The Canadian Society for Bioengineering
The Canadian society for engineering in agricultural, food, environmental, and biological systems.

La Société Canadienne de Génie Agroalimentaire et de Bioingénierie
La société canadienne de génie agroalimentaire, de la bioingénierie et de l'environnement

Paper No. CSBE09309

Compressive behavior of hemp fiber (*Cannabis sativa L.*) stalks

Md. Majibur Rahman Khan[1], Ying Chen[1]*, Claude Laguë[2], Hubert Landry[3], Qingjin Peng[4], Wen Zhong[5].
[1]Department of Biosystems Engineering, University of Manitoba, Winnipeg, Manitoba R3T 5V6, Canada
[2]Faculty of Engineering, University of Ottawa, *Ottawa*, Ontario *K1N6N5, Canada*
[3]Prairie Agricultural Machinery Institute, Humboldt, Saskatchewan S0K 2A0, Canada
[4]Department of Mechanical and Manufacturing Engineering, University of Manitoba, Winnipeg, MB, R3T 5V6, Canada
[5]Department of Textile Sciences, University of Manitoba, Winnipeg, Manitoba R3T 2N2, Canada
* Corresponding author. Tel: +1-204-474-6292, Fax: +1-204-474-7512.
Email address: ying_chen@umanitoba.ca

Written for presentation at the
CSBE/SCGAB 2009 Annual Conference
Rodd's Brudenell River Resort, Prince Edward Island
12-15 July 2009

Abstract. Compressive strength of hemp (*Cannabis Sativ L.*) stems is of great importance for the design of hemp handling and processing machines. A study was carried out to evaluate the compressive behavior of hemp stalks. Two varieties of hemp stalks produced for single purpose (Alyssa) and dual purposes (Petera) in Manitoba, Canada were used in the study. Each variety of hemp stalk was divided into three height regions of the stem: upper, middle and lower. The hemp stem specimens were cut into 25.4 mm in length and the physical properties of hemp specimen were measured before the compression tests. The outer diameter of hollow hemp stalk varied from 6 to 17 mm; the inner diameter varied from 3 to 8 mm; the linear density varied from 10 to 37 g m^{-1}. The diameters and linear density were greater at lower height regions of specimen. Specimens were compressed by a computer-aided laboratory scale compression apparatus both in axial and lateral directions of hemp stem. The force-displacement curve was recorded. The maximum compressive load at stem failure, stem modulus and energy requirement for compression were derived from the curve. The results showed the maximum compressive strength, modulus and energy requirements were significantly differ at different hemp height regions and were increased with increasing stalk diameters. In general, higher strength, modulus and more energy required for compression of the lower height region of hemp stalk both in axial and lateral directions of stem.

Keywords. hemp (*Cannabis sativa L.*), height region, diameter, compression, load, energy, modulus.

1. Introduction

Hemp (*Cannabis Sativ L.*) is one of the ancient plants with long cultivation history that can be harvested for single purpose (fiber only) or for dual purposes (seed and fiber). The world production of hemp grew from 50,000 tonnes in 2000 to almost 90,000 tonnes in 2005 (FAO, 2009). Hemp cultivation was stopped four decades ago due to the prohibition of the alternate use of hemp as drug. Due to the high demand on natural fiber from composite and textile industrial, several countries, including Canada, reintroduced the industrial hemp with a low tetrahydrocannabinol (THC) content. In Canada, more than 100 producers are now growing industrial hemp, following its legalization in 1998. The hemp acreage in Canada was 48,000 acres in 2006 and the reported net profits were from $200 to $250 per acre (Hansen, 2008).

Hemp handling involves tremendous energy and labour as hemp plants itself has large amount of biomass yield and a high percentage of cellulose and lignin (Bócsa & Karus, 1997), which makes it one of the most challenging crops to handle and process in operations such as harvesting, cutting, baling and decorticating for fibers. In these operations, one challenge is dealing with the high strength of the plant stalks with suitable machinery, and another challenge is the high energy requirement to perform these operations. Thus, the mechanical properties of hemp stalks ought to be known in order to design and develop efficient machinery for hemp processing and handling.

In recent years, research has been carried out to investigate some engineering perspectives of hemp plants, such as mechanical behaviors during cutting (Chen *et al*., 2004). The results showed that the values of the maximum force and the total cutting energy required for cutting a hemp stem were 243 N and 2.1 J, respectively. The linear relationship between cutting energy and specific mass of hemp stem has been used to estimate the power required to cut hemp material in a field condition. Many other engineering properties of hemp stalks are still unknown, for example, compressive behavior of hemp. Compressive behavior is very important, since compression of stalk is involved in all of harvesting, baling, and decorticating processes.

