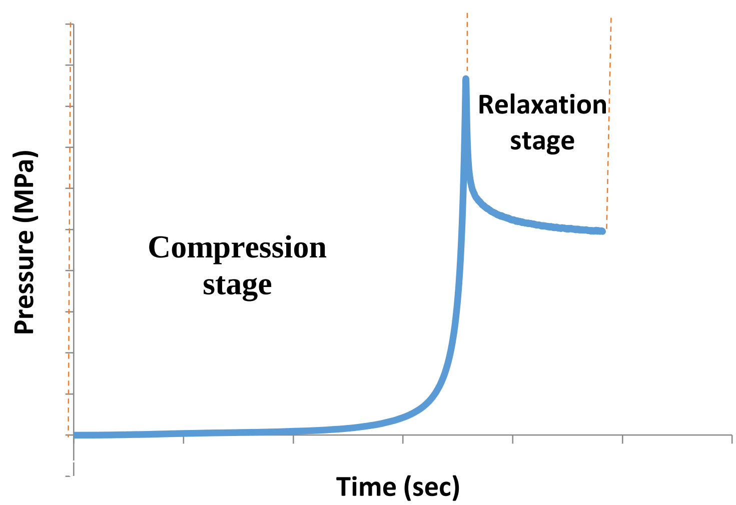


Fig. 3.13 Typical graph of pressure against time showing the compression and relaxation stages during compression test (redrawn from Talebi et al. 2011).

Relaxation (stress relaxation) is the rate of pressure drop with time at constant strain. It is an indication of physical changes experience at constant strain and helps determine the un-relaxed stress sustained by the material or asymptotic modulus (Shaw and Tabil, 2007). Peleg and Moreyra model (equation 3.10) was fitted into the regression data derived during the wheat straw compression test to determine its applicability to the test data (Talebi et al. 2011).

$$\frac{F_o.t}{F_o - F(t)} = k_3 + k_4.t \qquad (3.10)$$

where:

F_O = Initial relaxation force (kN)

F(t) = Relaxation force at time t (kN)

t = Time (s)

k_3, k_4, = Constants

The asymptotic modulus, E_A (MPa) and percentage average relaxation, R_{ap} (%) of each variety was computed using equations 3.11 and 3.12 respectively;

$$E_A = \frac{F_O}{A_a \varepsilon}\left(1 - \frac{1}{k_4}\right) \qquad (3.11)$$

$$R_{ap} = \frac{100 \times (F_O - F_e)}{F_O} \qquad (3.12)$$

where:

A_a = Cross sectional area of cylinder (m^2)

Ɛ = Strain

A tabular summary of the mechanical test carried out as well as equipment and other parameters are shown in Table 3.2.

Table 3.2 Test parameters for the mechanical properties measurement of wheat stem.

Dependent Variables	Independent Variables	Loading Rate (mm min^{-1})	Equipment	Number of replicate	Load cell (N)	Sample Length (mm)
Shearing Strength, and Shearing Energy	14 , 20, 22 N1, N2, N3 Solid, Hollow	300	INSTRON 3366, shear tool	5	1000	50
Cutting Strength, and Cutting Energy	14 , 20, 22 N1, N2, N3 Solid, Hollow	500	INSTRON 3366, knife and support	14	1000	50
Coefficient of Internal Friction	14 , 20, 22 N1, N2, N3 Solid, Hollow	0.4	Shear box apparatus	1	200, 600, 1000	40
Bending Strength, and Modulus of elasticity	14 , 20, 22 N1, N2, N3 Solid, Hollow	120	Texture Analyser, 3 point tool	5	500	50(30)
Tensile Strength	14 , 20, 22 N1, N2, N3 Solid, Hollow	10	INSTRON 3366, rubber clamp, and tiny rod	5	5000	80(50)
Compaction Test	14 Solid, Hollow	50	INSTRON 600 DX, cylinder, and plunger	1	150,000	50

- Figures in parenthesis are guage length.

The number of replicates (sample size) was computed using the following equation reported by Patil et al. (1996):

$$N = \frac{(t_1 v)^2}{B^2} \tag{3.13}$$

Where:

N = Number of replicates (sample size)

t_1 = Value of student's t for two sided limit at 95% probability level and infinite degrees of freedom, 1.96 (for population)

ν = Estimate of coefficient of variation, CV

B = 15% of average, the value of allowable variation.

3.4 Statistical analysis

The experimental data generated during the tests were analyzed using the analysis of variance (ANOVA) to determine the individual and interactive effect of the independent variables (physical properties: moisture content, internode position, and stem type) on the dependent variables (mechanical properties: coefficient of internal friction, shearing, cutting, bending, tensile, and compression). The test was carried out at a 5% significance level. Comparison of means was done using Duncan's multiple range tests in SPSS software (IBM SPSS Statistics 21, IBM Corporation, Armonk, NY).

3.5 Modeling

Mechanical properties of biological material are dependent on their physical properties. This characteristics is mostly presented as equations that can be in the form of linear, power, exponential, quadratic or other polynomial form for easy comparison.

Linear equation uses straight line (line of best fit) to show the relation between the dependent (Y) and independent variable (x). It is either a simple linear equation where there is only one independent variable (Y= bx + C) or multiple linear equation that have several independent variables, x1, x2… xn. Where 'n' indicates the number of independent variables (eg: Y = ax1 + bx2 + C) (Simkiss et al. 2015). A polynomial equation has a single variable of degree n where 'n' is greater or equals to 2. (e.g; $Y= x^2 + bx + C$). When the relationship between the dependent is a function of a constant number (n > 1) raise to the powers of the independent variables, such equation is called a power equation ($Y=n^x$, n=constant). An exponential equation is derived when the dependent variable (Y) increased by the multiple of a constant number (n > 1) for every increase in the independent variable. It is usually of the form $Y=e^x$ (Sheldon 2012)

Some models developed by previous researchers (Tavakoli et al. 2009; Galedar et al. 2009; Esehegbeyi et al. 2009; Hoseinzadeh et al. 2005; Kushwaha et al. 1983) relating each mechanical property as a function of moisture content are presented in Table 3.3.

Table 3.3 Models relating different mechanical properties as a function of moisture content.

References	**Materials**	**Mechanical test**	**Models**	**R^2 value**
Kushwaha et al. 1983	Wheat straw	Shearing strength	$Y = e^{(1.444 + 0.094MC)}$	0.941
Hoseinzadeh et al. 2005	Wheat stem	Shearing Energy	$Y = 0.9+0.29\cos(0.07MC+2.11)$	0.990
Tavakoli et al. 2009	Wheat straw	Bending strength	$Y = 19.21e^{-0.03MC}$	0.930
Esehegbeyi et al. 2009	Wheat stem	Modulus of elasticity	$Y=2.50 + 2.10\cos 0.01MC + 0.42$	0.960
Galedar et al. 2009	Alfafa stem	Tensile strength	$Y = 46.031e^{-0.006MC}$	0.983

- "Y" and "MC" represent mechanical property and moisture content (% wb), respectively.
- Reference internode: third (3rd) internode.

The models (Table 3.3) indicated that the relationship between shearing, bending, and tensile strength is exponential (Kushwaha et al. 1983; Tavakoli et al. 2009; Galedar et al. 2009) while the shearing energy and modulus of elasticity is trigonometric (Esehegbeyi et al. 2009; Hoseinzadeh et al. 2005). With this in mind, models were developed fitting each dependent mechanical property (coefficient of internal friction, shearing strength and energy, cutting strength and energy, bending strength, modulus of elasticity, and tensile strength) as a function of the physical property (moisture content, internode position, and stem type) using regression analysis.

CHAPTER FOUR

RESULTS AND DISCUSSION

Results from the experimentation outlined in chapter three (3) are presented in this chapter. Analysis of wheat stem physical property alongside their mechanical properties was carried out. Comparison of the present results with the published results from previous researchers was done. The applicability of compression and relaxation models fitted to wheat straw compression data was determined. Models were developed relating each mechanical test (shearing strength and energy, cutting strength and energy, tensile strength, bending and modulus of elasticity, and coefficient of internal friction) with moisture content.

4.1 Physical properties

Results of the physical properties of the 12 varieties of wheat stem investigated are presented in this section. The physical properties include moisture content and diameters (cross-sectional area).

4.1.1 Moisture content

The moisture content of the twelve varieties of wheat stems during initial storage is presented in Table 4.1. The mean moisture content was determined as 10.5% wb (0.62) which indicated the need to add moisture to achieve the desired moisture content (14, 18, and 22% wb). Samples conditioned to 22% wb moisture were noted to have mold growth on them. This may be due to their high moisture content. Samples set to attain 14 and 18% wb moisture content did not have mold growth.

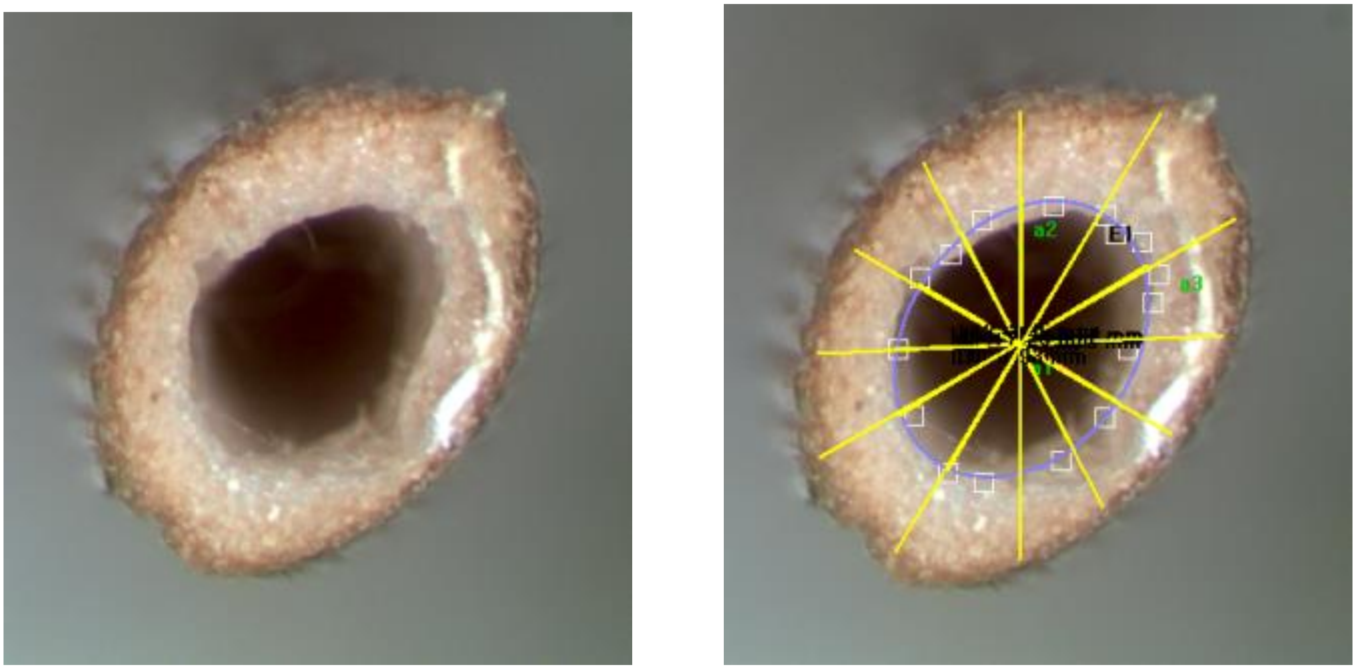
Table 4.1 Initial moisture content (MC) of 12 different varieties of wheat stem at storage, N=1.

Variety	Initial moisture content (% wb)
BW807*	10.3
DT818*	11.4
Lillian*	11.5
Blackbird	9.7
Carberry	11.1
Commander	10.3
DT833	10.5
HY1319	10.9
Shaw	9.5
Strongfield	10.4
Transcend	10.0
Unity	10.0

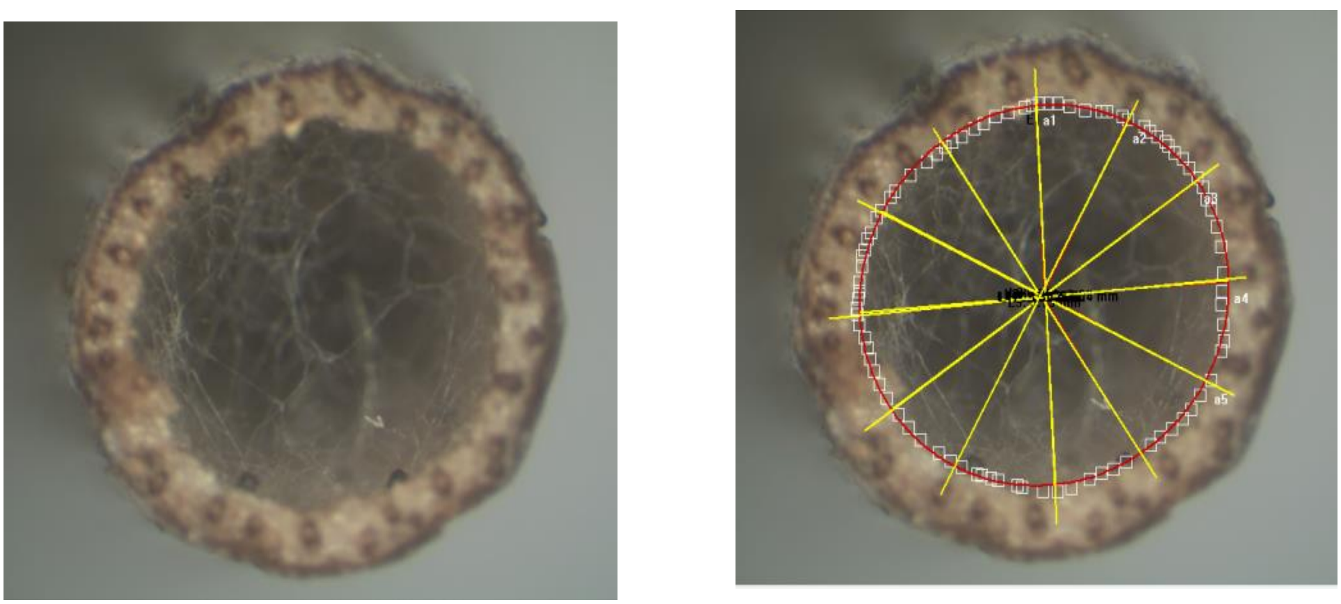
- Solid stem varieties are indicated with *

4.1.2 Stem imaging

The different orientations of fibers obtained during stem imaging of the different varieties of wheat under study are shown in Figs. 4.1 and 4.2. Hollow stem varieties ‘Shaw’, ‘HY1319’, ‘Unity’, and ‘Carberry’, and solid stem varieties ‘Lilian’ and ‘BW807’ had their fibers located on the circumference of the stem (Fig. 4.1a and 4.2a) while hollow stem varieties ‘Commander’, ‘Strongfield’, ‘Transcend’, ‘Blackbird’, and ‘DT833’, and solid stem variety ‘DT818’ had their fibers within the stem (Fig. 4.1b and 4.2b). ‘Lilian’ and ‘BW807’ (solid stem) were noted to have some hollow stem samples but this was not the case with ‘DT818’ variety (solid stem).

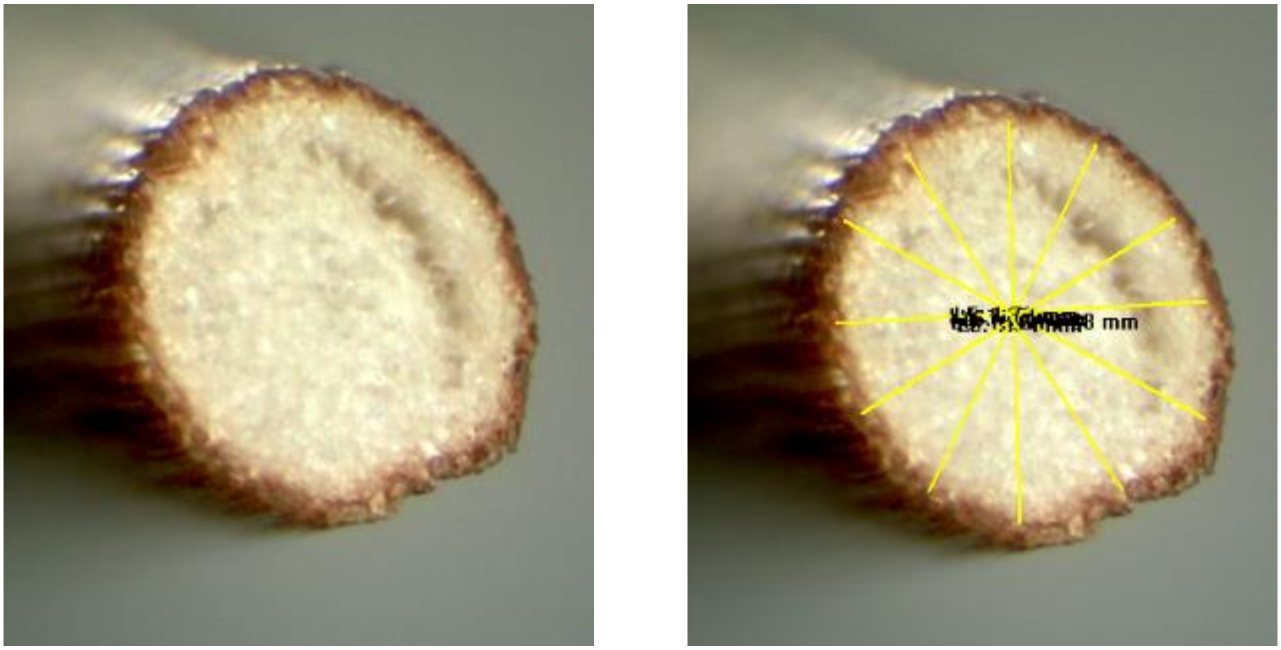


(a) Distribution of fiber at the circumference of the hollow stem during diameter measurement.

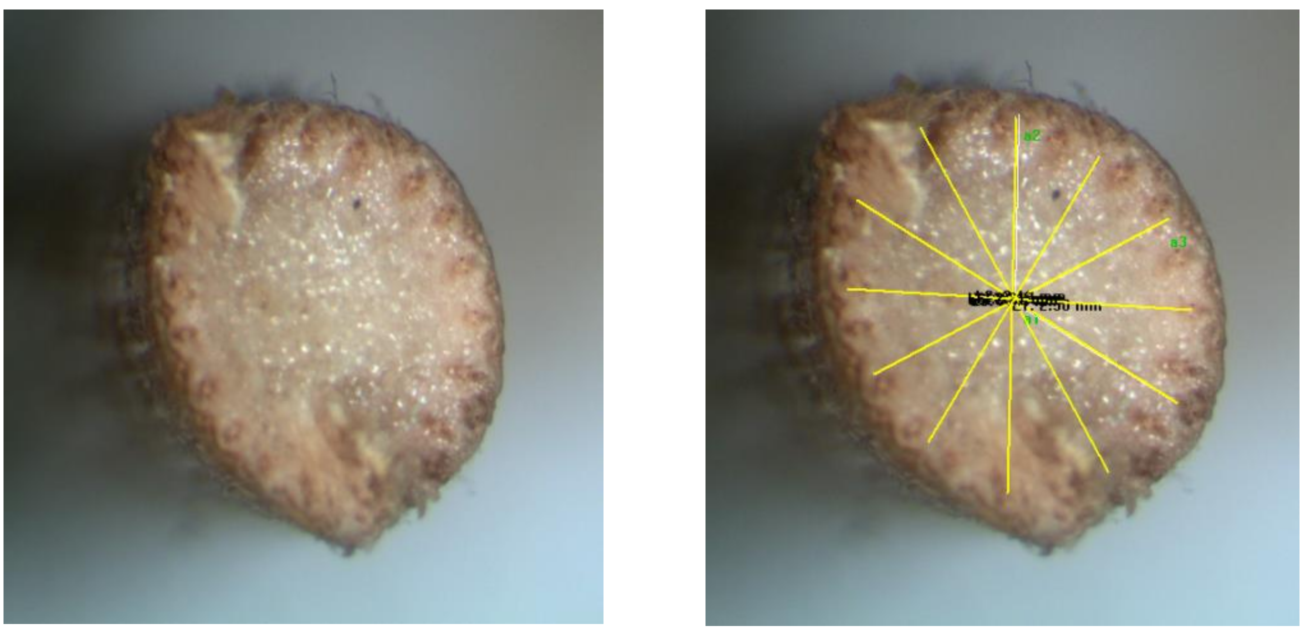


(b) Distribution of fiber within the hollow stem during diameter measurement.

Fig. 4.1 Stem imaging of the transverse section of hollow stem varieties revealing the different orientations of the fiber and measurement of the inner and outer diameters (Dark marks on the yellow lines are auto-dimensions indicated by the PAX-it! software).



(a) Distribution of fiber at the circumference of the solid stem during diameter measurement.



(b) Distribution of fiber within the solid stem during diameter measurement.

Fig.4.2 Stem imaging of the transverse section of solid stem varieties revealing the different orientations of the fiber and measurement of the outer diameters (Dark marks on the yellow lines are auto-dimensions indicated by the PAX-it! software).

4.1.3 Stem area

The wheat stems used during tensile strength test was used as reference for analyzing the stem area. Table 4.2 shows the mean area of the 12 varieties of wheat. Although there was significant effect of moisture content on the stem area, there was no consistent trend across the moisture (14 -18% wb). For example, at first internode, the stem area of ‘Commander’ increased from 14 to 22% (wb) while the stem area of ‘Carberry’ increased from 14 to 18% (wb) and decreased from 18 to 22% (wb) (see Fig. 4.3).

Inconsistent trend was also observed across the internode (first to third). The stem area of varieties namely; ‘Commander’, ‘Transcend’, ‘HY1319’, ‘Shaw’, ‘Carberry’, ‘Blackbird’, ‘DT833’, and ‘DT818’ increased from the first to third internode across all moisture content while varieties ‘Strongfield’, ‘Lilian’, ‘BW807’, and ‘Unity’ experienced an initial increased area from first to second internode but decreased area from the second to third internode (Table 4.2).

The wheat varieties have significant effect on the area of the stem. Each variety had different area in comparison to other varieties which can be accounted for by difference in composition and stem morphology across the wheat varieties (Fig 4.3). Varieties with solid stem had larger area than varieties with hollow stem. For example, at 18% wb, the area of the second internode of ‘BW807’, a solid stem variety was 6.52 mm^2 while the stem area of ‘Shaw’, a hollow stem variety was 2.82 mm^2 at the same moisture content and internode (Fig 4.4).

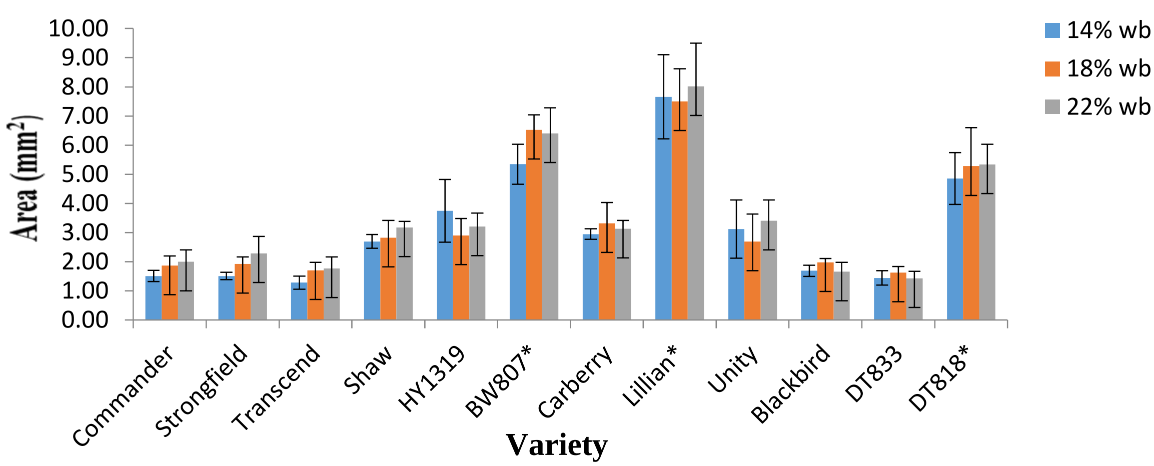


Fig. 4.3 The mean area of the 12 varieties of wheat stem at first internode (Solid stem varieties are indicated with *).

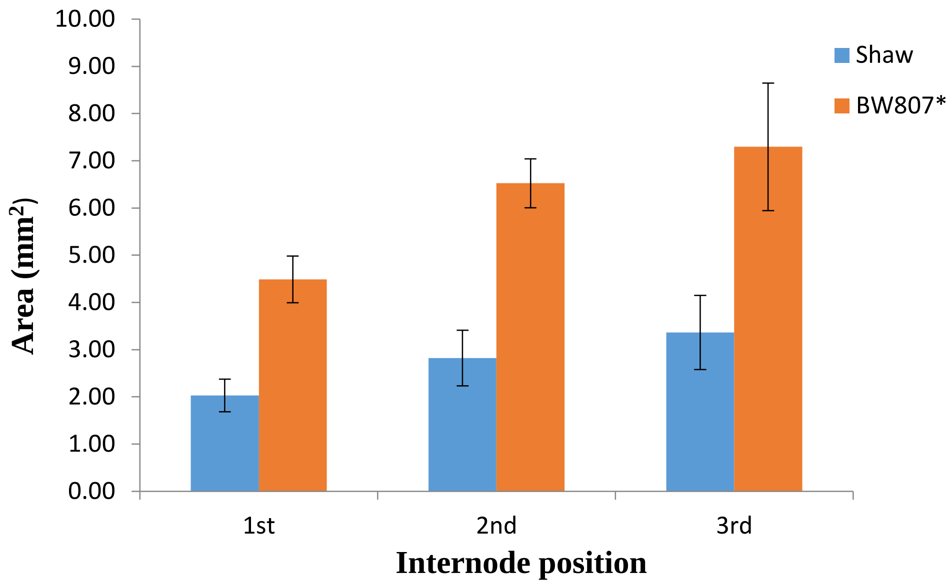


Fig. 4.4 Graph comparing stem areas of 'Shaw' and 'BW807' at different internode with 18% (wb) moisture content.

Analysis of the coefficient of variation across the stem length for each moisture content investigated revealed that aside from "Strongfield" that has less variability, the area of most varieties ("Commander", "Transcend", "Shaw", "HY1319", "BW807", "Carberry", "Lilian", and "Unity") varied across the stem length from the first to the third internode. "HY1319", "DT833", and "DT818" had the highest variation. The high disparity indicates that the area of the stem varies across the stem length from the first to the third internode (Table 4.3).

Table 4.2. Area (mm^2) of 12 different varieties of wheat stem at 3 moisture contents (MC) and 3 internode positions; N = 5.

Variety	Node	MC= 14%	MC= 18%	MC= 22%
BW807*	first	$6.27(4.2)^{fNz}$	$4.48(0.5)^{fMNx}$	$4.03(0.3)^{fMx}$
	second	$5.34(0.7)^{fMx}$	$6.52(0.5)^{fMNy}$	$6.40(0.9)^{fNy}$
	third	$6.09(0.9)^{fMy}$	$7.30(1.4)^{fMNz}$	$6.54(0.4)^{fNz}$
DT818*	first	$3.05(0.2)^{eMx}$	$2.93(0.3)^{eMNx}$	$3.48(1.0)^{eNx}$
	second	$4.85(0.9)^{eMy}$	$5.28(1.3)^{eMNy}$	$5.34(0.7)^{eNy}$
	third	$5.90(1.1)^{eMz}$	$5.84(0.9)^{eMNz}$	$7.28(0.9)^{eNz}$
Lillian*	first	$4.62(0.7)^{gMx}$	$4.38(0.5)^{gMNx}$	$4.95(0.6)^{gNx}$
	second	$7.66(1.4)^{gMz}$	$7.50(1.1)^{gMNy}$	$8.02(1.5)^{gNz}$
	third	$7.34(0.7)^{gNy}$	$8.03(1.2)^{gMNz}$	$7.09(1.1)^{gMy}$
Blackbird	first	$1.65(0.3)^{aNx}$	$1.13(0.4)^{aMNx}$	$1.34(0.3)^{aMx}$
	second	$1.68(0.2)^{aNy}$	$1.97(0.1)^{aMNy}$	$1.66(0.3)^{aMy}$
	third	$1.79(0.2)^{aMz}$	$2.53(0.5)^{aMNz}$	$2.16(0.5)^{aNz}$
Carberry	first	$2.40(0.4)^{cdNx}$	$2.50(0.4)^{cdMNx}$	$2.13(0.5)^{cdMx}$
	second	$2.95(0.2)^{cdMy}$	$3.32(0.7)^{cdMNy}$	$3.13(0.3)^{cdNy}$
	third	$3.71(1.0)^{cdMz}$	$4.04(0.7)^{cdMNz}$	$3.79(0.8)^{cdNz}$
Commander	first	$1.07(0.3)^{aMx}$	$1.46(0.3)^{aMNx}$	$1.57(0.2)^{aNx}$
	second	$1.51(0.2)^{aMy}$	$1.86(0.3)^{aMNy}$	$2.00(0.4)^{aNy}$
	third	$1.91(0.4)^{aMz}$	$2.04(0.5)^{aMNz}$	$2.67(0.8)^{aNz}$
DT833	first	$1.25(0.2)^{aMx}$	$1.46(0.2)^{aMNx}$	$1.25(0.2)^{aNx}$
	second	$1.44(0.2)^{aNy}$	$1.63(0.2)^{aMNy}$	$1.42(0.2)^{aMy}$
	third	$1.64(0.3)^{aMz}$	$2.08(0.6)^{aMNz}$	$1.87(0.4)^{aNz}$
HY1319	first	$1.91(0.3)^{dMx}$	$1.83(0.5)^{dMNx}$	$2.35(0.4)^{dNx}$
	second	$3.74(1.1)^{dNy}$	$2.89(0.6)^{dMNy}$	$3.21(0.5)^{dMy}$
	third	$4.27(1.4)^{dMz}$	$3.88(0.5)^{dMNz}$	$4.39(0.7)^{dNz}$
Shaw	first	$1.86(0.1)^{bMx}$	$2.03(0.3)^{bMNx}$	$1.96(0.2)^{bNx}$
	second	$2.69(0.2)^{bMy}$	$2.82(0.6)^{bMNy}$	$3.18(0.2)^{bNy}$
	third	$2.88(0.2)^{bMz}$	$3.36(0.8)^{bMNz}$	$3.57(0.5)^{bNz}$
Strongfield	first	$1.21(0.2)^{aMx}$	$1.30(0.2)^{aMNx}$	$1.98(0.3)^{aNx}$
	second	$1.51(0.1)^{aMy}$	$1.92(0.2)^{aMNz}$	$2.28(0.6)^{aNz}$
	third	$1.53(0.2)^{aMz}$	$1.78(0.2)^{aMNy}$	$2.23(0.3)^{aNy}$
Transcend	first	$1.15(0.2)^{aMx}$	$1.16(0.2)^{aMNx}$	$1.24(0.3)^{aNx}$
	second	$1.28(0.2)^{aMy}$	$1.70(0.3)^{aMNy}$	$1.77(0.4)^{aNy}$
	third	$1.47(0.1)^{aMz}$	$1.98(0.4)^{aMNz}$	$2.09(0.6)^{aNz}$
Unity	first	$1.95(0.4)^{bcMx}$	$1.56(0.1)^{bcMNx}$	$2.10(0.5)^{bcNx}$
	second	$3.12(1.0)^{bcMz}$	$2.69(0.9)^{bcMNy}$	$3.40(0.7)^{bcNy}$
	third	$2.98(1.2)^{bcMy}$	$3.71(0.7)^{bcMNz}$	$3.68(1.3)^{bcNz}$

Solid stem varieties are indicated with *; Figures in parentheses are standard deviation; Means values with different letters are significantly different ($P < 0.05$); a-g - comparison of mean values across varieties at the same moisture and internode position; M, N, O - comparison of mean values across moisture levels at the same variety and internode position; x, y, z - comparison of mean values across internode position at the same moisture and variety

Table 4.3 Coefficient of variation (CV) of area obtained by grouping the 3 internode positions under the same moisture contents (MC) and; N = 15.

Variety	MC= 14%	MC= 18%	MC= 22%
BW807*	8.3	23.8	24.9
DT818*	31.3	33.0	35.4
Lillian*	25.6	29.7	23.5
Blackbird	4.4	37.6	24.0
Carberry	21.9	23.3	27.8
Commander	28.2	16.7	26.6
DT833	13.3	18.6	21.1
HY1319	37.4	35.8	30.9
Shaw	21.9	24.5	28.9
Strongfield	12.5	19.4	7.5
Transcend	12.4	25.8	25.2
Unity	23.7	40.4	27.5

Solid stem varieties are indicated with *

Statistical analysis (ANOVA) of wheat stem area with respect to moisture, internode, and variety indicated that all three factors had significant effect on the stem area ($P<0.05$). The two way interaction of internode and moisture as well as internode and variety had significant effect ($P<0.05$) on the stem area. The two way interaction between moistures and varieties and the three way interaction of moisture, variety, and internode had no significant effect on the stem area ($P>0.05$).

4.2 Mechanical properties

Tables 4.4 to 4.11 show the mean values of the mechanical properties, namely, shearing, bending, cutting, and tensile strength, shearing and cutting energy, modulus of elasticity, and coefficient of internal friction, respectively, of the 12 varieties of wheat stem tested. It was observed that during shearing, cutting and tensile testing, wheat stem at 14% wb moisture content failed in a brittle manner while wheat stem at 22% wb tend to stretch a little before failing.

4.2.1 Shearing strength and energy

Table 4.4 shows the results of the shearing strength and energy obtained. Increase in stem moisture from 14 to 22% resulted in an increase in the shearing strength and energy with values ranging from 4.9-23.0 MPa and 62.4-319.1 mJ, respectively. Comparing the shearing strength and energy of hollow and solid stem types revealed that varieties with hollow stem type had higher shearing strength than varieties with solid stem type (Table 4.4). The shearing energy values of both stem types were observed to be similar (Table 4.4). This change in trend between the strength and energy of both stem type could be accounted for by the large stem area of the solid stem varieties used during data analysis which was not directly applicable when computing their energy.

Moving from the first to third internode, across the stem length showed different trends with respect to the shearing strength and energy. Some varieties, for example, 'Strongfield' had its highest shearing strength at 18% (wb) on the third internode (17.7 MPa) whereas for 'Transcend', the highest shearing strength was measured on the second internode (13.2 MPa) at the same moisture content (Fig 4.5).

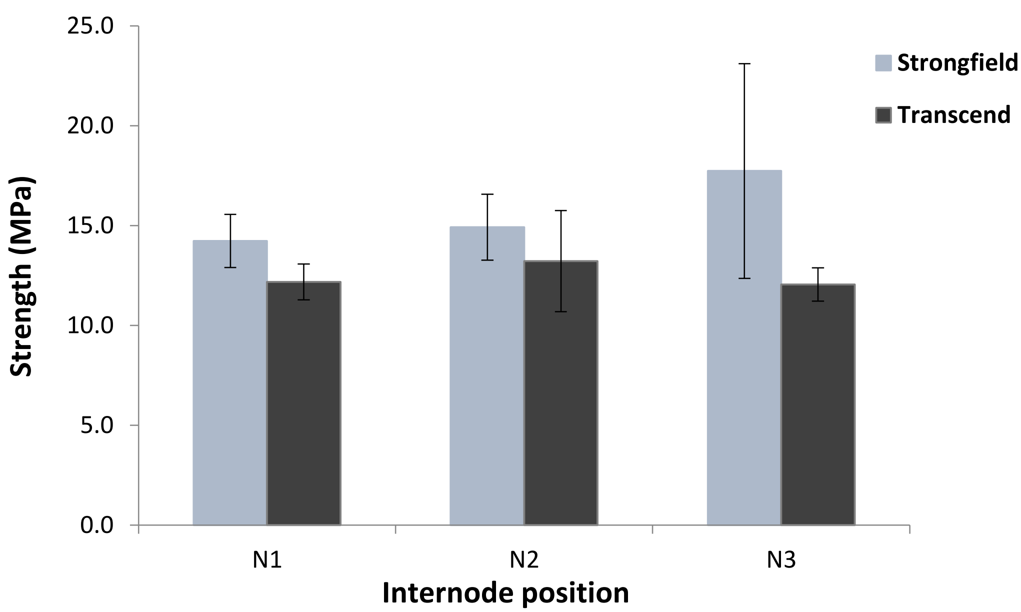


Fig. 4.5 Graph comparing stem shearing strength of 'Strongfield' and 'Transcend' at different internode with 18% (wb) moisture content.

Table 4.4. Shearing strength (MPa) and shearing energy (mJ) of 12 different varieties of wheat stem at 3 moisture contents (MC) and 3 internode positions; N = 5.

Variety	Node	Shearing Strength (MPa)			Shearing Energy (mJ)		
		MC=14%	**MC=18%**	**MC=22%**	**MC=14%**	**MC=18%**	**MC=22%**
BW807*	first	5.2(2.6)^{abcMy}	8.1(1.7)^{abcNx}	12.8(3.2)^{abcOz}	73.6(10.9)^{efMy}	90.7(36.6)^{efNx}	223.9(37.4)^{efOx}
	second	6.5(0.8)^{abcMz}	10.2(1.5)^{abcNz}	11.8(2.0)^{abcOy}	86.4(16.8)^{efMx}	134.4(20.1)^{efNy}	319.1(25.7)^{efOy}
	third	4.9(1.6)^{abcMx}	9.0(1.1)^{abcNy}	9.3(3.1)^{abcOx}	66.6(5.7)^{efMx}	129.5(11.2)^{efNy}	257.8(31.9)^{efOy}
DT818*	first	7.9(0.8)^{abMz}	9.1(1.5)^{abNz}	11.1(5.4)^{abOz}	101.0(22.1)^{fMx}	113.2(12.9)^{fNx}	119.9(21.2)^{fOx}
	second	7.6(0.3)^{abMy}	8.4(1.6)^{abNy}	9.8(6.4)^{abOy}	172.5(55.7)^{fMy}	181.0(24.5)^{fNy}	190.1(33.4)^{fOy}
	third	6.0(1.2)^{abMx}	6.8(1.7)^{abNx}	7.6(2.0)^{abOx}	166.3(34.8)^{fMy}	174.9(6.9)^{fNy}	188.2(28.4)^{fOy}
Lillian*	first	6.9(1.3)^{aMz}	7.2(1.4)^{aNy}	8.4(2.6)^{aOx}	66.0(15.8)^{efMx}	71.5(6.3)^{efNx}	156.8(57.9)^{efOx}
	second	5.5(0.5)^{aMx}	7.0(1.6)^{aNx}	9.7(2.3)^{aOz}	131.6(29.2)^{efMy}	150.7(15.0)^{efNy}	192.8(59.6)^{efOy}
	third	6.0(0.4)^{aMy}	8.1(0.9)^{aNz}	9.4(1.7)^{aOy}	151.3(34.5)^{efMy}	173.7(19.5)^{efNy}	270.0(33.0)^{efOy}
Blackbird	first	11.0(1.0)^{fMz}	14.3(0.8)^{fNz}	15.3(3.1)^{fOx}	62.4(11.9)^{abMx}	69.5(2.9)^{abNx}	96.5(16.1)^{abOx}
	second	9.9(1.2)^{fMy}	10.2(1.6)^{fNx}	16.4(3.1)^{fOy}	110.5(12.2)^{abMy}	121.8(13.7)^{abNy}	139.7(12.7)^{abOy}
	third	9.3(0.5)^{fMx}	14.3(4.2)^{fNy}	16.9(4.2)^{fOz}	124.1(29.1)^{abMy}	133.1(6.3)^{abNy}	154.7(16.2)^{abOy}
Carberry	first	9.7(1.6)^{bcMz}	10.1(2.0)^{bcNz}	11.7(1.7)^{bcOz}	90.5(21.5)^{bcMx}	96.7(6.2)^{bcNx}	118.1(15.4)^{bcOx}
	second	8.0(0.7)^{bcMy}	8.2(1.6)^{bcNx}	8.4(0.9)^{bcOx}	136.4(22.3)^{bcMy}	140.4(6.9)^{bcNy}	141.9(12.4)^{bcOy}
	third	7.3(1.1)^{bcMx}	8.5(2.1)^{bcNy}	10.3(1.8)^{bcOy}	122.2(43.6)^{bcMy}	126.8(24.2)^{bcNy}	135.0(18.8)^{bcOy}
Commander	first	12.3(0.7)^{deMz}	14.5(2.7)^{deNz}	19.2(2.1)^{deOz}	94.9(7.6)^{cdMy}	119.3(32.2)^{cdNy}	226.0(90.3)^{cdOy}
	second	5.2(0.9)^{deMx}	10.7(2.0)^{deNx}	11.1(3.9)^{deOx}	80.9(16.0)^{cdMx}	108.8(6.2)^{cdNx}	141.2(16.4)^{cdOx}
	third	6.2(1.0)^{deMy}	11.9(2.8)^{deny}	12.5(6.3)^{deOy}	102.0(9.5)^{cdMx}	133.7(11.4)^{cdNx}	156.7(29.8)^{cdOx}
DT833	first	11.7(0.7)^{efMz}	12.2(1.6)^{efNy}	13.2(2.4)^{efOx}	119.6(18.6)^{efMx}	120.7(8.6)^{efNx}	122.8(19.1)^{efOx}
	second	11.4(0.7)^{efMy}	12.9(2.7)^{efNz}	13.9(1.6)^{efOy}	159.2(38.0)^{efMy}	165.1(6.4)^{efNy}	169.9(31.9)^{efOy}
	third	10.2(0.5)^{efMx}	11.4(0.2)^{efNx}	15.1(1.6)^{efOz}	158.2(38.6)^{efMy}	165.7(12.6)^{efNy}	175.1(43.1)^{efOy}
HY1319	first	11.9(2.6)^{dMz}	14.8(2.7)^{dNz}	17.2(9.8)^{dOz}	92.4(37.2)^{cdMx}	112.3(17.3)^{cdNx}	141.4(46.5)^{cdOx}
	second	9.9(0.6)^{dMy}	10.5(3.4)^{dNy}	11.8(1.0)^{dOy}	111.4(25.7)^{cdMy}	131.0(11.8)^{cdNy}	200.7(33.1)^{cdOy}
	third	6.8(0.8)^{dMx}	8.3(0.4)^{dNx}	9.2(2.4)^{dOx}	95.2(18.4)^{cdMy}	135.3(6.0)^{cdNy}	154.7(35.9)^{cdOy}
Shaw	first	10.4(0.9)^{dMy}	11.4(0.5)^{dNy}	11.8(1.4)^{dOy}	92.5(20.1)^{deMx}	99.1(16.6)^{deNx}	148.3(40.5)^{deOx}
	second	11.6(1.1)^{dMz}	12.3(1.3)^{dNz}	13.2(2.8)^{dOz}	155.7(23.5)^{deMy}	160.0(21.3)^{deny}	165.4(1.3)^{deOy}
	third	7.4(0.7)^{dMx}	8.6(1.3)^{dNx}	9.0(0.5)^{dOx}	136.9(23.9)^{deMy}	147.7(20.1)^{deny}	158.9(24.8)^{deOy}
Strongfield	first	13.7(1.7)^{gMx}	14.2(1.3)^{gNx}	14.7(3.5)^{gOx}	111.3(13.5)^{gMx}	120.5(18.0)^{gNx}	235.9(84.7)^{gOy}
	second	14.2(0.5)^{gMy}	14.9(1.7)^{gNy}	15.8(2.3)^{gOy}	157.4(42.2)^{gMy}	173.6(10.8)^{gNy}	216.5(67.8)^{gOx}
	third	15.9(2.7)^{gMz}	17.7(5.4)^{gNz}	23.0(3.4)^{gOz}	200.3(26.9)^{gMy}	203.7(18.8)^{gNy}	213.2(44.2)^{gOx}
Transcend	first	9.2(0.9)^{efMx}	12.2(0.9)^{efNy}	13.7(4.8)^{efOy}	114.0(28.6)^{dMx}	123.1(5.3)^{dNx}	150.3(30.5)^{dOy}
	Second	11.6(0.7)^{efMz}	13.2(2.5)^{efNz}	15.8(4.1)^{efOz}	139.5(18.1)^{dMy}	145.6(24.0)^{dNy}	149.7(31.9)^{dOx}
	third	10.6(0.8)^{efMy}	12.1(0.8)^{efNx}	12.9(1.4)^{efOx}	132.8(25.3)^{dMy}	134.6(25.0)^{dNy}	134.7(19.4)^{dOx}
Unity	first	7.6(1.7)^{cMx}	8.4(0.6)^{cNx}	9.0(3.3)^{cOx}	71.6(10.4)^{aMx}	78.8(2.0)^{aNx}	104.4(7.6)^{aOx}
	second	10.1(1.9)^{cMz}	11.4(2.6)^{cNz}	12.1(3.9)^{cOz}	98.1(24.0)^{aMy}	103.8(11.9)^{aNy}	157.7(61.0)^{aOy}
	third	8.3(0.5)^{cMy}	8.6(2.1)^{cNy}	9.0(0.9)^{cOy}	93.7(25.1)^{aMy}	105.1(10.3)^{aNy}	127.0(35.5)^{aOy}

Solid stem varieties are indicated with *; Figures in parentheses are standard deviation; Means values with different letters are significantly different ($P < 0.05$); a-g - comparison of mean values across varieties at the same moisture and internode position; M, N, O - comparison of mean values across moisture levels at the same variety and internode position; x, y, z - comparison of mean values across internode position at the same moisture and variety.

The coefficient of variation obtained by grouping the 3 internode positions under the same moisture contents is presented in Table 4.5. “Commander”, “Shaw”, and “HY1319” had the highest variation of shearing strength across the stem length while “Lilian” and “DT833” had the least variation. “Transcend”, “Blackbird”, “Carberry”, “DT818”, “BW807”, “Unity”, and “Strongfield” were in between (Table 4.5).

On the other hand, the shearing energy of “Lilian”, “Strongfield”, “Shaw”, and “DT818” varieties were largely dispersed across the stem length from the first internode to the third internode. This is indicated by their high coefficient of variation value (Table 4.5). “Transcend”, “BW833”, and “Unity” varieties had the least variation while “Blackbird”, “BW807”, “Carberry”, “Commander”, “Transcend”, and “BW807” varieties were in between (Table 4.5). The low variation indicates similarities in the shearing energy across the stem length.

Table 4.5 Coefficient of variation (CV) of shearing strength and energy obtained by grouping the 3 internode positions under the same moisture contents (MC) and; N = 15.