The compression behavior of plant materials depends on species, variety, stalk structure, stalk diameter, maturity, moisture content and cellular structure (Persson, 1987). To develop rape stalk harvesting technology, research on compressive behavior of rape stalk was carried out using a computer-servo material testing system by Qingxi *et al*. (2007). They found that rape stalk was heterogeneous, non-linear and anisotropic, and that physico-mechanical properties were different in all directions of the stem. The average value of rape stalk compression destruction stress measured was 11.9 MPa and the elasticity modulus of compression was 172 MPa. The mechanical properties including compression strength of sorghum stalk specimens were studied by Oke *et al*. (1984) who reported that compressive behavior of sorghum stalks remarkably varied in different height regions: upper, middle and bottom levels of sorghum stalk. The sorghum stalk specimens were deformed in a quasi-static process using flat knives with 30-70^{o} bevel angles at different loading rate by Chattopadhyay and Pandey (1999). They showed that the compressive strength and the energy absorbed in compression increased as the bevel angle was increased and both decreased as the rate of loading increased from 10 to 100 mm min^{-1}. To know the influence of diameter and age of bamboo fiber on its physical properties, the compressive strength was evaluated for two types of bamboo (Lo *et al.*, 2004). The results showed that the compressive strength decreased with increasing the outer diameter of bamboo and the range of strength value was 37.7 – 62.8 N mm^{-1}. Study of compressive behavior of sugar cane was conducted for a harvester design and development (Bhaholyotin *et al.*, 1988). The compression force of sugarcane stalk varied in different height regions of stem, particularly between the bottom and top height portion. Blahovec (1988) studied the Young's modulus, compressive strength and shear strength of several agricultural products. They found that the tensile compressive strength (σ_m) and Young's modulus (E) of vegetable flesh and cultural plant stalks had an exponential relationship ($\sigma_m = 0.2E^{0.75}$).

In summary, there have been some studies on compressive behaviors of different plant materials. However, no data have been reported for compressive properties of hemp stalk. The goal of this study was to understand the compression behavior of hemp stalk, which will lead to the design of effective and efficient machinery for hemp handling and processing. The specific objectives were to study the compressive strength, modulus, and energy requirement of hemp stems as affected by different varieties of hemp, height regions of hemp stem, and compression directions of hemp stem.

2. Materials and methods

2.1 *Specimen preparation*

(a) Alyssa

(b) Petera

Fig. 1. Two varieties of hemp stem specimens before compression: (a) Alyssa; (b) Petera.

Two hemp varieties, Alyssa and Petera, were used in the compression experiment. Both were grown in Manitoba, Canada in 2008. Alyssa was cultivated for single purpose (fiber only) and

Petera was for dual purposes (seed and fiber), and both were unretted and unbaled. Before the compression tests, the seed portion of hemp stalk was removed. Then, the rest of the stem wasdivided equally into three height regions as upper, middle and lower. The hemp specimens were prepared according to ASTM standard method for compression test of plastic materials (ASTM D-695, 2008). Stems were cut into short sections having a fixed length of 25.4 mm (Figs. 1a,b). As the hemp stem is hollow, special attention was taken to ensure smooth cutting without any breakage of the stem.

2.2 *Testing apparatus*

Compression tests were performed using a universal testing system. Fig. 2 shows the schematic diagram of the main machine frame of the system. The system can be used for stretching, compression and relaxation of different biomaterials. The system was composed of main test frame hardware, data acquisition system and a computer. The capacity of load cell of the machine was 0-890 N. The loading rate was 10 mm min^{-1}.

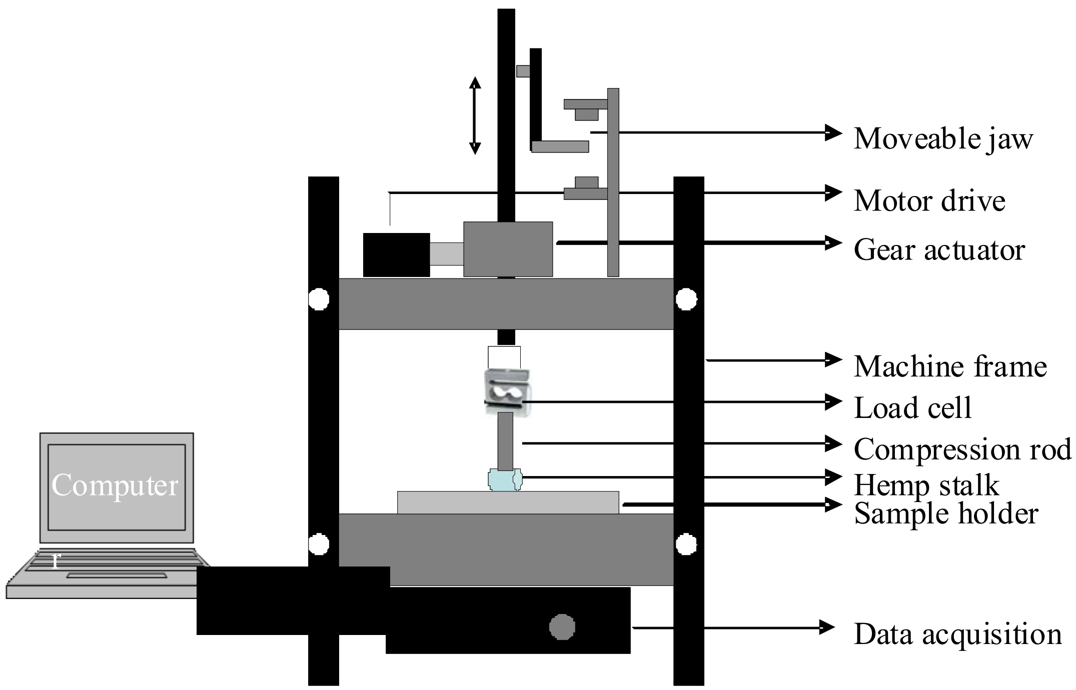


Fig. 2. Schematic diagram of the compression test machine.