	Shearing strength			**Shearing energy**		
Variety	**MC=14%**	**MC=18%**	**MC=22%**	**MC=14%**	**MC=18%**	**MC=22%**
BW807*	15.0	11.4	15.8	13.4	20.2	18.1
DT818*	14.5	14.6	18.7	27.0	24.0	24.1
Lillian*	11.3	8.0	7.2	38.4	40.6	28.0
Blackbird	8.4	18.0	5.1	32.7	31.4	23.2
Carberry	15.0	11.6	16.3	20.2	18.4	9.3
Commander	48.2	16.0	30.5	11.6	10.4	25.9
DT833	6.9	5.9	6.8	15.5	17.1	18.5
HY1319	26.7	29.5	32.2	10.3	9.7	18.8
Shaw	21.8	18.2	18.7	25.2	23.7	5.5
Strongfield	8.0	11.9	25.3	28.5	25.4	5.5
Transcend	11.2	5.1	13.0	10.3	8.4	5.7
Unity	15.3	17.6	17.9	16.2	15.5	20.6

Solid stem varieties are indicated with *

4.2.2 Cutting strength and energy

The average values for cutting strength and energy of the 12 varieties of wheat stem at different moisture contents and internode positions are presented in Table 4.6. Moisture content had positive correlation with cutting strength and energy. Mean values of cutting strength and energy varied between 1.4- 10.2 MPa and 27.0-133.3 mJ, respectively. The effect of the stem type (solid and hollow) on the cutting strength indicated that solid stems had lower strength than hollow stems (Tables 4.6). There was no difference between the cutting energy of both stem types (Tables 4.6). Although the internode position had significant effect on the cutting strength and energy, no consistent trend was observed. The wheat varieties greatly contributed in determining the cutting strength and energy investigated. Some varieties had higher strength and energy than others. For example, a force of 14.1 N was needed to cut 'Commander' stem but lower force of 7.2 N was required to cut 'Carberry' stem at the same internode position (first) and moisture content (14% wb) (Fig. 4.6). This may be due to difference in the composition and stem morphology of each wheat varieties.

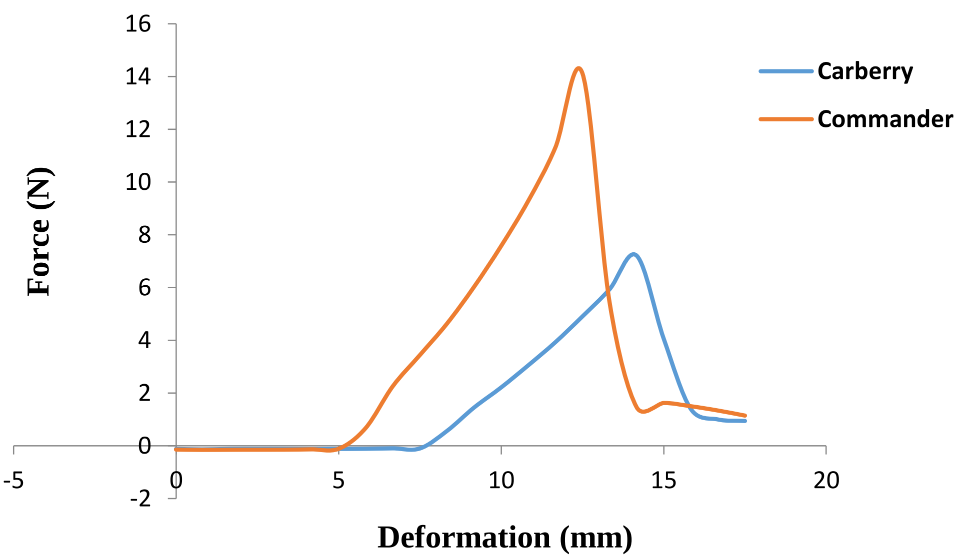


Fig. 4.6 Force-deformation curve comparing forces needed to cut the first internode of 'Commander' and 'Carberry' stem at 14%.

Table 4.6 Cutting strength (MPa) and cutting energy (mJ) of 12 different varieties of wheat stem at 3 moisture contents (MC) and 3 internode positions; N = 14.

		Cutting Strength (MPa)			**Cutting Energy (mJ)**		
Variety	**Node**	**MC=14%**	**MC=18%**	**MC=22%**	**MC=14%**	**MC=18%**	**MC=22%**
BW807*	first	2.8(0.9)^{aMy}	3.0(0.7)^{aNy}	4.8(1.9)^{aOy}	48.2(10.5)^{eMx}	64.0(8.3)^{eNx}	81.6(19.7)^{eOx}
	second	2.4(0.6)^{aMx}	2.8(0.5)^{aNx}	3.2(1.6)^{aOx}	95.1(17.2)^{eMz}	96.3(22.4)^{eNz}	97.8(31.6)^{eOz}
	third	1.8(0.8)^{aMx}	2.1(0.4)^{aNx}	2.3(0.4)^{aOx}	88.6(32.5)^{eMy}	91.3(18.1)^{eNy}	96.9(25.3)^{eOy}
DT818*	first	3.2(0.5)^{bMy}	3.3(0.5)^{bNy}	4.0(1.2)^{bOy}	72.7(12.6)^{gMx}	78.5(12.5)^{gNx}	80.4(12.5)^{gOx}
	second	2.8(0.5)^{bMx}	3.2(0.5)^{bNx}	3.4(0.7)^{bOx}	108.2(17.5)^{gMz}	120.6(33.7)^{gNz}	122.0(33.0)^{gOz}
	third	2.4(0.8)^{bMx}	2.7(0.7)^{bNx}	3.6(2.0)^{bOx}	90.3(20.6)^{gMy}	106.0(13.5)^{gNy}	110.1(31.6)^{gOy}
Lillian*	first	2.3(0.9)^{aMy}	2.4(0.6)^{aNx}	3.6(1.0)^{aOy}	37.4(11.5)^{fMx}	56.2(14.2)^{fNx}	58.9(10.7)^{fOx}
	second	2.2(0.8)^{aMx}	2.7(0.9)^{aNy}	3.1(0.5)^{aOx}	87.0(14.6)^{fMy}	106.3(16.9)^{fNy}	109.6(22.8)^{fOy}
	third	2.3(0.9)^{aMx}	2.8(1.2)^{aNy}	3.2(0.8)^{aOx}	97.1(16.0)^{fMz}	129.6(29.5)^{fNz}	133.3(34.2)^{fOz}
Blackbird	first	2.7(0.8)^{eMx}	4.2(0.9)^{eNy}	6.2(1.3)^{eOx}	32.2(5.0)^{cMx}	46.9(5.0)^{cNx}	50.9(7.1)^{cOx}
	second	3.5(1.4)^{eMy}	3.8(0.8)^{eNx}	9.7(2.2)^{eOy}	47.0(9.6)^{cMy}	59.9(4.1)^{cNy}	88.8(16.0)^{cOy}
	third	4.9(1.4)^{eMy}	5.9(1.7)^{eNx}	8.4(2.5)^{eOy}	61.8(15.1)^{cMz}	84.3(5.8)^{cNz}	104.9(26.1)^{cOz}
Carberry	first	2.5(0.7)^{aMy}	3.0(0.9)^{aNy}	5.6(1.7)^{aOy}	38.1(8.0)^{bMx}	46.4(4.4)^{bNx}	52.2(12.8)^{bOx}
	second	2.0(0.5)^{aMx}	2.2(0.4)^{aNx}	3.9(0.9)^{aOx}	44.2(8.3)^{bMy}	62.6(6.4)^{bNz}	67.9(11.1)^{bOz}
	third	1.8(0.4)^{aMx}	2.1(0.7)^{aNx}	2.7(0.9)^{aOx}	46.3(11.0)^{bMz}	58.5(10.7)^{bNy}	60.9(15.9)^{bOy}
Commander	first	3.6(1.1)^{cMy}	5.3(0.9)^{cNy}	9.2(1.9)^{cOy}	45.7(11.2)^{aMz}	63.0(7.2)^{aNz}	65.1(11.6)^{aOz}
	second	2.2(0.8)^{cMx}	2.9(1.3)^{cNx}	3.8(1.0)^{cOx}	27.0(10.7)^{aMx}	35.8(18.4)^{aNx}	42.1(13.4)^{aOx}
	third	2.8(0.7)^{cMx}	3.1(1.2)^{cNx}	3.3(0.8)^{cOx}	31.0(8.9)^{aMy}	36.5(15.6)^{aNy}	42.4(18.0)^{aOy}
DT833	first	5.3(0.8)^{gMx}	5.7(1.2)^{gNx}	9.9(1.9)^{gOy}	47.8(11.9)^{eMx}	75.0(16.3)^{eNx}	85.8(18.2)^{eOx}
	second	5.4(0.8)^{gMy}	6.3(1.4)^{gNy}	9.7(2.3)^{gOx}	61.8(17.0)^{eMy}	88.1(16.6)^{eNy}	104.0(23.8)^{eOz}
	third	5.8(1.1)^{gMy}	6.5(0.7)^{gNy}	8.3(1.7)^{gOx}	82.9(10.9)^{eMz}	96.9(23.8)^{eNz}	100.1(14.7)^{eOy}
HY1319	first	3.6(0.7)^{bMy}	4.1(0.9)^{bNy}	6.8(2.2)^{bOy}	37.3(9.5)^{bMx}	55.1(7.9)^{bNy}	57.9(13.7)^{bOy}
	second	2.2(0.4)^{bMx}	2.6(0.6)^{bNx}	5.0(0.8)^{bOx}	58.7(10.7)^{bMz}	72.9(8.6)^{bNz}	78.4(25.9)^{bOz}
	third	1.4(0.6)^{bMx}	1.7(0.3)^{bNx}	2.3(1.1)^{bOx}	39.3(7.1)^{bMy}	41.5(9.1)^{bNx}	42.2(12.2)^{bOx}
Shaw	first	3.3(0.7)^{dMy}	3.7(0.9)^{dNy}	7.7(2.9)^{dOy}	34.2(10.9)^{dMx}	55.7(3.7)^{dNx}	59.1(9.9)^{dOx}
	second	2.7(1.0)^{dMx}	3.0(0.4)^{dNx}	6.6(1.3)^{dOx}	44.8(11.5)^{dMy}	86.7(7.6)^{dNy}	91.9(18.0)^{dOy}
	third	3.7(0.8)^{dMx}	3.9(0.9)^{dNx}	5.8(1.8)^{dOx}	75.8(16.3)^{dMz}	107.9(14.5)^{dNz}	111.4(25.8)^{dOz}
Strongfield	first	4.8(0.9)^{eMy}	5.2(0.9)^{eNx}	7.2(1.7)^{eOy}	67.7(11.2)^{fMy}	68.3(8.9)^{fNx}	69.7(9.7)^{fOx}
	second	3.3(0.5)^{eMx}	5.5(1.0)^{eNy}	6.2(1.1)^{eOx}	58.0(9.2)^{fMx}	91.8(14.9)^{fNy}	94.7(22.2)^{fOy}
	third	5.7(1.0)^{eMx}	6.4(0.8)^{eNy}	7.4(1.8)^{eOx}	120.6(20.6)^{fMz}	125.0(18.9)^{fNz}	131.9(47.2)^{fOz}
Transcend	first	5.7(1.5)^{fMy}	6.3(1.4)^{fNy}	10.2(2.4)^{fOy}	55.8(13.4)^{cMz}	64.7(11.6)^{cNy}	69.8(13.7)^{cOy}
	second	4.2(0.9)^{fMx}	4.8(1.1)^{fNx}	8.5(2.3)^{fOx}	50.1(15.0)^{cMx}	68.1(10.7)^{cNz}	80.0(19.2)^{cOz}
	third	4.3(1.4)^{fMx}	4.6(1.5)^{fNx}	6.1(2.2)^{fOx}	52.4(11.3)^{cMy}	62.6(12.1)^{cNx}	66.5(16.2)^{cOx}
Unity	First	2.6(0.5)^{cMy}	2.8(0.5)^{cNx}	3.9(0.4)^{cOx}	34.2(6.7)^{cMx}	42.7(7.0)^{cNx}	45.1(8.7)^{cOx}
	Second	2.5(0.6)^{cMx}	3.1(1.0)^{cNy}	6.9(2.4)^{cOy}	54.6(13.8)^{cMy}	78.5(3.9)^{cNz}	80.1(21.8)^{cOz}
	Third	3.2(0.6)^{cMx}	3.9(0.8)^{cNy}	5.0(0.7)^{cOy}	70.1(17.7)^{cMz}	72.7(8.3)^{cNy}	76.0(15.8)^{cOy}

Solid stem varieties are indicated with *; Figures in parentheses are standard deviation; Means values with different letters are significantly different ($P < 0.05$); a-g - comparison of mean values across varieties at the same moisture and internode position; M, N, O - comparison of mean values across moisture levels at the same variety and internode position; x, y, z - comparison of mean values across internode position at the same moisture and variety.

The coefficient of variation of cutting strength computed indicated that “HY1319”, “Blackbird”, “Commander”, and “BW807” varieties had the largest variation from the first internode to the third internode while “Lilian” and “DT833” varieties had the least variation across the stem length (Table 4.7). “DT818”, “Shaw”, “Transcend”, “Carberry”, and “Unity” varieties were in between (Table 4.7).

Comparing the coefficient of variation for cutting energy revealed that “HY1319”, “DT833”, “DT818”, “Commander”, and “BW807” varieties had moderate variation across the stem length while “Strongfield”, “Shaw”, “Lilian”, “Blackbird”, and “Unity” had the highest variation. “Transcend” and “Carberry” were noted to have the least variation across the stem length (Table 4.7). The low coefficient of variation value indicates that there are great similarities in the stem’s cutting energy from the first to the third internode of the wheat stem of the above named varieties.

Table 4.7 Coefficient of variation (CV) of cutting strength and energy obtained by grouping the 3 internode positions under the same moisture contents (MC) and; N = 15.

	Cutting strength			**Cutting energy**		
Variety	**MC=14%**	**MC=18%**	**MC=22%**	**MC=14%**	**MC=18%**	**MC=22%**
BW807*	22.4	16.5	37.7	32.9	20.7	9.9
DT818*	14.3	11.7	8.1	19.6	21.0	20.6
Lillian*	3.2	7.5	8.5	43.2	38.6	37.8
Blackbird	30.0	23.3	21.9	31.5	29.8	34.0
Carberry	17.8	20.9	35.1	9.9	15.0	13.1
Commander	24.4	35.6	60.9	28.6	34.4	26.4
DT833	5.1	7.0	9.3	27.6	12.7	9.9
HY1319	44.6	43.0	48.2	26.2	27.9	30.6
Shaw	15.5	13.5	14.4	41.9	31.5	30.2
Strongfield	25.9	10.8	9.2	41.0	30.0	31.7
Transcend	17.2	17.6	25.1	5.4	4.3	9.8
Unity	13.8	17.9	28.9	33.9	29.7	28.5

Solid stem varieties are indicated with *

4.2.3 Bending strength and modulus of elasticity

Results of the data analysis indicated that moisture content have a negative correlation on bending strength and modulus of elasticity, respectively. Bending strength and modulus of elasticity values ranged from 43.9-4.2 MPa and 3.5-0.1 GPa, respectively (Table 4.8). Fig. 4.7 shows the force deformation curve of the first internode of "Commander" under bending at 14 and 22% (wb) moisture. The graph shows that much force was needed to bend the stem at 14% (wb) moisture than when the stem was at 22% (wb), indicating a reduction in bending strength as moisture increased.

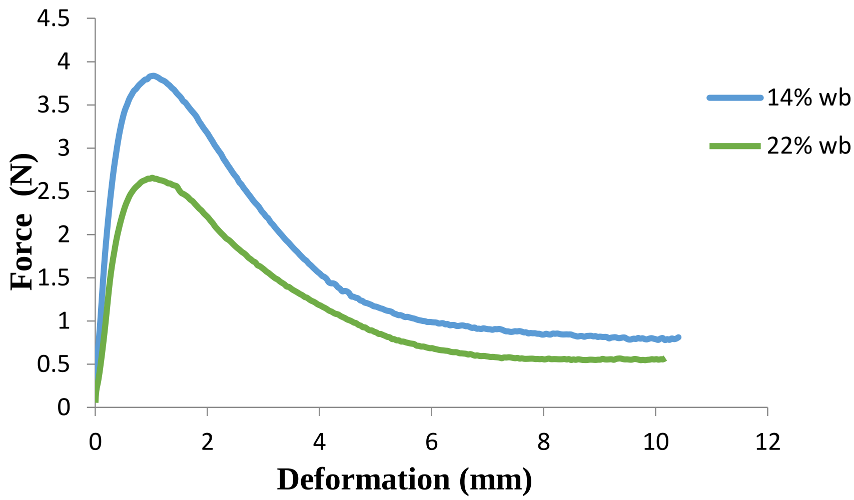


Fig. 4.7 Force-deformation curve of 'Commander' comparing forces needed to bend the stem at the first internode with 14 and 22% (wb) moisture content.

There was variations in the bending strength and modulus of elasticity across varieties. 'DT818' had the highest bending strength while 'Commander' recorded the least strength. The other varieties ("HY1319", "Blackbird", "BW807", "Lilian", "DT833", "Shaw", "Transcend", "Carberry", "Strongfield", and "Unity") were in between.

Analysis of the bending strength and modulus of elasticity values obtained across the stem length revealed that there was no consistent trend from the first internode to third internode across varieties. Similarly, there was also no difference in the bending strength and modulus of elasticity values when comparing both stem types (hollow and solid).

Table 4.8 Bending strength (MPa) and modulus of elasticity (GPa) of 12 different varieties of wheat stem at 3 moisture contents (MC) and 3 internode positions; N = 5.

		Bending Strength (MPa)			**Modulus of elasticity (GPa)**		
Variety	**Node**	**MC=14%**	**MC=18%**	**MC=22%**	**MC=14%**	**MC=18%**	**MC=22%**
	First	25.3(2.7)^{dOz}	21.4(1.7)^{dNz}	17.1(2.8)^{dMz}	1.61(0.48)^{bOy}	1.46(0.37)^{bNy}	0.99(0.36)^{bMy}
BW807*	second	21.9(3.7)^{dOy}	16.2(0.9)^{dNy}	10.4(4.0)^{dMy}	1.00(0.37)^{bOx}	0.82(0.09)^{bNx}	0.42(0.17)^{bMx}
	Third	16.1(4.7)^{dOx}	12.4(1.1)^{dNx}	7.1(1.5)^{dMx}	0.79(0.14)^{bOx}	0.57(0.06)^{bNx}	0.25(0.08)^{bMx}
	First	43.9(1.5)^{hOz}	33.3(4.1)^{hNz}	32.1(6.9)^{hMz}	2.93(0.47)^{eOy}	2.72(0.49)^{eNy}	2.34(0.88)^{eMy}
DT818*	second	25.1(2.7)^{hOy}	19.0(4.0)^{hNx}	17.3(7.5)^{hMx}	1.37(0.11)^{eOx}	1.13(0.34)^{eNx}	0.79(0.30)^{eMx}
	Third	19.6(6.9)^{hOx}	20.2(3.1)^{hNy}	19.6(3.2)^{hMy}	0.84(0.28)^{eOx}	0.97(0.09)^{eNx}	0.86(0.22)^{eMx}
	First	17.0(2.6)^{cOx}	12.4(2.6)^{cNx}	10.4(1.8)^{cMx}	0.98(0.12)^{bOy}	0.75(0.10)^{bNy}	0.46(0.13)^{bMx}
Lillian*	second	18.8(1.3)^{cOy}	15.4(2.3)^{cNy}	13.2(3.7)^{cMz}	0.80(0.13)^{bOx}	0.63(0.06)^{bNx}	0.59(0.18)^{bMy}
	Third	19.8(2.5)^{cOz}	17.5(2.1)^{cNz}	11.4(4.1)^{cMy}	0.97(0.09)^{bOx}	0.86(0.14)^{bNx}	0.86(0.49)^{bMy}
	First	39.9(3.5)^{fOz}	27.8(6.9)^{fNz}	17.8(2.7)^{fMz}	3.50(0.74)^{dOy}	2.70(0.96)^{dNy}	1.56(0.31)^{dMy}
Blackbird	second	22.4(3.0)^{fOy}	20.4(3.0)^{fNy}	17.4(4.7)^{fMy}	1.16(0.32)^{dOx}	1.06(0.25)^{dNx}	0.72(0.24)^{dMx}
	Third	18.7(1.4)^{fOx}	16.3(2.3)^{fNx}	14.2(2.1)^{fMx}	0.84(0.12)^{dOx}	0.69(0.25)^{dNx}	0.55(0.17)^{dMx}
	First	17.8(2.2)^{cOz}	15.1(1.9)^{cNy}	13.4(1.4)^{cMy}	0.72(0.10)^{aOy}	0.67(0.22)^{aNy}	0.55(0.16)^{aMy}
Carberry	second	17.1(0.8)^{cOy}	11.4(1.4)^{cNx}	9.3(2.0)^{cMx}	0.46(0.16)^{aOx}	0.29(0.08)^{aNx}	0.18(0.06)^{aMx}
	Third	16.9(3.4)^{cOx}	16.5(0.7)^{cNz}	15.7(7.2)^{cMz}	0.59(0.13)^{aOx}	0.54(0.12)^{aNx}	0.49(0.24)^{aMx}
	First	26.7(1.1)^{aOz}	17.5(2.8)^{aNz}	7.4(1.9)^{aMz}	1.88(0.37)^{aOy}	1.07(0.20)^{aNy}	0.54(0.15)^{aMy}
	second	12.7(1.5)^{aOx}	6.9(1.4)^{aNx}	4.7(1.0)^{aMy}	0.49(0.12)^{aOx}	0.26(0.10)^{aNx}	0.16(0.07)^{aMx}
Commander	Third	14.0(2.2)^{aOy}	10.1(1.6)^{aNy}	4.2(0.6)^{aMx}	0.46(0.18)^{aOx}	0.30(0.05)^{aNx}	0.16(0.04)^{aMx}
	First	32.4(2.9)^{fOz}	25.8(1.9)^{fNz}	16.8(3.0)^{fMz}	1.99(0.33)^{cOy}	1.80(0.17)^{cNy}	1.14(0.41)^{cMy}
DT833	second	31.0(1.8)^{fOy}	23.2(3.8)^{fNy}	13.7(1.5)^{fMx}	1.40(0.22)^{cOx}	1.12(0.39)^{cNx}	0.54(0.10)^{cMx}
	Third	22.3(2.8)^{fOx}	18.8(1.6)^{fNx}	15.4(7.9)^{fMy}	0.82(0.08)^{cOx}	0.66(0.23)^{cNx}	0.61(0.14)^{cMx}
	First	21.6(3.9)^{bOz}	17.5(0.8)^{bNz}	12.6(0.5)^{bMz}	1.19(0.14)^{aOy}	0.91(0.16)^{aNy}	0.54(0.17)^{aMy}
HY1319	second	15.8(2.5)^{bOy}	12.1(1.5)^{bNy}	8.3(3.2)^{bMy}	0.53(0.10)^{aOx}	0.37(0.02)^{aNx}	0.19(0.13)^{aMx}
	Third	14.2(2.1)^{bOx}	10.0(1.0)^{bNx}	5.0(1.4)^{bMx}	0.49(0.10)^{aOx}	0.32(0.02)^{aNx}	0.14(0.04)^{aMx}
	First	25.2(2.4)^{eOy}	18.5(2.3)^{eNy}	16.4(2.1)^{eMy}	1.25(0.16)^{bOy}	1.08(0.41)^{bNy}	0.82(0.28)^{bMy}
Shaw	second	16.7(1.5)^{eOx}	14.4(2.6)^{eNx}	7.7(1.0)^{eMx}	0.58(0.22)^{bOx}	0.46(0.15)^{bNx}	0.29(0.07)^{bMx}
	Third	27.8(1.7)^{eOz}	24.6(2.1)^{eNz}	21.2(3.7)^{eMz}	1.24(0.22)^{bOx}	1.08(0.21)^{bNx}	0.95(0.23)^{bMx}
	First	26.7(2.6)^{fOx}	21.5(2.3)^{fNz}	20.7(9.0)^{fMz}	1.46(0.22)^{bOy}	1.18(0.53)^{bNy}	0.66(0.07)^{bMy}
Strongfield	second	27.5(1.3)^{fOz}	16.8(2.3)^{fNx}	13.1(3.6)^{fMx}	1.04(0.09)^{bOx}	0.69(0.06)^{bNx}	0.44(0.15)^{bMx}
	Third	27.3(1.9)^{fOy}	20.2(1.6)^{fNy}	15.2(6.5)^{fMy}	0.99(0.22)^{bOx}	0.81(0.10)^{bNx}	0.47(0.28)^{bMx}
	First	31.1(3.0)^{eOz}	25.6(2.2)^{eNz}	15.5(2.6)^{eMz}	1.79(0.64)^{bOy}	1.65(0.28)^{bNy}	1.08(0.30)^{bMy}
Transcend	second	22.9(4.4)^{eOx}	18.8(3.3)^{eNy}	10.1(1.6)^{eMy}	0.84(0.36)^{bOx}	0.58(0.22)^{bNx}	0.40(0.07)^{bMx}
	Third	25.0(3.9)^{eOy}	15.9(2.3)^{eNx}	8.4(1.3)^{eMx}	0.72(0.14)^{bOx}	0.56(0.19)^{bNx}	0.25(0.08)^{bMx}
	First	26.8(2.6)^{gOy}	24.9(1.6)^{gNy}	22.6(6.9)^{gMy}	1.83(0.50)^{deOy}	1.77(0.45)^{deny}	1.51(0.42)^{deMy}
Unity	second	22.0(2.1)^{gOx}	20.7(2.5)^{gNx}	15.5(2.9)^{gMx}	1.11(0.17)^{deOx}	0.98(0.18)^{deNx}	0.92(0.33)^{deMx}
	Third	33.0(1.5)^{gOz}	26.9(1.5)^{gNz}	23.7(3.0)^{gMz}	1.85(0.46)^{deOx}	1.55(0.28)^{deNx}	1.50(0.54)^{deMx}

Solid stem varieties are indicated with *; Figures in parentheses are standard deviation; Means values with different letters are significantly different ($P < 0.05$); a-g - comparison of mean values across varieties at the same moisture and internode position; M, N, O - comparison of mean values across moisture levels at the same variety and internode position; x, y, z - comparison of mean values across internode position at the same moisture and variety.