2.3 *Experimental design*

A completely randomized design was used for each of two varieties: Alyssa and Petera. The treatments were the combinations of two specimen compression directions: axial and lateral, and three height regions: upper, middle and lower. Forty replicates were tested for each treatment, and total number of test was 480 (2 varieties x 2 directions x 3 regions x 40 replications). The treatments are summarized in Table 1.

Table 1 Summary of the experimental treatments

Treatment	Description
Hemp variety	
Alyssa	Single purpose (fiber only)
Petera	Dual purpose (fiber and seed)
Stem direction	
Axial	Compressed in the axial direction of stem
Lateral	Compressed in the lateral direction of stem
Height regio	
Lower	Lower height region of hemp stem
Middle	Middle height region of hemp stem
Upper	Tender height region of hemp stem

2.4 *Measurements*

2.4.1 *Physical properties*

Prior to compression tests, the outer and inner diameters $(d_1 \& d_2)$ of each specimen were measured using a micrometer. Because of the variation of diameter along a hemp stem, the diameters at two ends of specimen were measured to get the mean diameter. The stem wall thickness (t) was calculated by the difference of outer and inner diameters of specimen. The mass of each specimen was measured, and the linear density (μ) was defined as the mass per unit length.

2.4.2 *Compressive properties*

(b) Alyssa

(b) Petera

Fig. 3. Two varieties of hemp specimens after compression: (a) Alyssa; (b) Petera.

During a compression test, a specimen shown in Figs. 1a,b was placed on the sample holder. The specimen was compressed by the compression rod at a constant speed. After some compression, the specimens broke, mainly because of the stem wall being collapsed (Figs. 3a,b). The data acquisition system recorded the load and the displacement automatically during the course of compression.

The load-displacement curves of the tested specimens were used to derive the compressive properties of hemp stem. The maximum compressive load, P_{max} i.e. load was defined as the peak of the load-displacement curve. To elucidate the compressive strength of a hemp stem at a specific stem cross-sectional area, maximum stress (stress at which failure takes place) was determined. Treating the hollow hemp stem as tubing, the maximum load was transformed into the maximum stress according to the following equation (Qingxi *et al.*, 2007):

$$\sigma_{\max} = \frac{P_{\max}}{\frac{\pi}{4}(d_1^2 - d_2^2)} \tag{1}$$

where $\sigma_{\max}$ is the maximum stress in MPa; $P_{\max}$ is the maximum load in N, d_1 and d_2 is the outer and inner diameter of stem in mm. P_{max} and $\sigma_{\max}$ respectively represent the maximum compressive load and maximum compressive stress of the hemp stem specimens.

The value of the modulus of compression, M was obtained from the slope of the first linear part of the load-displacement curve up to the peak point by using standard method for plant materials (Mohsenin, 1986). The compressive energy, E was calculated as the area beneath the entire load-displacement curve evaluated by numerical integration (Chattopadhyay and Pandey, 1999; Chen *et al*., 2004).

2.5 *Data analysis*

Analysis of variance (ANOVA) (Steel & Torrie, 1980) was performed to examine the main effects of experimental factors and their interactions using the statistical analysis software V9.1 (SAS/STAT). No interactions of the experimental factors were detected. Thus the main effects are presented. Means of treatments were compared using Duncan's multiple range tests. Regression analysis was made on the data to examine the trends of compressive properties in relation to stalk outer diameter. A significance level of probability $P < 0.05$ was used for all analyses.

3. Results and discussion

3.1 *Physical properties*

The Alyssa variety had an average outer diameter of 6.7, 8.5 and 9.2 mm for the upper, middle and lower height regions, respectively (Table 2). Larger values of outer diameters were observed for the Petera specimens: 8.7, 12.7, and 16.3 mm for the upper, middle and lower height regions, respectively. The diameter results were consistent with recently reported hemp stem diameter, ranging from 6 to 16 mm by Chen *et al*. (2004) and comparable with the diameters of maize stalks (7.6 – 15.3 mm) found by Prasad and Gupta (1975). The wall thickness of the stem in the upper, middle and lower height regions were 2.5, 3.4 and 6.6 mm (Alyssa), and 4.1, 5.3 and 8.7 mm (Petera), which gave cross-section area of 86.5, 147.8 and 249.1 mm^2 (Alyssa), and 171.9, 339.9 and 676.0 mm^2 (Petera), respectively. The wall thickness and cross-sectional area of hemp stems were much greater than those of alfalfa stems found by Galedar *et al.* (2008) and wheat straw reported by Skubisz (1980) and Huber (1991). The average linear density of the upper, middle and lower height regions was 14.9, 22.4 & 36.6 g m^{-1} for Petera and 9.8, 14.3 & 19.3 g m^{-1} for Alyssa, respectively. The linear density result for Alyssa was consistent with the report of hemp stem by Chen *et al*. (2004). The linear density of hemp was much higher than that for 16 grass species (2. 4 g m^{-1}) reported by McRandal and McNulty (1980).