Table 4.9 shows the coefficient of variation for bending strength and modulus of elasticity across the stem length (first, second, and third internode) for each moisture content investigated. The results revealed that “Shaw”, “HY1319”, “DT818”, “Commander”, and “BW807” had the highest variation in bending strength across their stem length followed by “DT833”, “DT818”, “Transcend”, “Carberry”, and “Unity” varieties. “Strongfield” and “Lilian” varieties recorded the least variation from the first internode to the third internode (Table 4.9).

Comparing the coefficient of variation values for modulus of elasticity revealed that most varieties (“Commander”, “Shaw”, “HY1319”, “Blackbird”, “DT833”, “DT818”, “Transcend”, and “BW807”) had high disparity across their stem length from the first internode to the third internode. “Strongfield”, “Carberry”, and “Unity” varieties had moderate variations while “Lilian” variety recorded the least variation (Table 4.9). The high coefficient of variation means high disparity in the bending properties from the first internode to the third internode.

Table 4.9 Coefficient of variation (CV) of bending strength and modulus of elasticity obtained by grouping the 3 internode positions under the same moisture contents (MC) and; N = 15.

	Bending strength			**Modulus of elasticity**		
Variety	**MC=14%**	**MC=18%**	**MC=22%**	**MC=14%**	**MC=18%**	**MC=22%**
BW807*	22.1	27.2	44.4	37.5	48.5	70.7
DT818*	43.3	32.9	34.6	63.3	60.5	66.0
Lillian*	7.7	16.8	12.4	11.2	15.3	32.0
Blackbird	42.1	27.1	12.0	79.3	72.0	57.1
Carberry	2.8	18.2	25.4	22.3	39.0	49.5
Commander	43.5	47.6	31.6	86.3	84.5	75.9
DT833	19.2	15.6	10.7	41.6	48.3	46.3
HY1319	22.6	29.3	43.9	52.9	61.2	76.1
Shaw	25.0	26.7	44.1	37.4	41.1	49.3
Strongfield	1.5	12.4	23.8	21.8	28.5	22.8
Transcend	16.4	24.7	32.7	52.2	67.2	76.3
Unity	20.1	13.1	21.8	26.3	28.7	25.8

Solid stem varieties are indicated with *

4.2.4 Tensile strength

Table 4.10 shows the results of the tensile strength obtained during data analysis. Increase in moisture from 14 to 22% (wb) resulted in increase in tensile strength with values ranging from 14.3-114.7 MPa. The tensile strength of varieties with hollow stem type was higher than varieties with solid stem type. For example, “Commander”, a hollow stem type has a higher tensile strength than “Lilain”, a solid stem type (Fig. 4.8).

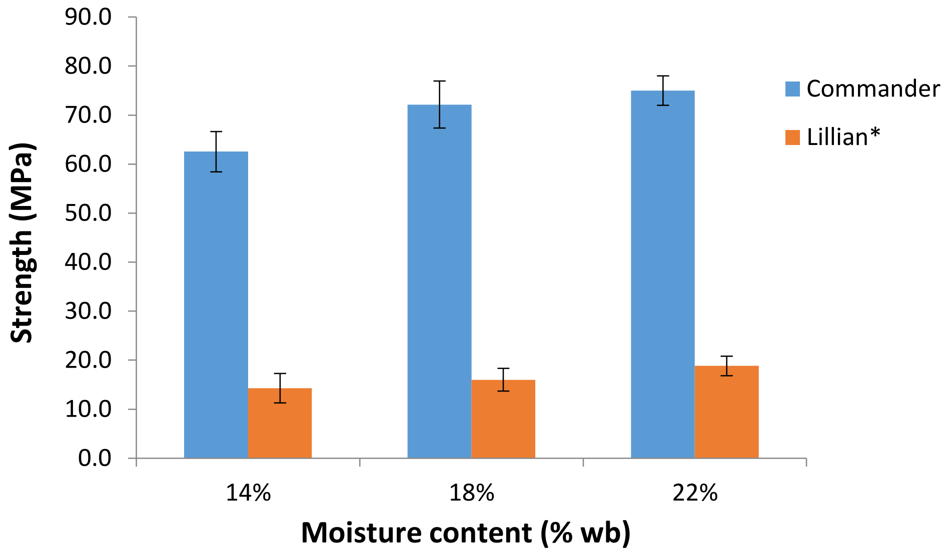


Fig. 4.8 Graph comparing stem tensile strength of ‘Commander’ and ‘Lilian’ first internode position at different moisture content (% wb).

Considering the tensile strength across the stem length revealed no consistent trend from the first to third internode. Some varieties like “Strongfield” and “Transcend” for example, had their highest strength at the third internode position while varieties like “HY1319” and “Carberry” had their highest value of tensile strength on the second internode position (Table 4.10).

Table 4.10 Tensile strength (MPa) of 12 different varieties of wheat stem at 3 moisture contents (MC) and 3 internode positions; N = 5.

Variety	Node	MC=14%	MC=18%	MC=22%
BW807*	First	22.4(2.2)^{bMx}	23.2(2.0)^{bNx}	33.3(3.6)^{bOx}
	second	26.5(1.7)^{bMy}	28.5(1.5)^{bNy}	34.4(4.0)^{bOy}
	Third	27.3(4.7)^{bMy}	29.6(5.0)^{bNy}	33.5(3.8)^{bOy}
DT818*	First	30.5(4.5)^{cMy}	32.2(4.9)^{cNy}	34.2(4.4)^{cOy}
	second	30.8(5.3)^{cMx}	32.7(5.9)^{cNx}	39.6(4.6)^{cOx}
	Third	26.7(3.5)^{cMx}	29.7(1.6)^{cNx}	33.6(2.5)^{cOx}
Lillian*	First	14.3(3.0)^{aMx}	16.0(2.3)^{aNx}	18.8(2.0)^{aOx}
	second	24.6(3.1)^{aMy}	26.3(2.5)^{aNy}	28.3(4.4)^{aOy}
	Third	24.0(1.6)^{aMy}	25.8(1.9)^{aNy}	35.6(5.0)^{aOy}
Blackbird	First	45.9(6.5)^{fMx}	60.3(12.0)^{fNx}	67.6(7.8)^{fOx}
	second	58.7(4.5)^{fMy}	62.3(6.8)^{fNy}	74.7(8.5)^{fOy}
	Third	68.2(6.2)^{fMy}	76.6(10.7)^{fNy}	83.0(5.0)^{fOy}
Carberry	First	43.2(9.3)^{dMx}	44.9(4.8)^{dNx}	51.3(11.9)^{dOx}
	second	50.1(1.7)^{dMy}	52.0(7.2)^{dNy}	57.3(4.1)^{dOy}
	Third	43.4(3.9)^{dMy}	47.7(5.3)^{dNy}	52.8(5.6)^{dOy}
Commander	First	62.5(4.1)^{fMy}	72.2(4.8)^{fNy}	75.0(3.0)^{fOy}
	second	59.8(5.3)^{fMx}	68.5(3.2)^{fNx}	72.1(5.6)^{fOx}
	Third	56.4(6.6)^{fMx}	60.0(4.8)^{fNx}	62.9(9.8)^{fOx}
DT833	First	65.5(10.0)^{gMx}	68.8(4.3)^{gNx}	77.4(5.6)^{gOx}
	second	90.1(7.9)^{gMy}	93.4(3.1)^{gNy}	114.7(7.8)^{gOy}
	Third	77.1(4.4)^{gMy}	79.5(9.6)^{gNy}	88.2(6.5)^{gOy}
HY1319	First	40.2(1.5)^{dMx}	44.6(5.2)^{dNy}	46.1(6.4)^{dOx}
	second	48.8(7.6)^{dMy}	56.6(6.9)^{dNx}	58.6(5.0)^{dOy}
	Third	41.0(7.8)^{dMy}	43.9(5.1)^{dNx}	47.2(7.5)^{dOy}
Shaw	First	37.3(1.5)^{eMx}	41.0(6.6)^{eNx}	46.9(4.1)^{eOx}
	second	64.4(2.8)^{eMy}	68.7(4.9)^{eNy}	73.4(3.3)^{eOy}
	Third	62.1(3.7)^{eMy}	66.9(6.7)^{eNy}	74.2(8.2)^{eOy}
Strongfield	First	41.8(9.1)^{fMx}	44.8(10.1)^{fNx}	48.3(7.5)^{fOx}
	second	52.5(5.6)^{fMy}	61.8(3.6)^{fNy}	79.7(6.9)^{fOy}
	Third	81.6(7.2)^{fMy}	85.7(5.2)^{fNy}	98.9(7.8)^{fOy}
Transcend	First	88.0(4.7)^{hMx}	92.9(5.7)^{hNx}	95.6(8.3)^{hOx}
	second	100.5(3.4)^{hMy}	103.1(2.8)^{hNy}	108.5(10.6)^{hOy}
	Third	94.8(5.9)^{hMy}	98.4(8.6)^{hNy}	108.3(12.3)^{hOy}
Unity	First	29.4(2.0)^{dMx}	36.8(3.3)^{dNx}	37.2(8.1)^{dOx}
	second	52.3(8.7)^{dMy}	55.6(7.6)^{dNy}	61.3(6.4)^{dOy}
	Third	51.3(7.0)^{dMy}	54.6(4.2)^{dNy}	62.9(9.5)^{dOy}

Solid stem varieties are indicated with *; Figures in parentheses are standard deviation; Means values with different letters are significantly different ($P < 0.05$); a-g - comparison of mean values across varieties at the same moisture and internode position; M, N, O - comparison of mean values across moisture levels at the same variety and internode position; x, y, z - comparison of mean values across internode position at the same moisture and variety.

Further analysis of the mean tensile strength obtained across the stem length (first, second, and third internode) revealed that “Strongfield”, “Shaw”, “Lilian”, and “Unity” had the highest variation across their stem length while “HY1319”, “Blackbird”, “DT833”, and “BW807” varieties recorded the least variation from the first internode to the third internode (Table 4.11). “DT818”, “Commander”, “Transcend”, and “Carberry” varieties were noted to have the least variation across the stem length (Table 4.11). The average coefficient of variation value indicates that there are similarities in the stem tensile strength from the first internode to the third internode.

Table 4.11 Coefficient of variation (CV) of tensile strength obtained by grouping the 3 internode positions under the same moisture contents (MC) and; N = 15.

Variety	**MC=14%**	**MC=18%**	**MC=22%**
BW807*	10.4	12.6	1.8
DT818*	7.8	5.1	9.2
Lillian*	27.6	25.6	30.5
Blackbird	19.4	13.4	10.3
Carberry	8.6	7.5	5.8
Commander	5.1	9.4	9.0
DT833	15.9	15.3	20.5
HY1319	10.9	14.8	13.7
Shaw	27.5	26.3	23.9
Strongfield	35.1	32.1	33.8
Transcend	6.6	5.2	7.1
Unity	29.2	21.6	26.8

Solid stem varieties are indicated with *

Comparing the results obtained with trends reported by previous researchers. Tavakoli et al. (2008) reported positive correlation of moisture content with shearing strength and energy. Limpiti (1980) and Chandio et al. (2013) noted similar trend for tensile strength and cutting strength, respectively. Esehaghbeygi et al. (2009) reported a negative correlation of moisture content with bending strength and modulus of elasticity, respectively. O’Dogherty et al. (1995) noted inconsistent trend across the stem length (internode position) for modulus of elasticity.

Comparing the results derived from investigating these mechanical properties with previous related studies published revealed that the current results of the mechanical strength (shearing, cutting, bending, and tensile) and modulus of elasticity were higher than previous results published (Table 4.12) although conforming higher values for tensile strength (128-399 MPa) have also been reported by Burmistrova et al. (1963) during their investigation on the "physicomechanical properties of agricultural crops". They excluded the intercellular areas when measuring the stem diameter (wall area) which resulted in the higher tensile strength value.

The difference in value is a result of the method used in determining the diameters (inner and outer) and subsequently area of the wheat stem. Previous researchers (Kushwaha et al. 1983; Tavakoli et al. 2009b; Alizadeh et al 2011) measured stem diameter directly from the circumference of the stem using either digital caliper or micrometer, but in this study, stem imaging was used in measuring the stem diameters where measurements were taken from fiber to fiber as discussed earlier in chapter 3. Stem area determined through imaging are smaller than stem area determined through vernier caliper or micrometer screw gauge. O'Dogherty et al. (1995) stated that stem areas measured by excluding the intercellular areas were 5 to 10 times smaller than area computed from the geometrical wall. Srivastava et al. (1994) recommended computing stem area by taking measurement between adjacent fibers in order to avoid over- or underestimating the strength during computation of the wheat mechanical properties.

Table 4.12 Comparing current mechanical test results with previous published results.

Mechanical test	**Researchers**	**Previous**	**Current** (14 to 22% wb)
Shearing strength	Tavakoli et al. (2009c) barley straw	4.69 to 5.41 MPa 10 to 20% wb	4.9-23.0 MPa
Shearing energy	Tavakoli et al. (2009c) barley straw	88.41-114.39 mJ 10 to 20% wb	62.4-319 mJ
Tensile strength	O'Dogherty et al. (1995) wheat straw	22.7-31.2 MPa 10 to 22% wb	14.3-114.7 MPa
Bending strength	Esehaghbeygi et al. (2009) wheat stem	26.77-17.74 MPa 15 to 45% wb	43.9-4.2 MPa
Modulus of elasticity	Tavakoli et al. (2009b) wheat straw	1.82-0.65 GPa 10.2 to 22.6% wb	3.5-0.14 GPa

4.2.5 Coefficient of friction

The coefficient of internal friction experienced an initial increase from 14 to 18% (wb) but subsequently decreased as the moisture increased to 22% (wb) with values varying between 0.095-0.669 and R^2 values ranging from 0.83-1.0, 0.72-1.0, and 0.78-1.0 for 14, 18, and 22% (wb), respectively (Table 4.13). This may be due to increase in the lubricating effect caused by the increased moisture content of the stem. However, some varieties ('Carberry' and 'DT818') did not follow this trend. The coefficient of internal friction of 'Carberry' variety decreased from 14 to 22% (wb) and increased with increased moisture for 'DT818' variety. No difference between the coefficient of friction of hollow stem and solid stem varieties was observed.

Table 4.13 Coefficient of internal friction of 12 different varieties of wheat stem at 3 moisture contents; N = 1.

	MC= 14%		**MC= 18%**		**MC= 22%**	
Variety	**Coefficient of internal friction**	**Cohesion (KPa)**	**Coefficient of internal friction**	**Cohesion (KPa)**	**Coefficient of internal friction**	**Cohesion (KPa)**
BW807*	0.399^{acN}	98.138	0.557^{bcM}	27.165	0.511^{abN}	28.121
DT818*	0.508^{aM}	41.895	0.534^{cN}	41.704	0.669^{aM}	51.46
Lillian*	0.339^{bcN}	52.417	0.451^{abM}	16.643	0.301^{bcN}	62.556
Blackbird	0.402^{acN}	55.095	0.496^{bcM}	36.539	0.261^{abN}	122.62
Carberry	0.482^{bcM}	23.722	0.307^{abN}	100.43	0.095^{bcM}	130.66
Commander	0.347^{bcN}	55.669	0.353^{abM}	102.73	0.287^{bcN}	130.85
DT833	0.410^{cN}	42.278	0.471^{bM}	91.060	0.247^{bN}	135.06
HY1319	0.250^{bcN}	78.243	0.488^{abM}	23.339	0.195^{bcN}	84.173
Shaw	0.207^{bcN}	110.96	0.603^{abM}	38.643	0.149^{bcN}	117.840
Strongfield	0.296^{bcN}	124.16	0.445^{abM}	77.478	0.336^{bcN}	70.973
Transcend	0.422^{acN}	56.052	0.488^{bcM}	66.191	0.278^{abN}	73.269
Unity	0.181^{bN}	95.843	0.187^{aM}	113.820	0.161^{cN}	103.3

Solid stem varieties are indicated with *
Means values with different letters are significantly different ($P < 0.05$)
a, b, c- comparison of mean values across varieties
M, N, O - comparison of mean values across moisture levels.

Comparison of the study was difficult to carry out as literatures found were focused on coefficient of internal friction of biomass grind and other bio-materials. However, those literatures reported varying values and trend. For example, Unuigbe et al. (2013) reported that the coefficient of internal friction of Dika nut increased from 0.52 to 0.90 for increased moisture content range of 8.25 and 18.98% db. Afzalinia and Roberge's (2007) reported that the coefficient of internal friction of alfalfa hay and barley straw at four cut lengths (10, 30, 60, and 90 mm) and 12% moisture content (wb) was 0.44-0.48 and 0.30-0.32, respectively, while the cohesion coefficient decreased from 27.9-10.5 kPa for alfalfa. The cohesion coefficient of barley had an initial increase from 34.4 to 36.1 kPa for cut length between 10 to 30 mm and subsequently decreased from 34.4-26.0 kPa as the length increased to 90 mm. Ghorbani et al. (2011) noted a decrease in the coefficient of internal friction of alfafa grind from 0.794-0.690 as the moisture content increased from 8-11% wb. The cohesion value increased between 5.793-6.705 kPa for the same moisture content range.

4.2.6 Compression properties

The particle densities of compressed straw of the twelve varieties of wheat straws as well as parameters B_1, B_2, h, and f values obtained in fitting the Power model (equation 3.8), and Pitt and Gebremedhin model (equation 3.9) to the compression data, respectively, are shown in Table 4.14. The test which was carried out at 14% (wb) moisture content and maximum pressure of 15 MPa indicated that particle density (compact) varied across varieties from 1059.12 to 1383.73 kg m^{-3} with 'Strongfield' having the highest particle density (1383.73 kg m^{-3}) while 'Commander' recorded the lowest (1059.12 kg m^{-3}).

Compression models (Pitt-Gebremedhin model and Power model) fitted to the experimental data indicated that both models could accurately predict the pressure acting on wheat straw during compression across all varieties although the Pitt-Gebremedhin model had more accuracy than Power model (Table 4.14). The values of 'h' and 'f' obtained across varieties by fitting Pitt-Gebremedhin model ranged from 0.564 to 1.667 and -0.0039 to -0.0024, respectively, with R^2 values between 0.989 and 1.00. The constant 'B1' and 'B2' in the power model varied between 2.13 to 2.81 and 0.47 x 10^{-7} to 45.4 x 10^{-7}, respectively, with R^2 values between 0.987 and 1.00. Grouping the varieties according to their stem types obtained h, f, B1, B2, and R^2 values as 0.993, -0.0032, 2.39, 8.55 x 10^{-7}, and 0.987, respectively, for hollow stem type and 1.034, -0.0031, 2.33, 11.80 x 10^{-7}, and 0.992, respectively, for solid stem type (Table 4.14).

The B_1 value shows the rate of increase in bulk density with increased pressure (van Pelt, 2003). He noted that smaller B_1 value indicates a slow rate of increased bulk density with increase in pressure. In this study, there was no significant difference in the B_1 value across the wheat varieties. Similar observations have also been reported by van Pelt (2003).

The constant B_2 gives an indication of the material's resistance (toughness) to compression (van Pelt, 2003; Kemmerer and Liu, 2014). They reported that higher pressure is required to increase the bulk density of a material with smaller B_2 value in comparison to material with larger B_2 value. From Table 4.14, "Commander", and "Shaw" varieties had the lowest B_2 value while "BW807" and "Blackbird" varieties had the highest B_2 value. The other varieties ("Strongfield", "HY1319", "Transcend", "Carberry", "Lilian", "Unity", "DT833", and "DT818") were in between. Comparison of the B_2 values of solid and hollow stem types indicated that there was no significant difference between both stem types (Table 4.14).

Van Pelt's (2003) study on biomass densification revealed that B_1-value for soyabean straw, wet corn stalk, dry corn stalk, and dry alfalfa hay as 0.24, 0.24, 0.29, and 0.23, respectively, while the corresponding B_2-values were 36.0, 48.9, 24.7, and 55.7, respectively. Robert (2009) obtained $B_{1,}$ and B_2 value of 0.312, and 77.56, respectively, for corn stover (R^2 = 0.75). Kemmerer and Liu (2014) reported values of 0.374 and 34.19 for B_1 and B_2, respectively, for switchgrass at moisture content of 12.6% (R^2 = 0.99). They also noted that the value of B_2 was affected by the moisture content. Similar effect on B_2 was also reported by Talebi et al. (2011). They obtained mean B_1 value of 3.36 for timothy hay (R^2 = 1).

Table 4.14 Post-compression particle densities (ρ, kg m^{-3}) and parameters h, f, B_1, and B_2, h and f values in fitting the Power model, and Pitt and Gebremedhin model, respectively, to applied compression pressure (P, MPa). β = dry matter density (kg m^{-3}) and β_0 = compact dry matter density (kg m^{-3}) N = 1794 (Df = 1793).

		Pitt and Gebremedhin model $P = h[e^{f(\beta-\beta_o)} - 1]$				**Power model** $P = B_2(\rho^{B_1})$			
Variety	**Particle density (kg m^{-3})**	**h**	**f**	**R^2**	**MAD**	**B_1**	**B_2 (x 10^{-7})**	**R^2**	**MAD**
BW807*	1218.67	1.235	-0.0027	1.000	0.016	2.18	29.30	0.993	0.111
DT1818*	1217.19	1.092	-0.0028	1.000	0.026	2.31	12.0	0.992	0.133
Lillian*	1167.13	0.979	-0.0031	1.000	0.032	2.38	8.22	0.996	0.084
Blackbird	1201.31	1.667	-0.0025	0.999	0.023	2.13	45.40	0.992	0.132
Carberry	1179.25	1.124	-0.0029	0.999	0.051	2.31	12.60	0.996	0.071
Commander	1059.12	0.790	-0.0036	0.999	0.026	2.49	4.38	0.990	0.126
DT833	1174.71	1.103	-0.0029	1.000	0.022	2.27	16.50	0.992	0.119
HY1319	1147.94	1.000	-0.0031	1.000	0.024	2.35	10.10	0.994	0.094
Shaw	1101.28	0.564	-0.0039	0.995	0.104	2.81	0.47	1.000	0.013
Strongfield	1383.73	1.219	-0.0024	0.998	0.090	2.23	16.0	0.998	0.032
Unity	1119.86	0.930	-0.0033	0.999	0.039	2.37	9.04	0.996	0.069
Hollow stems		0.993	-0.0032	0.989	0.087	2.39	8.55	0.987	0.107
Solid stems		1.034	-0.0031	0.998	0.039	2.33	11.80	0.992	0.115
All varieties		1.007	-0.0032	0.991	0.076	2.37	9.42	0.988	0.110

- Solid stem varieties are indicated with *
- R^2: coefficient of multiple determination.
- MAD: mean absolute deviation.

The study related to Pitt and Gebremedhin model was not compared as most researchers' work associated with fitting the model to compression data did not report the constant values of "h" and "f" obtained.

Relaxation model (Peleg and Moreyra model) fitted to the experimental data indicated the model could accurately predict the relaxation taking place after compression of wheat straw across all varieties (Table 4.15). The values of 'k_3' and 'k_4' obtained by fitting Peleg and Moreyra model ranged from 3.59 to 4.57 and 2.30 to 2.53, respectively, with R^2 values between 0.99 and 1.00. Grouping the varieties according to their stem types obtained 'k_3', 'k_4', and R^2 values for hollow stem type as 4.50, 2.49, and 0.98, respectively, and 4.10, 2.36, and 0.99, respectively, for solid stem type (Table 4.15). Since k_4 values obtained from the analysis were greater than one (Table 4.15), this shows that there are still some unrelaxed stresses that would make the wheat straw compact solid (Mani et al. 2006a).

No significant difference was observed between the average percentage relaxation and asymptotic modulus values of solid and hollow stem types (Table 4.15). Average percentage relaxation and asymptotic modulus ranged from 38.6 to 42.4% and 10.57 to 11.49 MPa, respectively. Talebi et al. (2011) noted that at 14.88 MPa pressure and 16.42% wb, the percentage relaxation and asymptotic modulus values for high quality hay was 35.6% and 10.50 MPa, respectively, while the percentage relaxation and asymptotic modulus values for low quality hay at moisture content of 16.24% and the same pressure was 47.9% and 10.33 MPa, respectively. Mani et al. (2006a) reported variability in the asymptotic values among the various biomass (barley straw, wheat straw, corn stover, and switch grass) while studying their mechanical properties. Shaw and Tabil (2007) noted that the asymptotic modulus for wheat straw grind (0.65 mm) varied between 25.48-129.83 MPa at pre-set load of 1000-4400 N.

Table 4.15 Parameters k_3 and k_4 values in fitting the Peleg and Moreyra model to relaxation data, average percentage relaxation, and asymptotic modulus of 12 different varieties of wheat stem; N = 650. (Df = 649)

	Peleg and Moreyra model $\frac{F_o.t}{F_o - F(t)} = k_3 + k_4.t$				**% Average relaxation**	**Asymptotic modulus** (MPa)
Variety	**k3**	**k4**	**R^2**	**MAD**	$R_{ap}= \frac{100\times(F_o-F_e)}{F_O}$	$E_A= \frac{F_O}{A_a\varepsilon}(1-\frac{1}{k_4})$
BW807*	3.93	2.42	0.9997	0.573	40.3	11.37
DT1818*	4.52	2.30	0.9996	0.701	42.3	11.12
Lillian*	4.19	2.53	0.9998	0.564	38.6	11.20
Blackbird	4.50	2.50	0.9997	0.606	39.2	11.17
Carberry	4.07	2.42	0.9998	0.534	40.4	10.57
Commander	4.57	2.30	0.9997	0.616	42.4	10.63
DT833	4.40	2.50	0.9998	0.536	39.1	11.16
HY1319	4.16	2.42	0.9997	0.605	40.5	11.44
Shaw	3.66	2.48	0.9998	0.493	39.5	11.13
Strongfield	4.06	2.36	0.9997	0.543	41.5	11.08
Transcend	3.84	2.38	0.9998	0.475	41.1	11.49
Unity	3.74	2.45	0.9998	0.415	40.1	11.14
Hollow stems	4.50	2.49	0.9819	0.365		
Solid stems	4.10	2.36	0.9980	1.493		
All varieties	3.59	2.34	0.9947	2.153		

- Solid stem varieties are indicated with *
- R^2: coefficient of multiple determination.
- MAD: mean absolute deviation.

4.3 Statistical analysis

Statistical analysis (ANOVA) of each dependent variable (shearing, bending, cutting, and tensile strength, shearing and cutting energy, modulus of elasticity, and coefficient of internal friction) with respect to moisture content, internode position, and variety was carried out. The analyses revealed that all three factors (moisture, internode, and variety) had significant effect ($P<0.05$) on all mechanical properties under study. The two way interaction of moisture and variety as well as internode and variety had significant effect ($P<0.05$) on all dependent variables. There was no interaction with respect to moisture and variety on the coefficient of internal friction due to less degree of freedom for moisture and variety (n = 1). Aside from tensile strength, shearing strength, and shearing energy, the interaction between moisture and internode had significant effect all other dependent variables (bending strength, cutting strength and energy, and modulus of elasticity) ($P<0.05$). The interaction between moisture and internode on coefficient of internal friction was not investigated since bailing is carried out irrespective of the internode position. Three way interaction of the independent variable (moisture, internode, and variety) only had significant effect on bending strength, cutting strength, and cutting energy ($P<0.05$).

4.4 Regression modeling

Further analysis was carried out to develop equations representing the relationship between each mechanical properties of wheat stem and the moisture content for each internode position (Table 4.16 to Table 4.23). It was observed that strength and energy results were slightly spread out mostly at 22% (wb). This led to some mechanical properties investigated (tensile strength, shearing strength and energy, and cutting strength and energy) having lower R^2 values while the bending strength and modulus of elasticity had higher R^2 values. Esehaghbeygi et al. (2009) reported a quadratic relationship with R^2 value of 96 % for shearing strength of wheat stem while Kushwaha et al. (1983) on the other hand, noted an exponential function with R^2 values ranging from 80 to 99 %. Tavakoli et al. (2009b) reported an exponential relationship between the bending strength and moisture content of wheat straw (R^2 = 0.93). Similar relationship with moisture content was presented by Galedar et al. (2009) on the tensile strength of alfafa. Laskowski (1999) developed a quadratic model relating moisture content to coefficient of internal friction for wheat, barley, and rye grain (R^2 = 0.84). Tavakoli et al. (2009b) reported quadratic relationship with R^2 value of 99.1 % for specific shearing energy of wheat straw and modulus of elasticity (0.961).

From the analysis of data, the quadratic relationship was able to describe the trend obtained across each mechanical properties best (highest R^2 value) in comparison to other mathematical functions (linear, exponential, and logarithm) which is similar to what Tavakoli et al. (2009b) reported for bending strength and specific shearing energy of wheat straw, Esehaghbeygi et al. (2009) for shearing energy of wheat stem, and Laskowski (1999) for coefficient of internal friction of wheat grain.

Table 4.16 Equations representing the relationship between the bending strength (σ_b in MPa) of wheat stem and moisture content (MC in % wb) for each internode position (first, second, and third); N=15 (Df = 13).

Variety	First Internode	Second Internode	Third Internode
BW807*	$\sigma_b = -0.0125MC^2 - 0.5759MC + 35.859$ $R^2 = 0.6984$	$\sigma_b = 0.0012MC^2 - 1.4864MC + 42.52$ $R^2 = 0.7315$	$\sigma_b = -0.0511MC^2 + 0.7111MC + 16.156$ $R^2 = 0.6711$
DT818*	$\sigma_b = 0.2913MC^2 - 11.964MC + 154.32$ $R^2 = 0.6104$	$\sigma_b = 0.139MC^2 - 5.9728MC + 81.468$ $R^2 = 0.3407$	$\sigma_b = -0.0477MC^2 + 1.6889MC + 5.2677$ $R^2 = 0.0076$
Lillian*	$\sigma_b = 0.0777MC^2 - 3.6182MC + 52.379$ $R^2 = 0.6287$	$\sigma_b = 0.039MC^2 - 2.1042MC + 40.623$ $R^2 = 0.4891$	$\sigma_b = -0.1268MC^2 + 3.4812MC - 4.104$ $R^2 = 0.6817$
Blackbird	$\sigma_b = 0.0676MC^2 - 5.2051MC + 99.569$ $R^2 = 0.8195$	$\sigma_b = -0.0302MC^2 + 0.4625MC + 21.832$ $R^2 = 0.2856$	$\sigma_b = 0.0079MC^2 - 0.8448MC + 28.937$ $R^2 = 0.5213$
Carberry	$\sigma_b = 0.0353MC^2 - 1.8209MC + 36.414$ $R^2 = 0.5513$	$\sigma_b = 0.1106MC^2 - 4.9592MC + 64.857$ $R^2 = 0.8582$	$\sigma_b = -0.0109MC^2 + 0.2399MC + 15.689$ $R^2 = 0.0144$
Commander	$\sigma_b = -0.0294MC^2 - 1.3551MC + 51.441$ $R^2 = 0.9471$	$\sigma_b = 0.1147MC^2 - 5.1357MC + 62.132$ $R^2 = 0.8915$	$\sigma_b = -0.0629MC^2 + 1.0497MC + 11.58$ $R^2 = 0.8835$
DT833	$\sigma_b = -0.0717MC^2 + 0.625MC + 37.741$ $R^2 = 0.8797$	$\sigma_b = -0.0496MC^2 - 0.3794MC + 46.062$ $R^2 = 0.904$	$\sigma_b = -0.0254MC^2 - 0.0663MC + 28.233$ $R^2 = 0.232$
HY1319	$\sigma_b = -0.0286MC^2 - 0.0946MC + 28.514$ $R^2 = 0.7596$	$\sigma_b = -0.0086MC^2 - 0.628MC + 26.228$ $R^2 = 0.651$	$\sigma_b = -0.0236MC^2 - 0.3001MC + 23.062$ $R^2 = 0.8772$
Shaw	$\sigma_b = 0.1437MC^2 - 6.2698MC + 84.823$ $R^2 = 0.7729$	$\sigma_b = -0.138MC^2 + 3.8469MC - 10.136$ $R^2 = 0.8481$	$\sigma_b = -0.007MC^2 - 0.5671MC + 37.069$ $R^2 = 0.5621$
Strongfield	$\sigma_b = 0.1367MC^2 - 5.6773MC + 79.411$ $R^2 = 0.2224$	$\sigma_b = 0.2191MC^2 - 9.6786MC + 120.03$ $R^2 = 0.8726$	$\sigma_b = 0.0653MC^2 - 3.8619MC + 68.563$ $R^2 = 0.6558$
Transcend	$\sigma_b = -0.1433MC^2 + 3.2078MC + 14.321$ $R^2 = 0.8849$	$\sigma_b = -0.1485MC^2 + 3.7494MC - 0.5242$ $R^2 = 0.7671$	$\sigma_b = 0.0477MC^2 - 3.7857MC + 68.608$ $R^2 = 0.8847$
Unity	$\sigma_b = -0.0166MC^2 + 0.0752MC + 28.964$ $R^2 = 0.1611$	$\sigma_b = -0.1231MC^2 + 3.6103MC - 4.3736$ $R^2 = 0.6174$	$\sigma_b = 0.0465MC^2 - 2.9945MC + 65.771$ $R^2 = 0.8428$
Hollow	$\sigma_b = 0.0104MC^2 - 1.835MC + 51.244$ $R^2 = 0.4032$	$\sigma_b = -0.0059MC^2 - 1.0124MC + 36.234$ $R^2 = 0.3589$	$\sigma_b = 0.0042MC^2 - 1.2367MC + 38.612$ $R^2 = 0.2199$
Solid	$\sigma_b = 0.1188MC^2 - 5.386MC + 80.853$ $R^2 = 0.1187$	$\sigma_b = 0.0597MC^2 - 3.1878MC + 54.87$ $R^2 = 0.4012$	$\sigma_b = -0.0752MC^2 + 1.9604MC + 5.7732$ $R^2 = 0.2113$

- Solid stem varieties are indicated with *

Table 4.17 Equations representing the relationship between the modulus of elasticity (E in GPa) of wheat stem and moisture content (MC in % wb) for each internode position (first, second, and third); N=15 (Df = 13).

Variety	First internode	Second internode	Third internode
BW807*	$E = -0.01MC^2 + 0.2842MC - 0.4107$ $R^2 = 0.3388$	$E = -0.0068MC^2 + 0.1733MC - 0.0924$ $R^2 = 0.5535$	$E = -0.0032MC^2 + 0.0459MC + 0.7653$ $R^2 = 0.8658$
DT818*	$E = -0.0054MC^2 + 0.1194MC + 2.31$ $R^2 = 0.1538$	$E = -0.003MC^2 + 0.0336MC + 1.4803$ $R^2 = 0.4952$	$E = -0.0077MC^2 + 0.2758MC - 1.5171$ $R^2 = 0.0834$
Lillian*	$E = -0.0018MC^2 + 0.0004MC + 1.3286$ $R^2 = 0.804$	$E = 0.004MC^2 - 0.1682MC + 2.379$ $R^2 = 0.3768$	$E = 0.0031MC^2 - 0.1268MC + 2.1484$ $R^2 = 0.0467$
Blackbird	$E = -0.0107MC^2 + 0.1415MC + 3.6072$ $R^2 = 0.6042$	$E = -0.0074MC^2 + 0.2126MC - 0.3591$ $R^2 = 0.3784$	$E = 0.0001MC^2 - 0.0392MC + 1.3619$ $R^2 = 0.3181$
Carberry	$E = -0.0023MC^2 + 0.0623MC + 0.3062$ $R^2 = 0.1926$	$E = 0.0018MC^2 - 0.1008MC + 1.5122$ $R^2 = 0.5915$	$0.0003MC^2 - 0.0235MC + 0.8658$ $R^2 = 0.0705$
Commander	$E = 0.0085MC^2 - 0.4755MC + 6.8651$ $R^2 = 0.8522$	$E = 0.0041MC^2 - 0.187MC + 2.311$ $R^2 = 0.7148$	$E = 0.0007MC^2 - 0.0631MC + 1.1985$ $R^2 = 0.5914$
DT833	$E = -0.0148MC^2 + 0.4252MC - 1.0658$ $R^2 = 0.6213$	$E = -0.0094MC^2 + 0.231MC + 0.014$ $R^2 = 0.6988$	$E = 0.0019MC^2 - 0.1028MC + 1.8871$ $R^2 = 0.2431$
HY1319	$E = -0.0025MC^2 + 0.0103MC + 1.538$ $R^2 = 0.7737$	$E = -0.0003MC^2 - 0.0335MC + 1.0539$ $R^2 = 0.7198$	$E = -0.0005MC^2 - 0.0267MC + 0.9598$ $R^2 = 0.867$
Shaw	$E = -0.0032MC^2 + 0.0606MC + 1.0229$ $R^2 = 0.3025$	$E = -0.0013MC^2 + 0.0115MC + 0.6777$ $R^2 = 0.4165$	$E = 0.0013MC^2 - 0.0833MC + 2.1474$ $R^2 = 0.264$
Strongfield	$E = -0.0076MC^2 + 0.1757MC + 0.4933$ $R^2 = 0.5467$	$E = 0.0031MC^2 - 0.1849MC + 3.028$ $R^2 = 0.8738$	$E = -0.0048MC^2 + 0.1064MC + 0.4441$ $R^2 = 0.5677$
Transcend	$E = -0.0135MC^2 + 0.3959MC - 1.1149$ $R^2 = 0.3765$	$E = 0.003MC^2 - 0.1642MC + 2.5506$ $R^2 = 0.4039$	$E = -0.0047MC^2 + 0.1094MC + 0.1054$ $R^2 = 0.6919$
Unity	$E = -0.0061MC^2 + 0.1804MC + 0.5109$ $R^2 = 0.1047$	$E = 0.0026MC^2 - 0.1191MC + 2.2659$ $R^2 = 0.1263$	$E = 0.0065MC^2 - 0.2816MC + 4.5305$ $R^2 = 0.1557$
Hollow	$E = -0.0058MC^2 + 0.1085MC + 1.3514$ $R^2 = 0.1904$	$E = -0.0004MC^2 - 0.0372MC + 1.4505$ $R^2 = 0.1984$	$E = 1E-04MC^2 - 0.0449MC + 1.5001$ $R^2 = 0.0865$
Solid	$E = -0.0057MC^2 + 0.1347MC + 1.076$ $R^2 = 0.0657$	$E = -0.0019MC^2 + 0.0129MC + 1.2556$ $R^2 = 0.3047$	$E = -0.0026MC^2 + 0.065MC + 0.4655$ $R^2 = 0.1038$

- Solid stem varieties are indicated with *

Table 4.18 Equations representing the relationship between the shearing strength (τ_s in MPa) of wheat stem and moisture content (MC in % wb) for each internode position (first, second, and third); N=15 (Df = 13).

Varieties	First internode	Second internode	Third internode
BW807*	$\tau_s = 0.0549MC^2 - 1.0218MC + 8.7271$ $R^2 = 0.6468$	$\tau_s = -0.0651MC^2 + 3.0119MC - 22.951$ $R^2 = 0.7503$	$\tau_s = -0.1144MC^2 + 4.6718MC - 38.087$ $R^2 = 0.5304$
DT818*	$\tau_s = 0.0259MC^2 - 0.5302MC + 10.24$ $R^2 = 0.1701$	$\tau_s = 0.0192MC^2 - 0.414MC + 9.6389$ $R^2 = 0.0674$	$\tau_s = -0.0003MC^2 + 0.2133MC + 3.0374$ $R^2 = 0.1699$
Lillian*	$\tau_s = 0.028MC^2 - 0.8089MC + 12.703$ $R^2 = 0.1419$	$\tau_s = 0.0367MC^2 - 0.7923MC + 9.4031$ $R^2 = 0.5774$	$\tau_s = -0.0283MC^2 + 1.4437MC - 8.7018$ $R^2 = 0.6692$
Blackbird	$\tau_s = -0.075MC^2 + 3.2352MC - 19.641$ $R^2 = 0.5306$	$\tau_s = 0.2101MC^2 - 6.7555MC + 63.285$ $R^2 = 0.7213$	$\tau_s = -0.0733MC^2 + 3.5871MC - 26.552$ $R^2 = 0.5106$
Carberry	$\tau_s = 0.0382MC^2 - 1.119MC + 17.857$ $R^2 = 0.2363$	$\tau_s = 0.0023MC^2 - 0.0256MC + 7.884$ $R^2 = 0.034$	$\tau_s = 0.0167MC^2 - 0.2234MC + 7.1028$ $R^2 = 0.3938$
Commander	$\tau_s = 0.076MC^2 - 1.8641MC + 23.466$ $R^2 = 0.718$	$\tau_s = -0.1576MC^2 + 6.4024MC - 53.507$ $R^2 = 0.5729$	$\tau_s = -0.155MC^2 + 6.3701MC - 52.594$ $R^2 = 0.3853$
DT833	$\tau_s = 0.0128MC^2 - 0.2736MC + 13.003$ $R^2 = 0.1391$	$\tau_s = -0.0129MC^2 + 0.786MC + 2.8994$ $R^2 = 0.2839$	$\tau_s = 0.0767MC^2 - 2.1559MC + 25.383$ $R^2 = 0.8507$
HY1319	$\tau_s = -0.0136MC^2 + 1.1599MC - 1.701$ $R^2 = 0.14$	$\tau_s = 0.018MC^2 - 0.4124MC + 12.11$ $R^2 = 0.1535$	$\tau_s = -0.0157MC^2 + 0.8607MC - 2.1576$ $R^2 = 0.3442$
Shaw	$\tau_s = -0.0186MC^2 + 0.8431MC + 2.2284$ $R^2 = 0.2882$	$\tau_s = 0.0033MC^2 + 0.0834MC + 9.7624$ $R^2 = 0.2466$	$\tau_s = -0.0221MC^2 + 0.995MC - 2.1719$ $R^2 = 0.4171$
Strongfield	$\tau_s = -0.0006MC^2 + 0.1536MC + 11.662$ $R^2 = 0.0396$	$\tau_s = 0.0053MC^2 + 0.0049MC + 13.112$ $R^2 = 0.154$	$\tau_s = 0.1096MC^2 - 3.0581MC + 37.263$ $R^2 = 0.4182$
Transcend	$\tau_s = -0.0438MC^2 + 2.1385MC - 12.14$ $R^2 = 0.3508$	$\tau_s = 0.0279MC^2 - 0.4782MC + 12.789$ $R^2 = 0.3191$	$\tau_s = -0.0567MC^2 + 2.1805MC - 8.8191$ $R^2 = 0.2082$
Unity	$\tau_s = -0.0107MC^2 + 0.5622MC + 1.8067$ $R^2 = 0.0812$	$\tau_s = -0.0169MC^2 + 0.8552MC + 1.4883$ $R^2 = 0.087$	$\tau_s = 0.0062MC^2 - 0.1346MC + 8.9704$ $R^2 = 0.0569$
Hollow	$\tau_s = -0.0039MC^2 + 0.5373MC + 4.0601$ $R^2 = 0.1272$	$\tau_s = 0.0088MC^2 + 0.0511MC + 7.7581$ $R^2 = 0.1421$	$\tau_s = -0.0126MC^2 + 0.9357MC - 1.5084$ $R^2 = 0.1274$
Solid	$\tau_s = 0.0363MC^2 - 0.787MC + 10.557$ $R^2 = 0.2868$	$\tau_s = -0.0031MC^2 + 0.6019MC - 1.3032$ $R^2 = 0.2907$	$\tau_s = -0.0476MC^2 + 2.1096MC - 14.584$ $R^2 = 0.389$

- Solid stem varieties are indicated with *

Table 4.19 Equations representing the relationship between the shearing energy (S_E in mJ) of wheat stem and moisture content (MC in % wb) for each internode position (first, second, and third); N=15 (Df = 13).