Table 2* Physical properties of hemp for two different varieties in different stem height regions

Property	Alyssa			Petera		
	Upper	Middle	Lower	Upper	Middle	Lower
d_1 (mm)	6.7^c (0.13)	8.5^b (0.12)	9.2^a (0.18)	8.7^C (0.18)	12.7^B (0.25)	16.3^A (0.36)
t (mm)	2.5^c (0.07)	3.4^b (0.12)	6.6^a (0.19)	4.1^C (0.14)	5.3^B (0.20)	8.7^A (0.22)
A (mm^2)	21.7^c (0.85)	36.9^b (1.47)	62.3^a (2.76)	43.0^C (1.92)	85.0^B (3.92)	168.9^A (7.19)
μ (g m^{-1})	9.8^c (0.33)	14.3^b (0.46)	19.3^a (0.71)	14.9^C (0.73)	22.9^B (1.06)	36.6^A (1.60)

*Means in the same raw followed by the same lowercase or uppercase letters are not significantly different (probability $P<0.05$) according to Duncan's multiple range tests. Values in parentheses are standard errors of the mean. d_1, t, A, μ: outer diameter, wall thickness, cross-section area, and linear density of hemp stem.

All physical properties measured were significantly increased towards the lower height regions of stem. Also, the values of the physical properties of Alyssa were significantly lower than those of Petera. The results showed that Alyssa and Petera could be considered as two distinct hemp plants, which were appropriate for investigating how the initial properties affected that of the mechanical performances during different handling and processing conditions, such as, compressions.

3.2 *Compressive properties*

3.2.1. *Typical load-displacement curves*

Fig. 4 illustrates typical load-displacement curves recorded from the compression tests. The curves showed some fluctuations, but mainly have two stages: pre-failure (A) and post-failure (B). In stage A, the force increased from zero at the moment of initial contact between the compression rod and the hemp specimen, and reached a peak when the specimen structure failed. In stage B, after the failure, some specimens were able to provide some resistance to the continued displacement of the compression rod, while some specimens showed drastically decreased strength. This abrupt drop in load-carrying capacity of stem is related to the hollow structure of hemp stem.

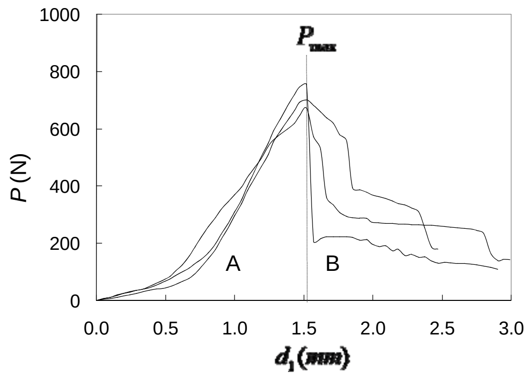
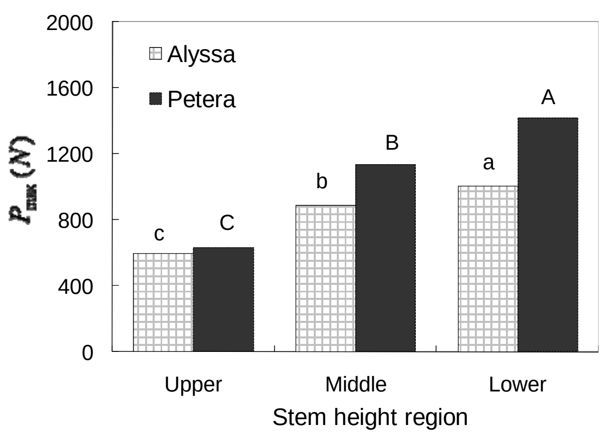


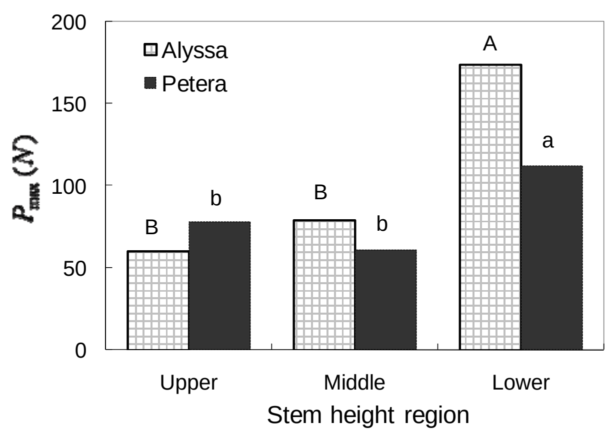
Fig. 4. Typical compressive load-displacement curves of hemp stem.

3.2.2. *Compressive strength*

The values of P_{max} increased linearly with the upper height region to the lower height region for both varieties in the axial compression direction (Fig. 5a). Differences in P_{max} among three regions were all significant. For the upper, middle, and lower height regions of stem, the corresponding values of the axial P_{max} was 624, 903 & 1090 N for Alyssa. Much higher values (762, 1233 & 1425 N) were obtained for Petera. For the lateral compression direction, the values of P_{max} were 58, 80, & 173 N for Alyssa; again, higher P_{max} (82, 59 & 110 N) were the case for Petera (Fig. 5b). Trends of variations of P_{max} with the height region and the magnitudes of P_{max} for the lateral direction were different than those for the axial compression direction. First, the values of P_{max} for the lateral compression direction were about one tenth of those for the axial compression direction. Secondly,



(a)