Varieties	**First internode**	**Second internode**	**Third internode**
BW807*	$S_E = 3.6253MC^2 - 111.72MC + 927.05$ $R^2 = 0.8558$	$S_E = 4.2751MC^2 - 124.82MC + 996.03$ $R^2 = 0.9673$	$S_E = 2.0442MC^2 - 49.686MC + 361.49$ $R^2 = 0.952$
DT818*	$S_E = -0.1734MC^2 + 8.6003MC + 14.59$ $R^2 = 0.172$	$S_E = 0.0162MC^2 + 1.6088MC + 146.85$ $R^2 = 0.0384$	$S_E = 0.1468MC^2 - 2.5469MC + 173.21$ $R^2 = 0.1286$
Lillian*	$S_E = 2.4896MC^2 - 78.28MC + 673.95$ $R^2 = 0.6397$	$S_E = 0.7183MC^2 - 18.199MC + 245.56$ $R^2 = 0.3467$	$S_E = 2.3079MC^2 - 68.256MC + 654.58$ $R^2 = 0.7884$
Blackbird	$S_E = 0.6224MC^2 - 18.144MC + 194.43$ $R^2 = 0.6629$	$S_E = 0.2036MC^2 - 3.6828MC + 122.17$ $R^2 = 0.5206$	$S_E = 0.3936MC^2 - 10.349MC + 191.85$ $R^2 = 0.3494$
Carberry	$S_E = 0.4741MC^2 - 13.62MC + 188.25$ $R^2 = 0.4159$	$S_E = -0.0735MC^2 + 3.3323MC + 104.2$ $R^2 = 0.0276$	$S_E = 0.1106MC^2 - 2.377MC + 133.78$ $R^2 = 0.0358$
Commander	$S_E = 2.5713MC^2 - 76.175MC + 657.38$ $R^2 = 0.5678$	$S_E = 0.1422MC^2 + 2.4155MC + 19.252$ $R^2 = 0.8014$	$S_E = -0.268MC^2 + 16.483MC - 76.195$ $R^2 = 0.6248$
DT833	$S_E = 0.0309MC^2 - 0.7216MC + 123.69$ $R^2 = 0.0079$	$S_E = -0.0343MC^2 + 2.5743MC + 129.88$ $R^2 = 0.0279$	$S_E = 0.0624MC^2 - 0.13MC + 147.77$ $R^2 = 0.0489$
HY1319	$S_E = 0.2905MC^2 - 4.3358MC + 96.209$ $R^2 = 0.2831$	$S_E = 1.5643MC^2 - 45.154MC + 436.93$ $R^2 = 0.7438$	$S_E = -0.6448MC^2 + 30.648MC - 207.48$ $R^2 = 0.5801$
Shaw	$S_E = 1.3305MC^2 - 40.929MC + 404.76$ $R^2 = 0.5002$	$S_E = 0.032MC^2 + 0.0682MC + 148.43$ $R^2 = 0.0306$	$S_E = 0.0096MC^2 + 2.4098MC + 101.24$ $R^2 = 0.1608$
Strongfield	$S_E = 3.3204MC^2 - 103.97MC + 916.06$ $R^2 = 0.6109$	$S_E = 0.8383MC^2 - 22.788MC + 312.17$ $R^2 = 0.2643$	$S_E = 0.1916MC^2 - 5.2838MC + 236.75$ $R^2 = 0.0356$
Transcend	$S_E = 0.5649MC^2 - 15.804MC + 224.58$ $R^2 = 0.3341$	$S_E = -0.0642MC^2 + 3.5794MC + 102$ $R^2 = 0.0329$	$S_E = -0.0212MC^2 + 1.1194MC + 121.32$ $R^2 = 0.0033$
Unity	$S_E = 0.5774MC^2 - 16.678MC + 191.89$ $R^2 = 0.8144$	$S_E = 1.5031MC^2 - 46.665MC + 456.79$ $R^2 = 0.3781$	$S_E = 0.3251MC^2 - 7.5462MC + 135.64$ $R^2 = 0.2636$
Hollow	$S_E = 1.0869MC^2 - 32.264MC + 333.03$ $R^2 = 0.2447$	$S_E = 0.4568MC^2 - 11.813MC + 203.53$ $R^2 = 0.1602$	$S_E = 0.0176MC^2 + 2.7749MC + 87.186$ $R^2 = 0.0861$
Solid	$S_E = 1.9805MC^2 - 60.466MC + 538.53$ $R^2 = 0.5015$	$S_E = 1.6699MC^2 - 47.137MC + 462.81$ $R^2 = 0.4203$	$S_E = 1.4996MC^2 - 40.163MC + 396.43$ $R^2 = 0.553$

- Solid stem varieties are indicated with *

Table 4.20 Equations representing the relationship between the cutting strength (σ_c in MPa) of wheat stem and moisture content (MC in % wb) for each internode position (first, second, and third); N=42 (Df = 40).

Variety	First internode	Second internode	Third internode
BW807*	$\sigma_c = 0.0527MC^2 - 1.6432MC + 15.489$ $R^2 = 0.3562$	$\sigma_c = 0.0005MC^2 + 0.0761MC + 1.2487$ $R^2 = 0.0877$	$\sigma_c = -0.0076MC^2 + 0.3382MC - 1.4677$ $R^2 = 0.1395$
DT818*	$\sigma_c = 0.0156MC^2 - 0.4605MC + 6.5512$ $R^2 = 0.1605$	$\sigma_c = -0.0067MC^2 + 0.3181MC - 0.3464$ $R^2 = 0.1631$	$\sigma_c = 0.0401MC^2 - 1.2115MC + 11.476$ $R^2 = 0.2038$
Lillian*	$\sigma_c = 0.0324MC^2 - 1.0074MC + 10.069$ $R^2 = 0.3447$	$\sigma_c = -0.0031MC^2 + 0.219MC - 0.2758$ $R^2 = 0.178$	$\sigma_c = -0.0052MC^2 + 0.2936MC - 0.7699$ $R^2 = 0.121$
Blackbird	$\sigma_c = 0.0147MC^2 - 0.095MC + 1.1212$ $R^2 = 0.6704$	$\sigma_c = 0.1712MC^2 - 5.3959MC + 45.497$ $R^2 = 0.7721$	$\sigma_c = 0.0484MC^2 - 1.3022MC + 13.615$ $R^2 = 0.3897$
Carberry	$\sigma_c = 0.0649MC^2 - 1.9582MC + 17.234$ $R^2 = 0.5915$	$\sigma_c = 0.0499MC^2 - 1.5662MC + 14.19$ $R^2 = 0.6352$	$\sigma_c = 0.0094MC^2 - 0.2235MC + 3.0728$ $R^2 = 0.2589$
Commander	$\sigma_c = 0.0619MC^2 - 1.541MC + 13.016$ $R^2 = 0.7497$	$\sigma_c = 0.0013MC^2 + 0.1503MC - 0.1798$ $R^2 = 0.2777$	$\sigma_c = -0.0005MC^2 + 0.076MC + 1.8463$ $R^2 = 0.0438$
DT833	$\sigma_c = 0.1176MC^2 - 3.6606MC + 33.483$ $R^2 = 0.7096$	$\sigma_c = 0.0761MC^2 - 2.2036MC + 21.322$ $R^2 = 0.5825$	$\sigma_c = 0.0344MC^2 - 0.9287MC + 12.076$ $R^2 = 0.4347$
HY1319	$\sigma_c = 0.0669MC^2 - 1.9994MC + 18.444$ $R^2 = 0.524$	$\sigma_c = 0.0642MC^2 - 1.9614MC + 17.083$ $R^2 = 0.8056$	$\sigma_c = 0.0088MC^2 - 0.2089MC + 2.6422$ $R^2 = 0.2001$
Shaw	$\sigma_c = 0.1142MC^2 - 3.5576MC + 30.705$ $R^2 = 0.5743$	$\sigma_c = 0.1061MC^2 - 3.3253MC + 28.459$ $R^2 = 0.7818$	$\sigma_c = 0.0534MC^2 - 1.6612MC + 16.476$ $R^2 = 0.3757$
Strongfield	$\sigma_c = 0.0521MC^2 - 1.5703MC + 16.573$ $R^2 = 0.4531$	$\sigma_c = -0.0485MC^2 + 2.1109MC - 16.741$ $R^2 = 0.6671$	$\sigma_c = 0.0091MC^2 - 0.108MC + 5.3806$ $R^2 = 0.2518$
Transcend	$\sigma_c = 0.1042MC^2 - 3.1886MC + 29.885$ $R^2 = 0.5553$	$\sigma_c = 0.1006MC^2 - 3.0902MC + 27.79$ $R^2 = 0.6176$	$\sigma_c = 0.0357MC^2 - 1.0611MC + 12.139$ $R^2 = 0.1758$
Unity	$\sigma_c = 0.0319MC^2 - 0.9944MC + 10.303$ $R^2 = 0.6098$	$\sigma_c = 0.0989MC^2 - 3.0087MC + 25.226$ $R^2 = 0.6305$	$\sigma_c = 0.0147MC^2 - 0.3019MC + 4.5585$ $R^2 = 0.5501$
Hollow	$\sigma_c = 0.0698MC^2 - 2.0628MC + 18.974$ $R^2 = 0.3899$	$\sigma_c = 0.0689MC^2 - 2.0322MC + 18.072$ $R^2 = 0.3801$	$\sigma_c = 0.0237MC^2 - 0.6355MC + 7.9785$ $R^2 = 0.1033$
Solid	$\sigma_c = 0.0336MC^2 - 1.0371MC + 10.703$ $R^2 = 0.2534$	$\sigma_c = -0.0031MC^2 + 0.2044MC + 0.2088$ $R^2 = 0.1198$	$\sigma_c = 0.0091MC^2 - 0.1932MC + 3.0796$ $R^2 = 0.1143$

- Solid stem varieties are indicated with *

Table 4.21 Equations representing the relationship between the cutting energy (C_E in mJ) of wheat stem and moisture content (MC in % wb) for each internode position (first, second, and third); N=42 (Df = 40).

Variety	First internode	Second internode	Third internode
BW807*	$C_E = 0.0577MC^2 + 2.0986MC + 7.5233$ $R^2 = 0.515$	$C_E = 0.0101MC^2 - 0.0329MC + 93.62$ $R^2 = 0.0021$	$C_E = 0.0881MC^2 - 2.1407MC + 101.3$ $R^2 = 0.0185$
DT818*	$C_E = -0.124MC^2 + 5.4162MC + 21.214$ $R^2 = 0.0673$	$C_E = -0.347MC^2 + 14.221MC - 22.918$ $R^2 = 0.0472$	$C_E = -0.1502MC^2 + 8.7295MC - 2.423$ $R^2 = 0.2034$
Lillian*	$C_E = -0.3736MC^2 + 15.624MC - 104.04$ $R^2 = 0.2961$	$C_E = -0.4967MC^2 + 20.707MC - 105.48$ $R^2 = 0.2397$	$C_E = -0.9037MC^2 + 37.058MC - 244.61$ $R^2 = 0.271$
Blackbird	$C_E = -0.3392MC^2 + 14.545MC - 104.97$ $R^2 = 0.6744$	$C_E = 0.4989MC^2 - 12.73MC + 127.43$ $R^2 = 0.7304$	$C_E = -0.0598MC^2 + 7.5425MC - 32.08$ $R^2 = 0.5158$
Carberry	$C_E = -0.0803MC^2 + 4.646MC - 11.15$ $R^2 = 0.3029$	$C_E = -0.4076MC^2 + 17.641MC - 122.9$ $R^2 = 0.5898$	$C_E = -0.3016MC^2 + 12.686MC - 72.157$ $R^2 = 0.2119$
Commander	$C_E = -0.4748MC^2 + 19.512MC - 134.37$ $R^2 = 0.437$	$C_E = -0.0772MC^2 + 4.6689MC - 23.255$ $R^2 = 0.1638$	$C_E = 0.0129MC^2 + 0.9617MC + 15.032$ $R^2 = 0.098$
DT833	$C_E = -0.5116MC^2 + 23.178MC - 176.45$ $R^2 = 0.5285$	$C_E = -0.3223MC^2 + 16.876MC - 111.26$ $R^2 = 0.4636$	$C_E = -0.3347MC^2 + 14.194MC - 50.191$ $R^2 = 0.1655$
HY1319	$C_E = -0.4661MC^2 + 19.351MC - 142.23$ $R^2 = 0.4414$	$C_E = -0.272MC^2 + 12.26MC - 59.662$ $R^2 = 0.2066$	$C_E = -0.0479MC^2 + 2.0851MC + 19.45$ $R^2 = 0.0172$
Shaw	$C_E = -0.5669MC^2 + 23.517MC - 183.94$ $R^2 = 0.6294$	$C_E = -1.1487MC^2 + 47.237MC - 391.38$ $R^2 = 0.7357$	$C_E = -0.8977MC^2 + 36.773MC - 263.12$ $R^2 = 0.4217$
Strongfield	$C_E = 0.0244MC^2 - 0.6335MC + 71.801$ $R^2 = 0.0072$	$C_E = -0.9667MC^2 + 39.38MC - 303.8$ $R^2 = 0.5276$	$C_E = 0.081MC^2 - 1.5004MC + 125.76$ $R^2 = 0.0228$
Transcend	$C_E = -0.1182MC^2 + 6.0151MC - 5.2646$ $R^2 = 0.1782$	$C_E = -0.1911MC^2 + 10.619MC - 61.113$ $R^2 = 0.408$	$C_E = -0.1989MC^2 + 8.9157MC - 33.443$ $R^2 = 0.175$
Unity	$C_E = -0.189MC^2 + 8.1657MC - 43.022$ $R^2 = 0.2924$	$C_E = -0.6926MC^2 + 28.118MC - 203.26$ $R^2 = 0.3911$	$C_E = 0.0208MC^2 - 0.0067MC + 66.113$ $R^2 = 0.0292$
Hollow	$C_E = -0.3024MC^2 + 13.144MC - 81.065$ $R^2 = 0.2098$	$C_E = -0.3977MC^2 + 18.23MC - 127.69$ $R^2 = 0.2887$	$C_E = -0.1918MC^2 + 9.0723MC - 24.959$ $R^2 = 0.0462$
Solid	$C_E = -0.1466MC^2 + 7.713MC - 25.101$ $R^2 = 0.1879$	$C_E = -0.2779MC^2 + 11.631MC - 11.594$ $R^2 = 0.0484$	$C_E = -0.3219MC^2 + 14.549MC - 48.576$ $R^2 = 0.1152$

- Solid stem varieties are indicated with *

Table 4.22 Equations representing the relationship between the tensile strength (σ_t in MPa) of wheat stem and moisture content (MC in % wb) for each internode position (first, second, and third); N=15 (Df = 13).

Varieties	**First internode**	**Second internode**	**Third internode**
BW807*	$\sigma_t = 0.2892MC^2 - 9.0437MC + 92.319$ $R^2 = 0.8081$	$\sigma_t = 0.1236MC^2 - 3.4582MC + 50.69$ $R^2 = 0.6696$	$\sigma_t = 0.0474MC^2 - 0.9265MC + 30.946$ $R^2 = 0.2878$
DT818*	$\sigma_t = 0.0093MC^2 + 0.1359MC + 26.748$ $R^2 = 0.1216$	$\sigma_t = 0.1572MC^2 - 4.5655MC + 63.941$ $R^2 = 0.3888$	$\sigma_t = 0.0267MC^2 - 0.1033MC + 22.921$ $R^2 = 0.5905$
Lillian*	$\sigma_t = 0.0345MC^2 - 0.6707MC + 16.902$ $R^2 = 0.418$	$\sigma_t = 0.0063MC^2 + 0.2354MC + 20.041$ $R^2 = 0.1942$	$\sigma_t = 0.2486MC^2 - 7.5001MC + 80.287$ $R^2 = 0.7592$
Blackbird	$\sigma_t = -0.2202MC^2 + 10.638MC - 59.875$ $R^2 = 0.5514$	$\sigma_t = 0.2725MC^2 - 7.8152MC + 114.71$ $R^2 = 0.5578$	$\sigma_t = -0.0634MC^2 + 4.1343MC + 22.725$ $R^2 = 0.4363$
Carberry	$\sigma_t = 0.1513MC^2 - 4.4324MC + 75.637$ $R^2 = 0.1544$	$\sigma_t = 0.1018MC^2 - 2.7644MC + 68.8$ $R^2 = 0.3294$	$\sigma_t = 0.0229MC^2 + 0.3496MC + 34.004$ $R^2 = 0.4267$
Commander	$\sigma_t = -0.2122MC^2 + 9.1956MC - 24.626$ $R^2 = 0.6849$	$\sigma_t = -0.161MC^2 + 7.3272MC - 11.209$ $R^2 = 0.5841$	$\sigma_t = -0.0188MC^2 + 1.4805MC + 39.396$ $R^2 = 0.1377$
DT833	$\sigma_t = 0.1638MC^2 - 4.4086MC + 95.106$ $R^2 = 0.3868$	$\sigma_t = 0.5583MC^2 - 17.024MC + 218.99$ $R^2 = 0.7699$	$\sigma_t = 0.1961MC^2 - 5.6714MC + 118.02$ $R^2 = 0.3567$
HY1319	$\sigma_t = -0.0859MC^2 + 3.8293MC + 3.4659$ $R^2 = 0.2493$	$\sigma_t = -0.1817MC^2 + 7.7752MC - 24.482$ $R^2 = 0.3407$	$\sigma_t = 0.0144MC^2 + 0.2637MC + 34.488$ $R^2 = 0.145$
Shaw	$\sigma_t = 0.0667MC^2 - 1.1938MC + 40.909$ $R^2 = 0.4859$	$\sigma_t = 0.0094MC^2 + 0.7873MC + 51.492$ $R^2 = 0.5457$	$\sigma_t = 0.0781MC^2 - 1.2968MC + 64.922$ $R^2 = 0.4228$
Strongfield	$\sigma_t = 0.0166MC^2 + 0.2164MC + 35.484$ $R^2 = 0.0995$	$\sigma_t = 0.2673MC^2 - 6.2308MC + 87.376$ $R^2 = 0.8374$	$\sigma_t = 0.2824MC^2 - 7.9923MC + 138.1$ $R^2 = 0.5955$
Transcend	$\sigma_t = -0.0703MC^2 + 3.4798MC + 53.079$ $R^2 = 0.2297$	$\sigma_t = 0.0849MC^2 - 2.0586MC + 112.68$ $R^2 = 0.238$	$\sigma_t = 0.1952MC^2 - 5.3435MC + 131.35$ $R^2 = 0.318$
Unity	$\sigma_t = -0.2218MC^2 + 8.9584MC - 52.546$ $R^2 = 0.376$	$\sigma_t = 0.0702MC^2 - 1.4021MC + 58.15$ $R^2 = 0.2284$	$\sigma_t = 0.1539MC^2 - 4.0838MC + 78.267$ $R^2 = 0.3624$
Hollow	$\sigma_t = -0.0458MC^2 + 2.9203MC + 18.515$ $R^2 = 0.0476$	$\sigma_t = 0.1135MC^2 - 2.3783MC + 75.168$ $R^2 = 0.0835$	$\sigma_t = 0.0956MC^2 - 2.0177MC + 73.474$ $R^2 = 0.0571$
Solid	$\sigma_t = 0.111MC^2 - 3.1928MC + 45.323$ $R^2 = 0.1208$	$\sigma_t = 0.0957MC^2 - 2.5961MC + 44.891$ $R^2 = 0.2529$	$\sigma_t = 0.133MC^2 - 3.6872MC + 51.3$ $R^2 = 0.6336$

- Solid stem varieties are indicated with *

Table 4.23 Equations representing the relationship between the coefficient of internal friction (μ) of wheat straw and moisture content (MC in % wb); N=3 (Df = 1).

Variety	**Polynomial**	**Exponential**
BW807*	$\mu = -0.0064MC^2 + 0.243MC - 1.7565$ $R^2 = 1$	$\mu = 0.2777e^{0.0309MC}$ $R^2 = 0.5104$
DT818*	$\mu = 0.0034MC^2 - 0.1027MC + 1.2768$ $R^2 = 1$	$\mu = 0.3049e^{0.0344MC}$ $R^2 = 0.88$
Lillian*	$\mu = -0.0082MC^2 + 0.2891MC - 2.1092$ $R^2 = 1$	$\mu = 0.4658e^{-0.015MC}$ $R^2 = 0.0795$
Blackbird	$\mu = -0.0103MC^2 + 0.3537MC - 2.5285$ $R^2 = 1$	$\mu = 0.9843e^{-0.054MC}$ $R^2 = 0.4328$
Carberry	$\mu = -0.0012MC^2 - 0.0066MC + 0.802$ $R^2 = 1$	$\mu = 9.386e^{-0.203MC}$ $R^2 = 0.938$
Commander	$\mu = -0.0022MC^2 + 0.0732MC - 0.2385$ $R^2 = 1$	$\mu = 0.5029e^{-0.024MC}$ $R^2 = 0.6852$
DT833	$\mu = -0.0089MC^2 + 0.2992MC - 2.038$ $R^2 = 1$	$\mu = 1.1378e^{-0.064MC}$ $R^2 = 0.5586$
HY1319	$\mu = -0.0166MC^2 + 0.5904MC - 4.7649$ $R^2 = 1$	$\mu = 0.5004e^{-0.031MC}$ $R^2 = 0.0675$
Shaw	$\mu = -0.0265MC^2 + 0.9484MC - 7.8684$ $R^2 = 1$	$\mu = 0.5509e^{-0.041MC}$ $R^2 = 0.0497$
Strongfield	$\mu = -0.0081MC^2 + 0.2956MC - 2.2607$ $R^2 = 1$	$\mu = 0.2654e^{0.0159MC}$ $R^2 = 0.0925$
Transcend	$\mu = -0.0086MC^2 + 0.292MC - 1.9788$ $R^2 = 1$	$\mu = 0.9824e^{-0.052MC}$ $R^2 = 0.5096$
Unity	$\mu = -0.001MC^2 + 0.0329MC - 0.0872$ $R^2 = 1$	$\mu = 0.229e^{-0.015MC}$ $R^2 = 0.5627$
Hollow	$\mu = -0.0093MC^2 + 0.3199MC - 2.3292$ $R^2 = 0.4171$	$\mu = 0.7624e^{-0.052MC}$ $R^2 = 0.1471$
Solid	$\mu = -0.0037MC^2 + 0.1432MC - 0.863$ $R^2 = 0.1546$	$\mu = 0.3404e^{0.0169MC}$ $R^2 = 0.0534$

- Solid stem varieties are indicated with *

CHAPTER FIVE

SUMMARY AND CONCLUSIONS

This chapter presents the conclusions that were drawn from the experimental results of this research. The conclusions have been subdivided and itemized according to the research objectives stated in Chapter 1.2.

5.1 Moisture content, internode position, and wheat variety

The following conclusions were made based on the main and interactive effect of moisture content, internode position, and wheat variety on coefficient of internal friction, shearing, cutting, bending, and tensile:

1. Moisture content had significant effect on all mechanical properties investigated across all varieties.
2. The increase in stem moisture from 14 to 22% (wb) resulted in an increase in the shearing strength, and energy, cutting strength, and energy as well as the tensile strength; however, increased moisture content resulted in a decrease in bending strength and modulus of elasticity.
3. There was no consistent trend across the stem internode positions (from first to third) in relation to the tensile strength, shearing strength, and energy, cutting strength, and energy as well as bending strength, and modulus of elasticity.
4. Mechanical strength values obtained in this work were slightly higher than previously published results. The difference was due to the dissimilarity in the method used for measuring the stem diameters.
5. The coefficient of internal friction increased from 14 to 18% (wb) and subsequently decreased as the moisture increased to 22% (wb). The increased lubrication between straws caused by increase in moisture content could be responsible for this trend.
6. There was variation in the strength, energy, modulus of elasticity, and coefficient of internal friction obtained across the wheat varieties studied. This was accounted for by the difference in the composition and morphology of each stem.

5.2 Wheat stem type

The following conclusions were made based on analysis carried out on the mechanical properties of wheat stem type:

1. Solid stem type (“BW807”, “Lilian”, and “DT1818”) had lower shearing, cutting and tensile strength than hollow stem (“Commander”, “Strongfield”, “Transcend”, Shaw, “HY1319”, “Carberry”, “Unity”, “Blackbird”, and “DT833”).
2. There was no difference between both stem types in relation to coefficient of internal friction, shearing, and cutting energy as well as bending strength and modulus of elasticity.

5.3 Modelling

The following conclusions were made based on developing mathematical models for each mechanical property investigated:

1. Equations relating moisture content to shearing strength and energy, cutting strength and energy, bending strength, modulus of elasticity, and coefficient of internal friction, respectively, were developed.
2. Strength and energy results were slightly spread out mostly at 22% (wb) given rise to lower R^2 value in some mechanical properties investigated (tensile strength, shearing strength and energy, and cutting strength and energy).

5.4 Compression and relaxation characteristics

The following conclusions were made based on fitting compression and relaxation models to the compression and relaxation data of wheat straw:

1. The particle densities (compact) varied from 1059.12 to 1383.73 kg m^{-3} across varieties with ‘Strongfield’ having the highest particle density while ‘Commander’ recorded the lowest.
2. Compression models fitted to the experimental data accurately predicted pressure required to compress wheat straw as a function of straw density.

3. Between the two models fitted to experimental data of wheat straw compression, Pitt and Gebremedhin model fitted more accurately than the power model.
4. The B_2 value obtained in fitting the power model to the compression data indicated that to compact straw to the same bulk density, “Commander”, and “Shaw” varieties required highest pressure while “BW807”, and “Blackbird” varieties needed the lowest pressure. The other varieties (“Strongfield”, “HY1319”, “Transcend”, “Carberry”, “Lilian”, “Unity”, “DT833”, and “DT818”) were in between.
5. Comparing the B_2 values of both stem types revealed that there was no significant difference between varieties with solid stem type and varieties with hollow stem type.
6. Peleg and Moreyra model was applicable to the relaxation data of wheat straw.
7. The k_4 values obtained from fitting the Peleg and Moreyra model to the relaxation data were greater than one ($k_4 > 1$) indicating that there were still some unrelaxed stresses that would make the wheat straw compact solid.
8. There was no difference between the average percentage relaxation and asymptotic modulus of solid and hollow stem type.

5.5 General

The following conclusions were made from general observations during the course of the experiments reported:

1. Harvesting should be carried out at lower moisture content since it results in lower energy consumption and increase stem standability (higher bending strength).
2. Little or no modification to harvesting machines is needed to accommodate the solid stem type of wheat.
3. No internode position can be recommended to reduce strength and energy used during harvesting due to variation of strength and energy across the internode positions.

RECOMMENDATIONS

The following list of recommendations is presented for further research:

1. A study on the effect of loading rate on the tensile strength, shearing strength and energy, cutting strength and energy bending strength and modulus of elasticity should be considered.
2. During cutting test, it was observed that moisture might have affected the sharpness of the blade. It may also be beneficial to study the type of blade used for cutting.
3. Higher stereoscope's magnification should also be used during future studies to have a better quality of the wheat stem's image. This will aid measurement of the diameters and subsequently stem area.
4. In the coefficient of internal friction, single replicate was used for each treatment due to limited wheat varieties material. The number of replicate should be increase to ascertain the trend observed in relation with the coefficient of internal friction.
5. During compression and relaxation study, only one level of moisture content and compaction pressure, respectively, was investigated using a single replicate. More levels of moisture content and compaction pressure should be considered as well as the sample replicate should be increased to validate the applicability of the compression and relaxation model to wheat straw at different moisture content levels.

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APPENDIX

A.1 Experimental moisture content determination after conditioning

Desire Moisture (% wb)	**Sample**	**m_i** (g)	**m_f** (g)	$X = m_I - m_f$	**MC** = $\frac{X}{m_i} * 100$ (% wb)
14	1	3.842	3.269	0.573	14.9
	2	3.594	3.088	0.506	14.1
	3	3.487	2.988	0.499	14.3
18	1	3.741	3.053	0,688	18.4
	2	3.629	2.968	0.661	18.2
	3	3.453	2.837	0.616	17.8
22	1	3.638	2.838	0.800	22.0
	2	3.860	2.990	0.870	22.5
	3	3.716	2.888	0.828	22.3

MC = Moisture content of the sample (% wb)
m_i = Initial mass of the sample (g)
m_f = Final mass of the sample (g)

A.2 Mechanical property test

Figure-A.2.1. Shearing test

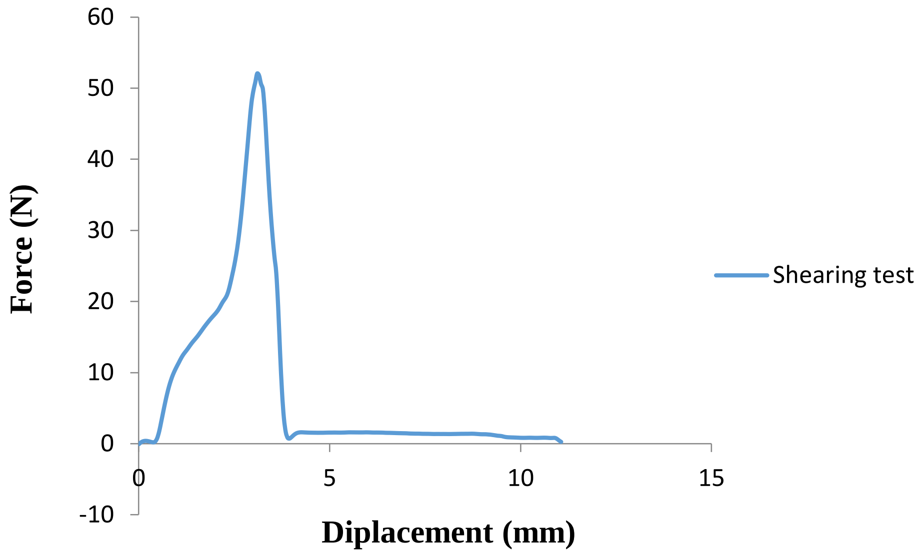

Figure-A.2.2. Bending test

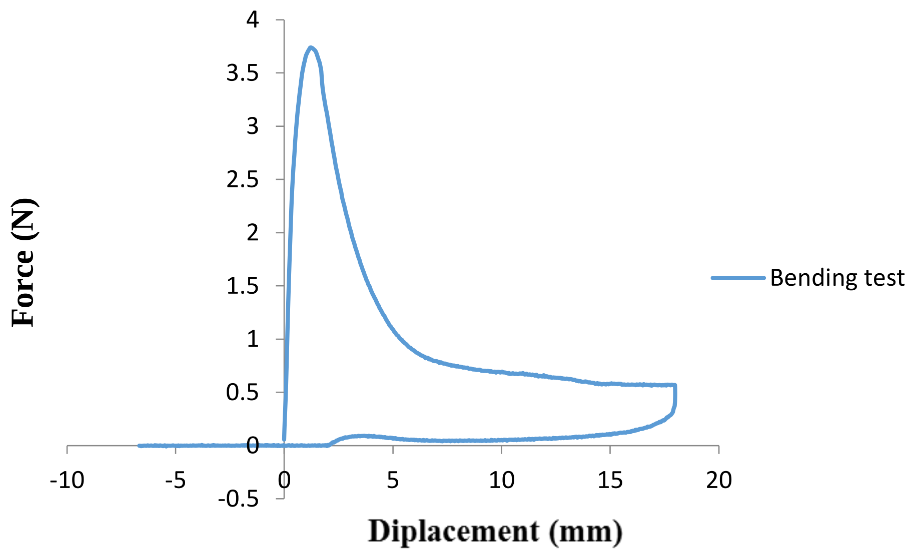

Figure-A.2.3. Cutting test

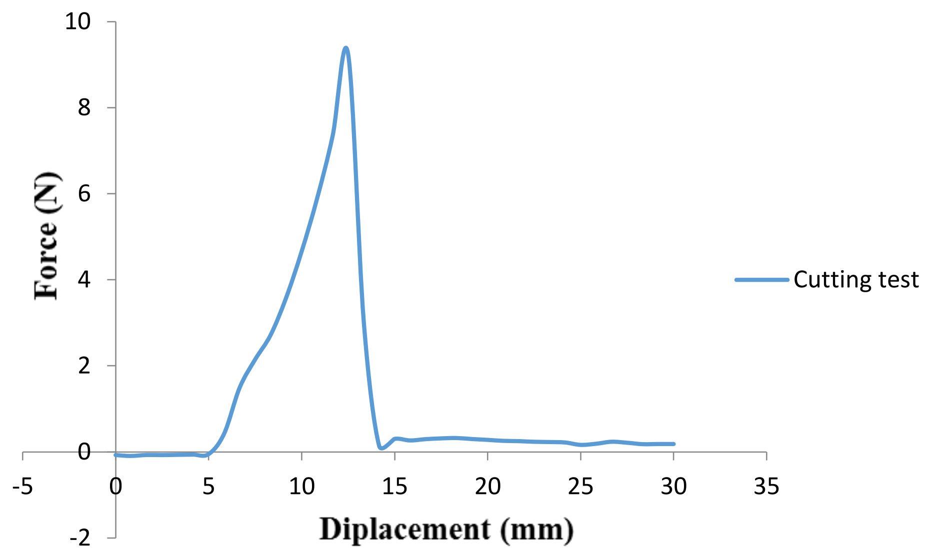

Figure-A.2.4. Tensile test

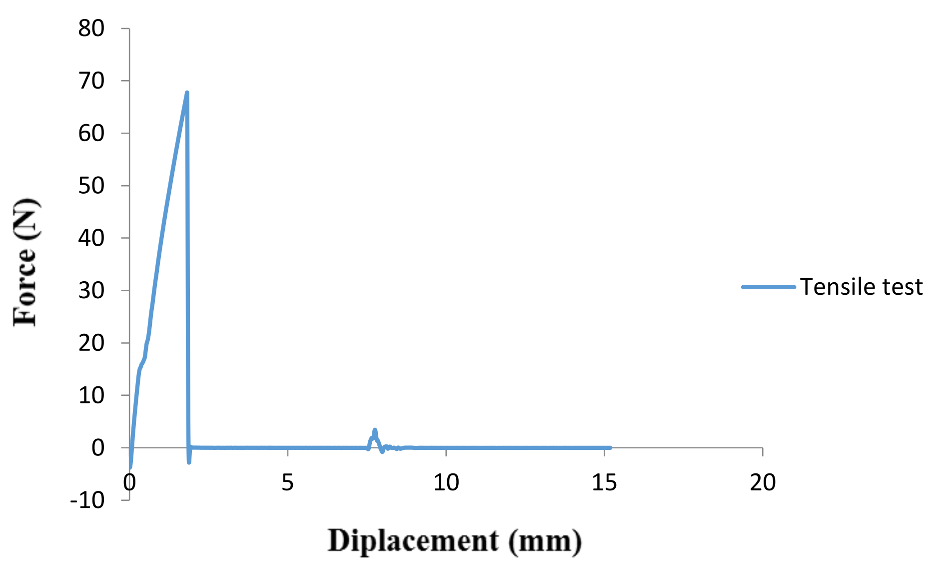

Figure-A.2.5. Coefficient of friction test

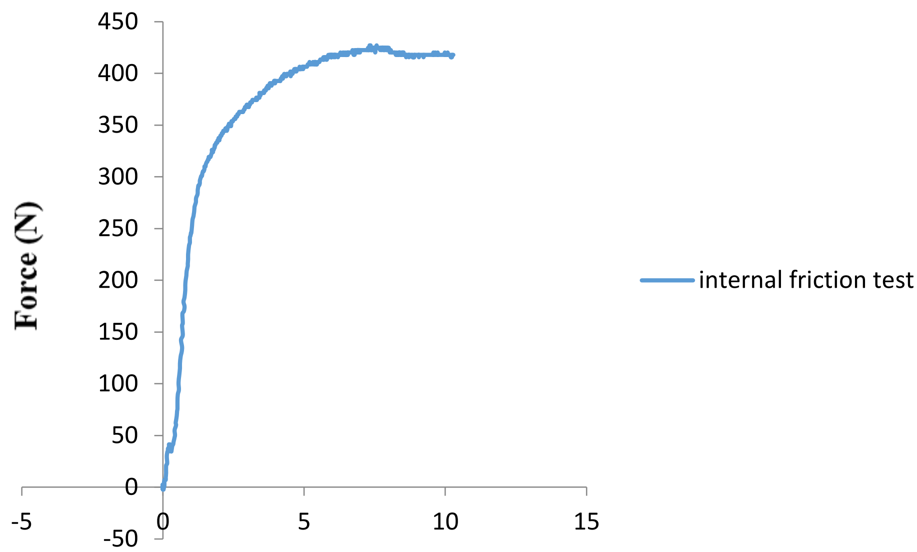

Figure-A.2.5. Compression test

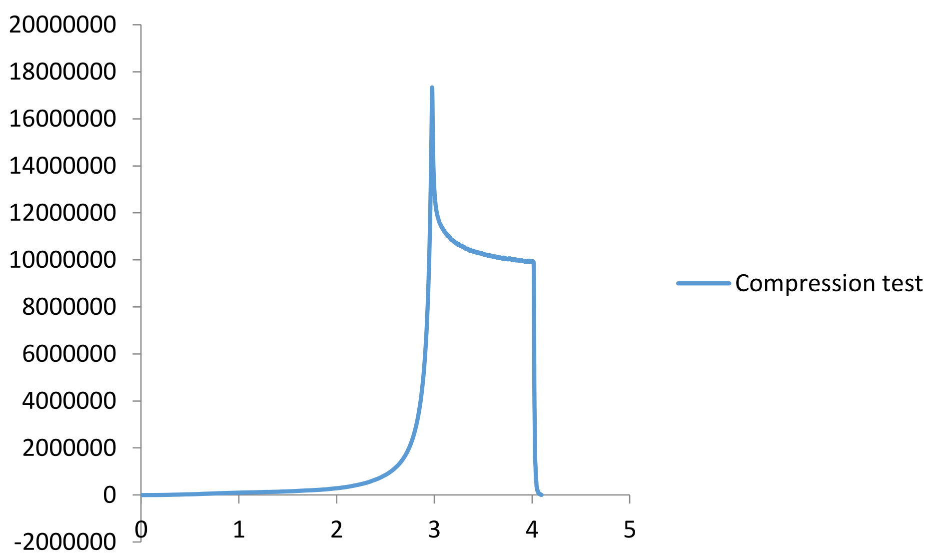

Table B-1. Analysis of variance of the shearing strength of wheat stem.

Source	Type III Sum of Squares	Df	Mean Square	F	Sig.
Corrected Model	5724.971[a]	107	53.504	8.975	0.000
Intercept	63355.959	1	63355.959	10627.449	0.000
Variety	2874.938	11	261.358	43.841	0.000
Internode	140.811	2	70.405	11.810	0.000
Moisture	1059.315	2	529.657	88.846	0.000
Variety * Internode	1101.755	22	50.080	8.400	0.000
Variety * Moisture	282.378	22	12.835	2.153	0.002
Internode * Moisture	8.629	4	2.157	0.362	0.836
Variety * Internode * Moisture	257.145	44	5.844	0.980	0.511
Error	2575.385	432	5.962		
Total	71656.315	540			
Corrected Total	8300.356	539			

a. R^2 = 0.690 (Adjusted R^2 = 0.613)

Table B-2. Analysis of variance of the shearing energy of wheat stem.

Source	Type III Sum of Squares	Df	Mean Square	F	Sig.
Corrected Model	1086584.132[a]	107	10154.992	12.105	0.000
Intercept	10459689.436	1	10459689.436	12468.718	0.000
Variety	221929.345	11	20175.395	24.051	0.000
Internode	154288.812	2	77144.406	91.962	0.000
Moisture	291960.225	2	145980.113	174.019	0.000
Variety * Internode	115126.150	22	5233.007	6.238	0.000
Variety * Moisture	240475.924	22	10930.724	13.030	0.000
Internode * Moisture	7732.155	4	1933.039	2.304	0.058
Variety * Internode * Moisture	55071.520	44	1251.625	1.492	0.026
Error	362393.767	432	838.874		
Total	11908667.334	540			
Corrected Total	1448977.899	539			

a. R^2 = 0.750 (Adjusted R^2 = 0.688)

Table B-3. Analysis of variance of the bending strength of wheat stem.

Source	Type III Sum of Squares	Df	Mean Square	F	Sig.
Corrected Model	28489.710[a]	107	266.259	24.775	0.000
Intercept	187231.986	1	187231.986	17421.839	0.000
Variety	9705.374	11	882.307	82.098	0.000
Moisture	8082.532	2	4041.266	376.038	0.000
Internode	3510.006	2	1755.003	163.302	0.000
Variety * Moisture	920.647	22	41.848	3.894	0.000
Variety * Internode	4845.461	22	220.248	20.494	0.000
Moisture * Internode	146.893	4	36.723	3.417	0.009
Variety * Moisture * Internode	1278.796	44	29.064	2.704	0.000
Error	4642.691	432	10.747		
Total	220364.387	540			
Corrected Total	33132.401	539			

a. $R^2 = 0.860$ (Adjusted $R^2 = 0.825$)

Table B-4. Analysis of variance of the Young's modulus of wheat stem.

Source	Type III Sum of Squares	Df	Mean Square	F	Sig.
Corrected Model	200799162.592[a]	107	1876627.688	22.575	0.000
Intercept	484930412.216	1	484930412.216	5833.480	0.000
Variety	64269555.558	11	5842686.869	70.285	0.000
Internode	60116822.848	2	30058411.424	361.588	0.000
Moisture	22023342.875	2	11011671.437	132.465	0.000
Variety * Internode	42287689.886	22	1922167.722	23.123	0.000
Variety * Moisture	3786440.207	22	172110.919	2.070	0.003
Internode * Moisture	3261687.693	4	815421.923	9.809	0.000
Variety * Internode * Moisture	5053623.525	44	114855.080	1.382	0.058
Error	35911658.127	432	83128.838		
Total	721641232.935	540			
Corrected Total	236710820.719	539			

a. $R^2 = 0.848$ (Adjusted $R^2 = 0.811$)

Table B-5. Analysis of variance of the cutting strength of wheat stem.

Source	Type III Sum of Squares	Df	Mean Square	F	Sig.
Corrected Model	6247.983[a]	107	58.392	39.469	0.000
Intercept	27775.185	1	27775.185	18773.932	0.000
Variety	2904.579	11	264.053	178.480	0.000
Internode	147.726	2	73.863	49.926	0.000
Moisture	1736.672	2	868.336	586.930	0.000
Variety * Internode	691.812	22	31.446	21.255	0.000
Variety * Moisture	367.412	22	16.701	11.288	0.000
Internode * Moisture	133.900	4	33.475	22.627	0.000
Variety * Internode * Moisture	265.884	44	6.043	4.084	0.000
Error	2077.155	1404	1.479		
Total	36100.323	1512			
Corrected Total	8325.138	1511			

a. $R^2 = 0.750$ (Adjusted $R^2 = 0.731$)

Table B-6. Analysis of variance of the cutting energy of wheat stem.

Source	Type III Sum of Squares	Df	Mean Square	F	Sig.
Corrected Model	1017844.673[a]	107	9512.567	34.122	0.000
Intercept	7811219.060	1	7811219.060	28019.199	0.000
Variety	448612.222	11	40782.929	146.290	0.000
Internode	176584.544	2	88292.272	316.708	0.000
Moisture	121947.844	2	60973.922	218.716	0.000
Variety * Internode	222259.161	22	10102.689	36.239	0.000
Variety * Moisture	21263.350	22	966.516	3.467	0.000
Internode * Moisture	3963.505	4	990.876	3.554	0.007
Variety * Internode * Moisture	23214.047	44	527.592	1.892	0.000
Error	391408.458	1404	278.781		
Total	9220472.191	1512			
Corrected Total	1409253.131	1511			

a. $R^2 = 0.722$ (Adjusted $R^2 = 0.701$)

Table B-7. Analysis of variance of the tensile strength of wheat stem.

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	298596.304[a]	107	2790.620	75.030	0.000
Intercept	1686031.049	1	1686031.049	45331.733	0.000
Variety	244961.485	11	22269.226	598.745	0.000
Internode	16569.964	2	8284.982	222.755	0.000
Moisture	10247.821	2	5123.911	137.765	0.000
Variety * Internode	23478.753	22	1067.216	28.694	0.000
Variety * Moisture	1687.163	22	76.689	2.062	0.003
Internode * Moisture	194.024	4	48.506	1.304	0.268
Variety * Internode * Moisture	1457.094	44	33.116	0.890	0.673
Error	16067.451	432	37.193		
Total	2000694.804	540			
Corrected Total	314663.755	539			

a. $R^2 = 0.949$ (Adjusted $R^2 = 0.936$)

Table B-8. Analysis of variance of the coefficient of internal friction of wheat straw.

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	0.468[a]	13	0.036	3.478	0.005
Intercept	4.773	1	4.773	460.700	0.000
Varieties	0.318	11	0.029	2.789	0.020
Moisture	0.151	2	0.075	7.268	0.004
Error	0.228	22	0.010		
Total	5.469	36			
Corrected Total	0.696	35			

a. $R^2 = 0.673$ (Adjusted $R^2 = 0.479$)

DMRT- **Duncan multiple range test**

Table C-1. DMRT of shearing strength for moisture

Duncan[a,b]

Moisture	N	Subset		
		1	2	3
14	180	9.100		
18	180		10.865	
22	180			12.530
Sig.		1.000	1.000	1.000

Means for groups in homogeneous subsets are displayed.
Based on observed means.
The error term is Mean Square (Error) = 5.962.
a. Uses Harmonic Mean Sample Size = 180.000.
b. Alpha = 0.05.

Table C-2. DMRT of shearing strength for variety

Duncana,b

Variety	N	Subset						
		1	2	3	4	5	6	7
lilian*	45	7.578						
dt818*	45	8.257	8.257					
bw807*	45	8.641	8.641	8.641				
Carberry	45		9.127	9.127				
Unity	45			9.389				
Shaw	45				10.625			
hy1319	45				11.144			
Commander	45				11.517	11.517		
Transcend	45					12.227	12.227	
dt833	45					12.446	12.446	
Blackbird	45						13.000	
Strongfield	45							16.030
Sig.		0.050	0.112	0.172	0.102	0.088	0.159	1.000

Means for groups in homogeneous subsets are displayed.
Based on observed means.
The error term is Mean Square (Error) = 5.962.
a. Uses Harmonic Mean Sample Size = 45.000.
b. Alpha = 0.05.

Table C-3. DMRT of shearing strength for internode

Duncan[a,b]

Internode	N	Subset 1	2	3
Third	180	10.197		
Second	180		10.850	
First	180			11.448
Sig.		1.000	1.000	1.000

Means for groups in homogeneous subsets are displayed.
Based on observed means.
The error term is Mean Square (Error) = 5.962.
a. Uses Harmonic Mean Sample Size = 180.000.
b. Alpha = 0.05.