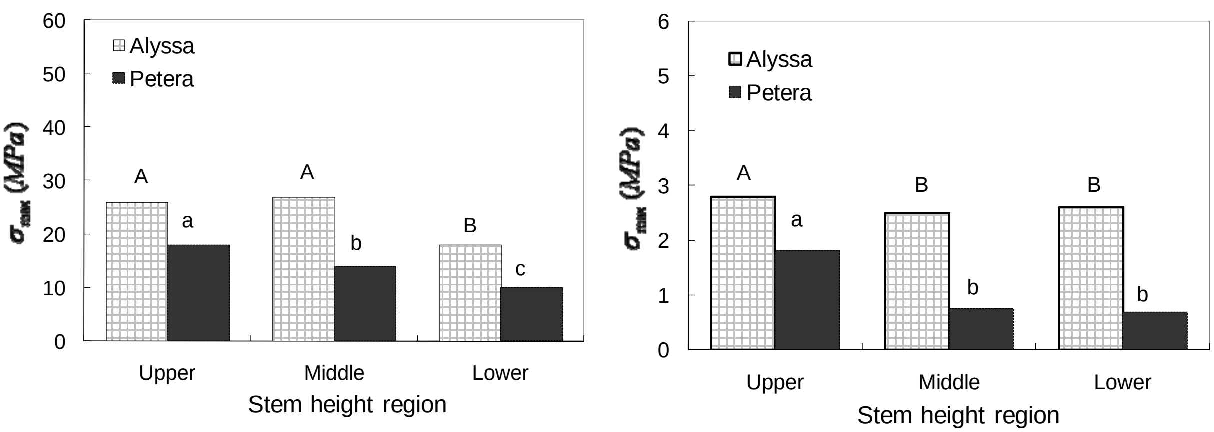


(b)

Fig. 5. Maximum compressive load (P_{max}) of two hemp plants (Alyssa and Petera) as a function of different height regions of stem: (a) axial compression direction, and (b) lateral compression direction. Means followed by the same lowercase or uppercase letters are not significantly different.

Petera did not always have higher lateral P_{max} than Alyssa. Thirdly, the upper and middle height regions had similar P_{max} that was significantly lower than that of the lower region for both varieties. The trends of hemp stem height region effects on the compression load obtained were consistent with the compression results of sorghum stalks (Oke *et al*., 1984). They reported that the compression load of sorghum stalks decreases as the stalk tapers from bottom to upwards. This may be explained by the following facts. The lower height region of stem is the oldest part of the plant and has the highest lignin content. Lignification causes the cell walls to thicken, greatly increasing their rigidity and consequently the compressive load.

Means of σ_{max} varied from 0.7 to 27 MPa, depending on the height region of stem and the compression direction. Similar to the P_{max}, the axial σ_{max} was much greater than the lateral σ_{max}. However, it was interesting that the trends of the effects height region on σ_{max} (Figs. 6a,b) were completely reverse of those of P_{max}. Alyssa that had lower P_{max} generally had greater σ_{max} in both compression directions, when compared to Petera.

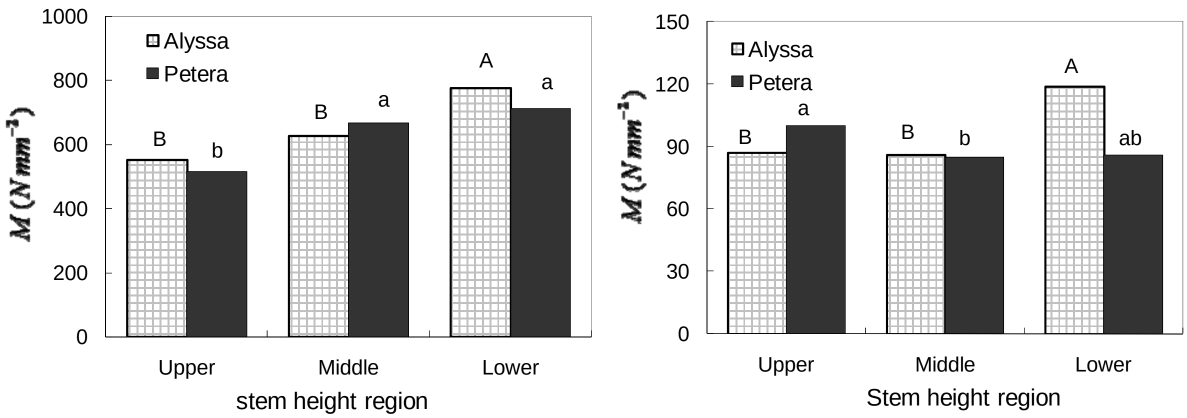


(a) (b)

Fig. 6. Maximum compressive stress (σ_{max}) of two hemp varieties (Alyssa and Petera) as a function of different stem height regions: (a) axial compression direction, and (b) lateral compression direction. Means followed by the same lowercase or uppercase letters are not significantly different.

3.2.3. *Modulus of compression*

The modulus of compression obtained for the axial compression direction was between 515 and 776 N mm^{-2} (Fig. 7a). The axial modulus of compression at the lower height region was greater for both varieties. Smaller lateral moduli (85-119 N mm^{-2}) were obtained (Fig. 7b). For Alyssa, a higher lateral modulus was observed at the lower region, while for Petera, a higher lateral modulus was observed at the upper region. The reasons were unknown.