Table C-4. DMRT of shearing energy for moisture

Duncan[a,b]

Moisture	N	Subset 1	2	3
14	180	116.09276038434975		
18	180		130.433886937324730	
22	180			170.999588093171380
Sig.		1.000	1.000	1.000

Means for groups in homogeneous subsets are displayed.
Based on observed means.
The error term is Mean Square (Error) = 838.874.
a. Uses Harmonic Mean Sample Size = 180.000.
b. Alpha = 0.05.

Table C-5. DMRT of shearing energy for variety

Duncan[a,b]

Variety	N	Subset 1	2	3	4	5	6	7
Unity	45	104.4611600084						
Blackbird	45	112.4780430908	112.4780430908					
Carberry	45		123.1053077258	123.1053077258				
commander	45			129.2902435738	129.290243573			
hy1319	45			130.4822935326	130.482293532			
Transcend	45				136.166654454			
Shaw	45				140.516941037	140.516941037		
dt833	45					150.693833871	150.693833871	
lilian*	45					151.598881512	151.598881512	
bw807*	45					153.558404283	153.558404283	
dt818*	45						156.359799999	
strongfield	45							181.3933785687
Sig.		0.190	0.082	0.258	0.094	0.050	0.406	1.000

Means for groups in homogeneous subsets are displayed.
Based on observed means.
The error term is Mean Square (Error) = 838.874.

a. Uses Harmonic Mean Sample Size = 45.000.

b. Alpha = 0.05.

Table C-6. DMRT of shearing energy for internode

Duncan[a,b]

Internode	N	Subset	
		1	2
First	180	115.270600147683550	
Third	180		151.123677211458980
Second	180		151.131958055703400
Sig.		1.000	0.998

Means for groups in homogeneous subsets are displayed.

Based on observed means.

The error term is Mean Square (Error) = 838.874.

a. Uses Harmonic Mean Sample Size = 180.000.

b. Alpha = 0.05.

Table C-7. DMRT of bending strength for moisture

Duncan[a,b]

Moisture	N	Subset		
		1	2	3
22	180	13.941		
18	180		18.506	
14	180			23.415
Sig.		1.000	1.000	1.000

Means for groups in homogeneous subsets are displayed.

Based on observed means.

The error term is Mean Square (Error) = 10.747.

a. Uses Harmonic Mean Sample Size = 180.000.

b. Alpha = 0.05.

Table C-8. DMRT of bending strength for variety

Duncan[a,b]

Variety	N	Subset 1	2	3	4	5	6	7	8
Commander	45	11.581							
hy1319	45		13.014						
Carberry	45			14.807					
lilian*	45			15.061					
bw807*	45				16.443				
Shaw	45					19.165			
Transcend	45					19.264			
Strongfield	45						21.002		
Blackbird	45						21.646		
dt833	45						22.063		
Unity	45							23.861	
dt818*	45								25.541
Sig.		1.000	1.000	0.714	1.000	0.886	0.149	1.000	1.000

Means for groups in homogeneous subsets are displayed.

Based on observed means.

The error term is Mean Square (Error) = 10.747.

a. Uses Harmonic Mean Sample Size = 45.000.

b. Alpha = 0.05.

Table C-9. DMRT of bending strength for internode
Duncan[a,b]

Internode	N	Subset 1	2	3
Second	180	16.386		
Third	180		17.287	
First	180			22.188
Sig.		1.000	1.000	1.000

Means for groups in homogeneous subsets are displayed.

Based on observed means.

The error term is Mean Square (Error) = 10.747.

a. Uses Harmonic Mean Sample Size = 180.000.

b. Alpha = 0.05.

Table C-10. DMRT of Young's modulus for moisture
Duncan[a,b]

Moisture	N	Subset 1	2	3
22	180	688.559		
18	180		973.090	
14	180			1181.267
Sig.		1.000	1.000	1.000

Means for groups in homogeneous subsets are displayed.

Based on observed means.

The error term is Mean Square (Error) = 83128.838.

a. Uses Harmonic Mean Sample Size = 180.000.

b. Alpha = 0.05.

Table C-11. DMRT of Young's modulus for variety

Duncan[a,b]

Variety	N	Subset				
		1	2	3	4	5
Carberry	45	497.893				
hy1319	45	519.895				
Commander	45	589.890				
lilian*	45		765.001			
Strongfield	45		860.053			
Shaw	45		860.754			
Transcend	45		874.933			
bw807*	45		877.383			
dt833	45			1115.495		
Blackbird	45				1419.649	
Unity	45				1444.242	1444.242
dt818*	45					1546.479
Sig.		0.155	0.101	1.000	0.686	0.093

Means for groups in homogeneous subsets are displayed.

Based on observed means.

The error term is Mean Square (Error) = 83128.838.

a. Uses Harmonic Mean Sample Size = 45.000.

b. Alpha = 0.05.

Table C-12. DMRT of Young's modulus for internode

Duncan[a,b]

Internode	N	Subset	
		1	2
Second	180	688.618	
Third	180	735.576	
First	180		1418.723
Sig.		0.123	1.000

Means for groups in homogeneous subsets are displayed.

Based on observed means.

The error term is Mean Square (Error) = 83128.838.

a. Uses Harmonic Mean Sample Size = 180.000.

b. Alpha = 0.05.

Table C-13. DMRT of cutting strength for moisture

Duncan[a,b]

Moisture	N	Subset		
		1	2	3
14	504	3.271722974387904		
18	504		3.817791271323130	
22	504			5.768498024680293
Sig.		1.000	1.000	1.000

Means for groups in homogeneous subsets are displayed.

Based on observed means.

The error term is Mean Square (Error) = 1.479.

a. Uses Harmonic Mean Sample Size = 504.000.

b. Alpha = 0.05.

Table C-14. DMRT of cutting strength for internode

Duncan[a,b]

Internode	N	Subset	
		1	2
Third	504	4.016884977090342	
Second	504	4.116861818191126	
First	504		4.724265475109851
Sig.		0.192	1.000

Means for groups in homogeneous subsets are displayed.

Based on observed means.

The error term is Mean Square (Error) = 1.479.

a. Uses Harmonic Mean Sample Size = 504.000.

b. Alpha = 0.05.

Table C-15. DMRT of cutting strength for variety

Duncan[a,b]

Variety	N	Subset						
		1	2	3	4	5	6	7
Lillian*	126	2.7237518073						
BW807*	126	2.8024504962						
Carberry	126	2.8638631756						
DT818*	126		3.23028204					
HY1319	126		3.31465108					
Unity	126			3.765908000				
Commander	126			3.999496288				
Shaw	126				4.4771809476			
Blackbird	126					5.4683812645		
Strongfield	126					5.7468859957		
Transcend	126						6.0554501445	
DT833	126							6.9837478352
Sig.		0.393	0.582	0.128	1.000	0.069	1.000	1.000

Means for groups in homogeneous subsets are displayed.

Based on observed means.

The error term is Mean Square (Error) = 1.479.

a. Uses Harmonic Mean Sample Size = 126.000.

b. Alpha = 0.05.

Table C-16. DMRT of cutting energy for moisture

Duncan[a,b]

Moisture	N	Subset		
		1	2	3
14	504	59.676038815967690		
18	504		74.917799215289970	
22	504			81.033969886225550
Sig.		1.000	1.000	1.000

Means for groups in homogeneous subsets are displayed.

Based on observed means.

The error term is Mean Square (Error) = 278.781.

a. Uses Harmonic Mean Sample Size = 504.000.

b. Alpha = 0.05.

Table C-17. DMRT of cutting energy for internode

Duncan[a,b]

internode	N	Subset		
		1	2	3
First	504	56.903180218690360		
Second	504		76.707974260790350	
Third	504			82.016653438002450
Sig.		1.000	1.000	1.000

Means for groups in homogeneous subsets are displayed.

Based on observed means.

The error term is Mean Square (Error) = 278.781.

a. Uses Harmonic Mean Sample Size = 504.000.

b. Alpha = 0.05.

Table C-18. DMRT of cutting energy for variety

Duncan[a,b]

Variety	N	Subset						
		1	2	3	4	5	6	7
Commander	126	43.1937441481						
Carberry	126		53.0225400152					
HY1319	126		53.6842878220					
Unity	126			61.5736029202				
Transcend	126			63.3370956389				
Blackbird	126			64.0783775073				
Shaw	126				74.1624129379			
DT833	126					82.4808554832		
BW807*	126					84.4223282913		
Lillian*	126						91.0517997483	
Strongfield	126						91.9739893411	
DT818*	126							99.5301978160
Sig.		1.000	0.753	0.264	1.000	0.356	0.661	1.000

Means for groups in homogeneous subsets are displayed.

Based on observed means.

The error term is Mean Square (Error) = 278.781.

a. Uses Harmonic Mean Sample Size = 126.000.

b. Alpha = 0.05.

Table C-19. DMRT of tensile strength for moisture

Duncan[a,b]

Moisture	N	Subset		
		1	2	3
14	180	50.936		
18	180		55.162	
22	180			61.534
Sig.		1.000	1.000	1.000

Means for groups in homogeneous subsets are displayed.

Based on observed means.

The error term is Mean Square (Error) = 37.193.

a. Uses Harmonic Mean Sample Size = 180.000.

b. Alpha = 0.05.

Table C-20. DMRT of tensile strength for internode

Duncan[a,b]

Internode	N	Subset	
		1	2
First	180	48.067	
Third	180		59.256
Second	180		60.309
Sig.		1.000	0.102

Means for groups in homogeneous subsets are displayed.

Based on observed means.

The error term is Mean Square (Error) = 37.193.

a. Uses Harmonic Mean Sample Size = 180.000.

b. Alpha = 0.05.

Table C-21. DMRT of tensile strength for variety

Duncan[a,b]

Variety	N	Subset							
		1	2	3	4	5	6	7	8
lilian*	45	23.744							
bw807*	45		28.751						
dt818*	45			32.226					
hy1319	45				47.446				
Unity	45				49.041				
Carberry	45				49.188				
Shaw	45					59.418			
Commander	45						65.481		
Strongfield	45						66.120		
Blackbird	45						66.363		
dt833	45							83.845	
Transcend	45								98.905
Sig.		1.000	1.000	1.000	0.204	1.000	0.522	1.000	1.000

Means for groups in homogeneous subsets are displayed.

Based on observed means.

The error term is Mean Square (Error) = 37.193.

a. Uses Harmonic Mean Sample Size = 45.000.

b. Alpha = 0.05.

Table C-22. DMRT of coefficient of internal friction for moisture

Duncan[a,b]

Moisture	N	Subset	
		1	2
22	12	0.29078	
14	12	0.35343	
18	12		0.44812
Sig.		0.146	1.000

Means for groups in homogeneous subsets are displayed.
Based on observed means.
The error term is Mean Square (Error) = 0.010.

a. Uses Harmonic Mean Sample Size = 12.000.

b. Alpha = 0.05.

Table C-23. DMRT of coefficient of internal friction for variety

Duncan[a,b]

Variety	N	Subset		
		1	2	3
Unity	3	0.17600		
Carberry	3	0.29460	0.29460	
HY1319	3	0.31083	0.31083	
Shaw	3	0.31947	0.31947	
Commander	3	0.32907	0.32907	
Strongfield	3	0.35870	0.35870	
Lillian*	3	0.36347	0.36347	
DT833	3		0.37590	
Blackbird	3		0.38640	0.38640
Transcend	3		0.39597	0.39597
BW807*	3		0.48883	0.48883
DT818*	3			0.57007
Sig.		0.059	0.056	0.053

Means for groups in homogeneous subsets are displayed.
Based on observed means.
The error term is Mean Square (Error) = 0.010.

a. Uses Harmonic Mean Sample Size = 3.000.

b. Alpha = 0.05.

Table D-1 Mean values of the shearing strength (MPa) and shearing energy (mJ) of the 12 different varieties of wheat stem obtained by grouping the 3 internode positions under the same moisture contents and; N = 15.

	Shearing Strength						**Shearing Energy**					
Varieties	**14%**	**CV**	**18%**	**CV**	**22%**	**CV**	**14%**	**CV**	**18%**	**CV**	**22%**	**CV**
Commander	7.9(3.8)	48.2	12.4(2.0)	16.0	14.3(4.4)	30.5	92.6(10.7)	11.6	120.6(12.5)	10.4	174.6(45.2)	25.9
Strongfield	14.6(1.2)	8.0	15.6(1.9)	11.9	17.9(4.5)	25.3	156.4(44.5)	28.5	165.9(42.1)	25.4	221.9(12.2)	5.5
Transcend	10.5(1.2)	11.2	12.5(0.6)	5.1	13.9(1.8)	13.0	128.8(13.2)	10.3	134.5(11.2)	8.4	145.2(8.3)	5.7
Shaw	9.8(2.1)	21.8	10.8(2.0)	18.2	11.3(2.1)	18.7	128.4(32.4)	25.2	135.6(32.2)	23.7	157.6(8.6)	5.5
HY1319	9.5(2.5)	26.7	11.2(3.3)	29.5	12.7(4.1)	32.2	99.7(10.2)	10.3	126.2(12.2)	9.7	165.6(31.1)	18.8
BW807*	5.5(0.8)	15.0	9.1(1.0)	11.4	11.3(1.8)	15.8	75.5(10.1)	13.4	118.2(23.9)	20.2	266.9(48.2)	18.1
Carberry	8.3(1.2)	15.0	8.9(1.0)	11.6	10.2(1.7)	16.3	116.4(23.5)	20.2	121.3(22.3)	18.4	131.7(12.3)	9.3
Lillian*	6.1(0.7)	11.3	7.4(0.6)	8.0	9.2(0.7)	7.2	116.3(44.7)	38.4	132.0(53.6)	40.6	206.5(57.8)	28.0
Unity	8.7(1.3)	15.3	9.5(1.7)	17.6	10.0(1.8)	17.9	87.8(14.2)	16.2	95.9(14.9)	15.5	129.7(26.7)	20.6
Blackbird	10.1(0.8)	8.4	12.9(2.3)	18.0	16.2(0.8)	5.1	99.0(32.4)	32.7	108.1(33.9)	31.4	130.3(30.2)	23.2
DT833	11.1(0.8)	6.9	12.2(0.7)	5.9	14.1(1.0)	6.8	145.7(22.5)	15.5	150.5(25.8)	17.1	155.9(28.8)	18.5
DT818*	7.2(1.0)	14.5	8.1(1.2)	14.6	9.5(1.8)	18.7	146.6(39.6)	27.0	156.4(37.5)	24.0	166.1(40.0)	24.1

Solid stem varieties are indicated with *
Figures in parentheses are standard deviation

Table D-2 Mean values of the cutting strength (MPa) and cutting energy (mJ) of the 12 different varieties of wheat stem obtained by grouping the 3 internode positions under the same moisture contents and; N = 15.

	Cutting Strength						**Cutting Energy**					
Varieties	**14%**	**CV**	**18%**	**CV**	**22%**	**CV**	**14%**	**CV**	**18%**	**CV**	**22%**	**CV**
Commander	2.85(0.7)	24.4	3.78(1.3)	35.6	5.41(3.3)	60.9	34.6(9.9)	28.6	45.1(15.5)	34.4	49.9(13.2)	26.4
Strongfield	4.58(1.2)	25.9	5.70(0.6)	10.8	6.95(0.6)	9.2	82.1(33.7)	41.0	95.0(28.5)	30.0	98.8(31.3)	31.7
Transcend	4.73(0.8)	17.2	5.20(0.9)	17.6	8.24(2.1)	25.1	52.8(2.9)	5.4	65.1(2.8)	4.3	72.1(7.1)	9.8
Shaw	3.22(0.5)	15.5	3.50(0.5)	13.5	6.71(1.0)	14.4	51.6(21.6)	41.9	83.5(26.3)	31.5	87.4(26.4)	30.2
HY1319	2.41(1.1)	44.6	2.82(1.2)	43.0	4.72(2.3)	48.2	45.1(11.8)	26.2	56.5(15.8)	27.9	59.5(18.2)	30.6
BW807*	2.33(0.5)	22.4	2.64(0.4)	16.5	3.43(1.3)	37.7	77.3(25.4)	32.9	83.9(17.4)	20.7	92.1(9.1)	9.9
Carberry	2.12(0.4)	17.8	2.42(0.5)	20.9	4.05(1.4)	35.1	42.9(4.2)	9.9	55.8(8.4)	15.0	60.4(7.9)	13.1
Lillian*	2.27(0.1)	3.2	2.64(0.2)	7.5	3.26(0.3)	8.5	73.9(31.9)	43.2	97.4(37.5)	38.6	100.6(38.0)	37.8
Unity	2.78(0.4)	13.8	3.25(0.6)	17.9	5.27(1.5)	28.9	53.0(18.0)	33.9	64.6(19.2)	29.7	67.1(19.1)	28.5
Blackbird	3.69(1.1)	30.0	4.63(1.1)	23.3	8.08(1.8)	21.9	47.0(14.8)	31.5	63.7(19.0)	29.8	81.5(27.8)	34.0
DT833	5.50(0.3)	5.1	6.17(0.4)	7.0	9.28(0.9)	9.3	64.2(17.7)	27.6	86.6(11.0)	12.7	96.6(9.6)	9.9
DT818*	2.77(0.4)	14.3	3.06(0.4)	11.7	3.65(0.3)	8.1	90.4(17.7)	19.6	101.7(21.4)	21.0	104.2(21.5)	20.6

Solid stem varieties are indicated with *
Figures in parentheses are standard deviation
Figures in superscript are coefficient of variation

Table D-3 Mean values of the bending strength (MPa) and modulus of elasticity (GPa) of the 12 different varieties of wheat stem obtained by grouping the 3 internode positions under the same moisture contents and; N = 15.

	Bending Strength						**Modulus of Elasticity**					
Varieties	**14%**	**CV**	**18%**	**CV**	**22%**	**CV**	**14%**	**CV**	**18%**	**CV**	**22%**	**CV**
Commander	17.8(7.7)	43.5	11.5(5.5)	47.6	5.4(1.7)	31.6	0.9(0.8)	86.3	0.5(0.5)	84.5	0.3(0.2)	75.9
Strongfield	27.2(0.4)	1.5	19.5(2.4)	12.4	16.3(3.9)	23.8	1.2(0.3)	21.8	0.9(0.3)	28.5	0.5(0.1)	22.8
Transcend	26.3(4.3)	16.4	20.1(5.0)	24.7	11.3(3.7)	32.7	1.1(0.6)	52.2	0.9(0.6)	67.2	0.6(0.4)	76.3
Shaw	23.2(5.8)	25.0	19.2(5.1)	26.7	15.2(6.7)	44.1	1.0(0.4)	37.4	0.9(0.4)	41.1	0.7(0.3)	49.3
HY1319	17.2(3.9)	22.6	13.2(3.9)	29.3	8.6(3.8)	43.9	0.7(0.4)	52.9	0.5(0.3)	61.2	0.3(0.2)	76.1
BW807*	21.1(4.7)	22.1	16.7(4.5)	27.2	11.5(5.1)	44.4	1.1(0.4)	37.5	0.9(0.5)	48.5	0.6(0.4)	70.7
Carberry	17.3(0.5)	2.8	14.3(2.6)	18.2	12.8(3.3)	25.4	0.6(0.1)	22.3	0.5(0.2)	39.0	0.4(0.2)	49.5
Lillian*	18.5(1.4)	7.7	15.1(2.5)	16.8	11.7(1.4)	12.4	0.9(0.1)	11.2	0.7(0.1)	15.3	0.6(0.2)	32.0
Unity	27.3(5.5)	20.1	24.2(3.2)	13.1	20.6(4.5)	21.8	1.6(0.4)	26.3	1.4(0.4)	28.7	1.3(0.3)	25.8
Blackbird	27.0(11.4)	42.1	21.5(5.8)	27.1	16.5(2.0)	12.0	1.8(1.5)	79.3	1.5(1.1)	72.0	0.9(0.5)	57.1
DT833	28.6(5.5)	19.2	22.6(3.5)	15.6	15.0(1.6)	10.7	1.4(0.6)	41.6	1.2(0.6)	48.3	0.7(0.3)	46.3
DT818*	29.5(12.8)	43.3	24.2(8.0)	32.9	23.0(8.0)	34.6	1.7(1.1)	63.3	1.6(1.0)	60.5	1.3(0.9)	66.0

Solid stem varieties are indicated with *

Figures in parentheses are standard deviation

Table D-4 Mean values of the tensile strength (MPa) of the 12 different varieties of wheat stem obtained by grouping the 3 internode positions under the same moisture contents and; N = 15.

Varieties	**14%**	**CV**	**18%**	**CV**	**22%**	**CV**
Commander	59.6(3.0)	5.1	66.9(6.3)	9.4	70.0(6.3)	9.0
Strongfield	58.6(20.6)	35.1	64.1(20.6)	32.1	75.6(25.6)	33.8
Transcend	94.4(6.2)	6.6	98.2(5.1)	5.2	104.1(7.4)	7.1
Shaw	54.6(15.0)	27.5	58.9(15.5)	26.3	64.8(15.5)	23.9
HY1319	43.3(4.7)	10.9	48.3(7.2)	14.8	50.7(6.9)	13.7
BW807*	25.4(2.6)	10.4	27.1(3.4)	12.6	33.8(0.6)	1.8
Carberry	45.6(3.9)	8.6	48.2(3.6)	7.5	53.8(3.1)	5.8
Lillian*	20.9(5.8)	27.6	22.7(5.8)	25.6	27.6(8.4)	30.5
Unity	44.3(12.9)	29.2	49.0(10.6)	21.6	53.8(14.4)	26.8
Blackbird	57.6(11.2)	19.4	66.4(8.9)	13.4	75.1(7.7)	10.3
DT833	77.5(12.3)	15.9	80.6(12.3)	15.3	93.4(19.2)	20.5
DT818*	29.3(2.3)	7.8	31.5(1.6)	5.1	35.8(3.3)	9.2

Solid stem varieties are indicated with *

Figures in parentheses are standard deviation

Table D-5 Area (mm^2) of the 12 different varieties of wheat stem obtained by grouping the 3 internode positions under the same moisture contents and; N = 15.

Varieties	**Mc=14%**	**CV**	**Mc=18%**	**CV**	**Mc=22%**	**CV**
Commander	1.50(0.4)	28.2	1.79(0.3)	16.7	2.08(0.6)	26.6
Strongfield	1.42(0.2)	12.5	1.67(0.3)	19.4	2.16(0.2)	7.5
Transcend	1.30(0.2)	12.4	1.61(0.4)	25.8	1.70(0.4)	25.2
Shaw	2.48(0.5)	21.9	2.74(0.7)	24.5	2.90(0.8)	28.9
HY1319	3.31(1.2)	37.4	2.87(1.0)	35.8	3.32(1.0)	30.9
BW807*	5.90(0.5)	8.3	6.10(1.5)	23.8	5.66(1.4)	24.9
Carberry	3.02(0.7)	21.9	3.29(0.8)	23.3	3.02(0.8)	27.8
Lillian*	6.54(1.7)	25.6	6.64(1.9)	29.7	6.68(1.6)	23.5
Unity	2.68(0.6)	23.7	2.65(1.1)	40.4	3.06(0.8)	27.5
Blackbird	1.71(0.1)	4.4	1.88(0.7)	37.6	1.72(0.4)	24.0
DT833	1.44(0.2)	13.3	1.72(0.3)	18.6	1.52(0.3)	21.1
DT818*	4.60(1.4)	31.3	4.68(1.5)	33.0	5.37(1.9)	35.4

Solid stem varieties are indicated with *
Figures in parentheses are standard deviation