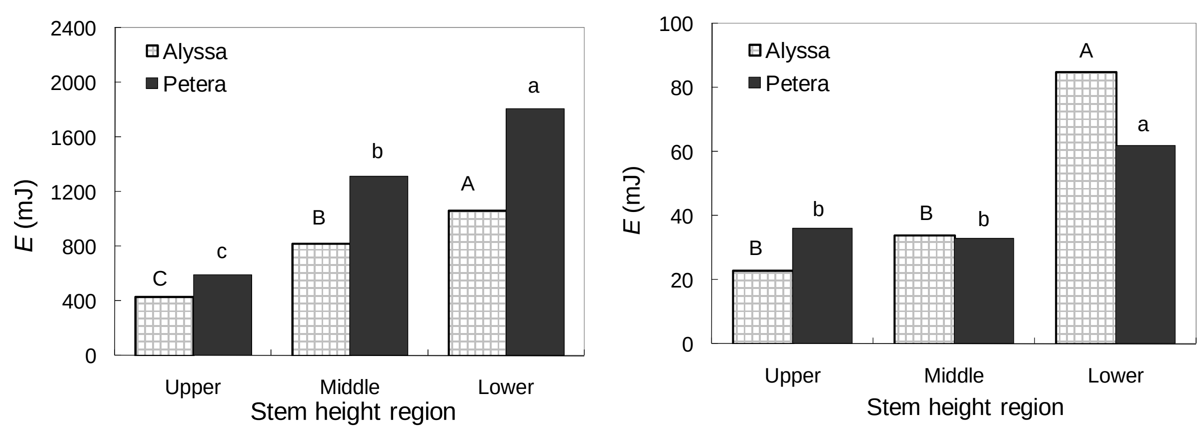


(a) (b)

Fig. 7. Modulus of compression (M) of two hemp varieties (Alyssa and Petera) as a function of different stem height regions: (a) axial compression direction, and (b) lateral compression direction. Means followed by the same lowercase or uppercase letters are not significantly different.

3.2.4. *Energy requirement*

The effect of stem height region on the energy requirement followed the trends: upper<middle<lower for the axial compression and upper=middle<lower for the lateral compression (Figs. 8a,b), regardless of the hemp varieties. For Alyssa, the compressive energy was 430, 822 & 1065 mJ in the axial compression direction and 23, 35 & 84 mJ in the lateral compression direction for the upper, middle and lower height regions, respectively. For Petera, the corresponding values were 593, 1311 & 1809 mJ in the axial direction and 36, 33 & 62 mJ in the lateral direction.



(a) (b)

Fig. 8. Maximum compressive energy (*E*) of two hemp varieties (Alyssa and Petera) as a function of different stem height regions: (a) axial compression direction, and (b) lateral compression direction. Means followed by the same lowercase or uppercase letters are not significantly different.

The results indicated that more energy was required to compress the lower region stem in the axial direction. These trends of E can be explained by the similar trends of P_{max} shown in Figs. 5a,b.

3.3. *Effects of hemp stem diameters on compressive properties*

It would be also interesting to know how diameters of hemp stem affected the compressive properties, regardless of the height regions of the stem. In most hemp handling and processing operations, stem diameter may be a more practical parameter than height region. Therefore, the data were interpreted based on effects of stem diameter (outer diameter) in the following discussion.

3.3.1. *Compressive strength*

The maximum load, P_{max}, increased with increasing stem outer diameters, d_1 in all cases (Figs. 9a,b). The axial P_{max} for both Alyssa and Petera seemed to be non-linearly related to d_1 (Fig. 9a). For the lateral compression direction, a linear relationship was observed between P_{max} and d_1 for both Alyssa and Petera (Fig. 9b). The regression equations representing these relationships and their coefficients of determination (R^2) are presented in Table 3.

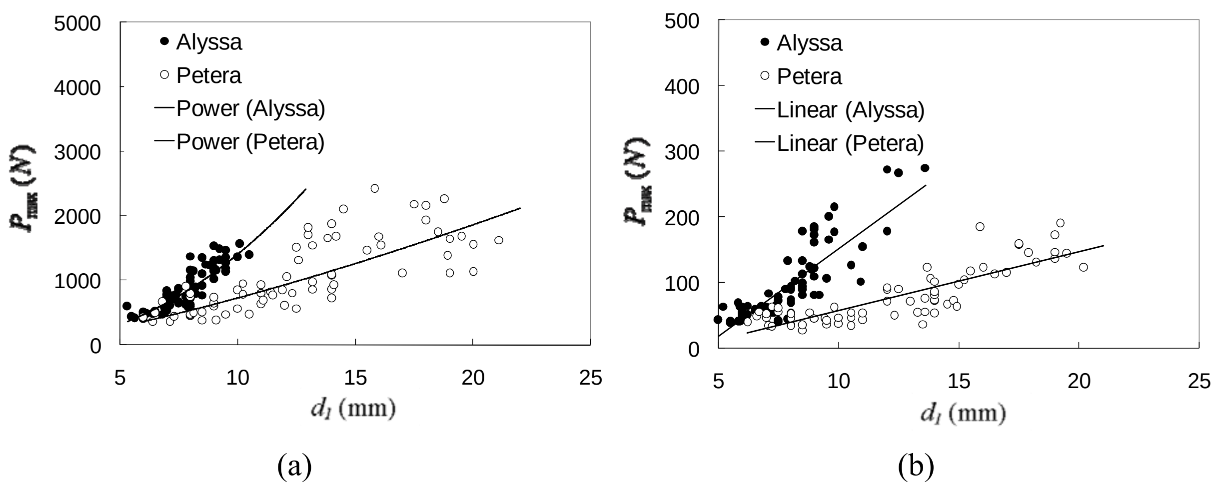
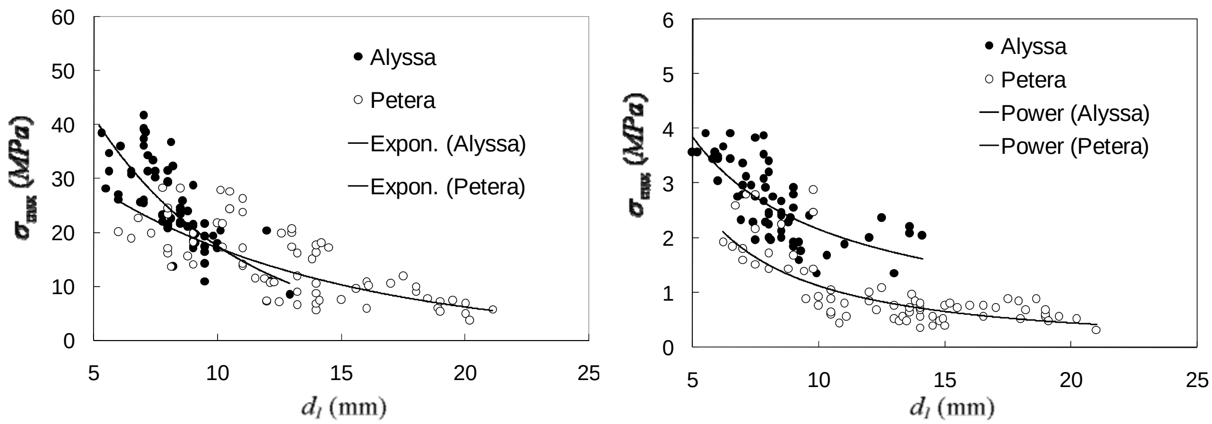


Fig. 9. Variation of maximum load (P_{max}) with outer diameters of hemp stem (d_1) for two varieties: Alyssa and Petera: (a) axial compression direction, and (b) lateral compression direction.

The maximum stress, σ_{max}, decreased with increasing d_1 for all cases (Figs. 10a,b). This trend also applies to other plant materials. Lo *et al*. (2004) reported that the compressive strength per unit area of cellulosic materials, such as bamboo fiber decreased significantly with the increase in its outer diameter. The compressive strength also depends on the wall thickness of the hollow rape stalk (Qingxi *et al*., 2007). For the axial compression direction, the relationships of σ_{max} and d_1 followed the exponential equations (Fig. 10a), while for the lateral direction, the relationships followed a non-linear power function (Fig. 10b). The regression equations and the R^2 values are presented in Table 3.

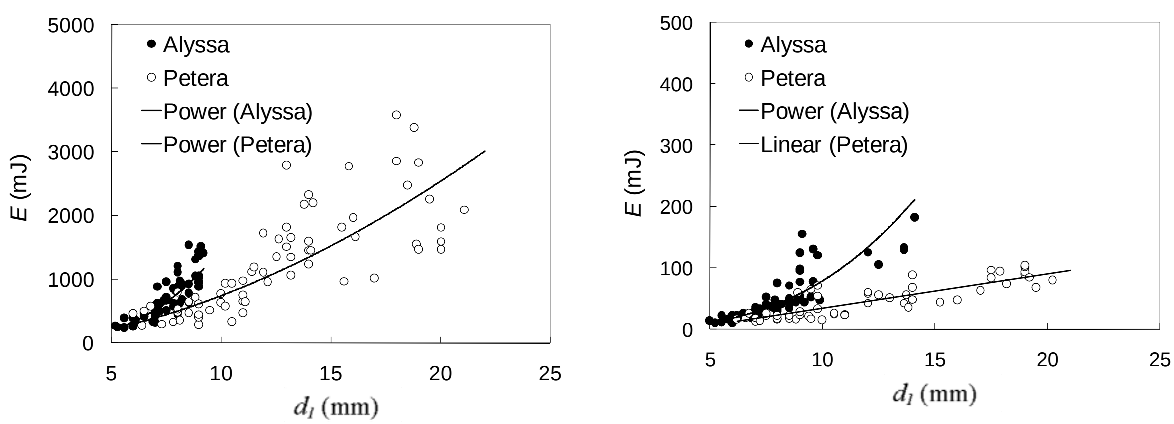


(a) (b)

Fig. 10. Variation of compressive stress (σ_{max}) with outer diameter (d_1) of hemp stem for two varieties (Alyssa and Petera): (a) axial compression direction, and (b) lateral compression direction.

3.3.2. *Energy requirement*

With increasing stalk diameters, more energy required for compression of hemp stalks (Figs. 11a,b). For the axial compression direction, the data for both Alyssa and Petera could be described by the non-linear power functions; whereas, for the lateral direction, Alyssa followed a non-linear power function and Petera followed a linear function (Table 3).



(a) (b)

Fig. 11. Variation of compressive energy (E) with outer diameter (d_1) of hemp stem for two varieties (Alyssa and Petera): (a) axial compression direction, and (b) lateral compression direction.

Table 3[*] Regression equations of compressive properties of hemp stem as functions of the outer diameters of stem.

Property	Compression direction	Alyssa		Petera	
		Equation	R^2	Equation	R^2
$P_{\max}\ (N)$	Axial	$P_{\max} = 10.842 d_1^{2.1145}$	0.79	$P_{\max} = 32.725 d_1^{1.3498}$	0.68
	Lateral	$P_{\max} = 26.639 d_1 - 113.85$	0.70	$P_{\max} = 8.9577 d_1 - 32.265$	0.70
$\sigma_{\max}\ (MPa)$	Axial	$\sigma_{\max} = 97.356 e^{-0.1717 d_1}$	0.61	$\sigma_{\max} = 47.456 e^{-0.1022 d_1}$	0.57
	Lateral	$\sigma_{\max} = 14.678 d_1^{-0.832}$	0.50	$\sigma_{\max} = 23.778 d_1^{-1.3246}$	0.61
$E\ (mJ)$	Axial	$E = 1.6474 d_1^{2.9592}$	0.75	$E = 12.535 d_1^{1.7733}$	0.71
	Lateral	$E = 0.1073 d_1^{2.8668}$	0.82	$E = 5.6116 d_1 - 21.245$	0.73

[*] P_{max}, σ_{max}, E, d_1: maximum compressive load, maximum compressive stress, compressive energy, and outer diameter of hemp stem.

4. Conclusions

Hemp stem diameter and linear density increased towards the lower height regions of stem. The dual purpose hemp stalk, Petera had greater diameters and linear density than the single purpose hemp, Alyssa. The average outer diameter of hemp stem in the upper, middle and lower height regions were 8.7, 12.7, and 16.3 mm for Petera and 6.7, 8.5 and 9.2 mm for Alyssa, respectively. The average linear density at the upper, middle and lower height region was 14.9, 22.4 & 36.6 g m^{-1} for Petera and 9.8, 14.3 & 19.3 g m^{-1} for Alyssa, respectively.

In general, higher maximum compression load and more energy requirement for compressing the lower height region of hemp stem in both axial and lateral directions. The average maximum compression load at the upper, middle and lower height regions were 624, 903 & 1090 N for Alyssa & 762, 1233 & 1425 N for Petera (in the axial direction) and 58, 80, & 173 N for Alyssa & 82, 59 & 110 N for Petera (in the lateral direction). The maximum stress varied from 10 to 27 MPa and 0.7 to 2.8 MPa in the axial and lateral directions, respectively. The modulus of compression was higher in the lower height regions for Alyssa and Petera for the axial compression direction. The modulus varied from 515 to 776 N mm^{-2} for two hemp varieties in the axial direction. In the lateral direction, modulus in the middle height region was similar for both hemp varieties, and different values were observed for the lower and upper height regions. The compressive energy requirements were significantly affected by the hemp height region. The average energy requirement at the upper, middle and lower height regions were 430, 822 & 1065 mJ for Alyssa & 593, 1311 & 1809 N for Petera (in the axial direction) and 23, 34, & 85 N for Alyssa & 36, 33 & 62 mJ for Petera (in the lateral direction).

The maximum compression load increased with increasing outer diameters of hemp stem. The relationship between maximum compression load and outer diameter of hemp stem could be described by a power function (in the axial direction) and a linear function (in the lateral direction). The maximum stress was exponentially decreased (in the axial direction) and followed a power function (in the lateral direction) with increasing outer diameter for both varieties. The energy requirements for compression increased with increasing stem diameters followed by a power function for two hemp varieties in both compression directions except for Petera in the lateral compression direction.

Acknowledgements

The study was funded by Natural Sciences and Engineering Research Council of Canada (NSERC). The authors wish to acknowledge Keith Watson, Manitoba Agriculture, Food & Rural Initiatives for providing hemp stalks. Thanks are given to Dr. Stefan Cenkowski for his technical guidance on the test apparatus. Thanks are also given to Composites Innovation Ctr Manitoba Inc, Emerson Hemp Distribution Company, and Parkland Industrial Hemp Growers Co-op Ltd for their supports to the project.

References

ASTM standards (2008). D-695: Standard test method for compressive properties., (www.astm.org)

Bhaholyotin B; Kradangna P; Ichito K; Gotoh Y (1988). Study on some physical properties of sugar cane for whole stalk harvester design. Kasetsart Journal (Natural Science), **22,** 88-90

Blahovec J (1988). Mechanical properties of some plant materials. Journal of Materials Science, **23,** 3588-3593

Bócsa I; Karus M (1997). The Cultivation of Hemp: Botany, Varieties, Cultivation, and Harvesting, HempTech, Sebastopol, CA

Chen Y; Gratton J; Liu J (2004). Power requirements of (Cannabis Sativa) cutting and conditioning. Biosystems Engineering, **87**(4), 417-424

Chattopadhyay P S; Pandey K P (1999). Mechanical properties of sorghum stalk in relation to quasi-static deformation. Journal of Agricultural Engineering Research, **73**, 199–206

FAO (2009). Agricultural Production., (www.fao.org)

Galedar M N; Jafari A; Mohtasebi S S; Tabatabaeefar A; Sharifi A; O'Dogherty M J; Rafiee S; Richard G (2008). Effects of moisture content and level in the crop on the engineering properties of alfalfa stems. Biosystems Engineering, **101**, 199-208

Huber J A (1991). A study of the physical properties of wheat straw. M.Phil., Cranfield Institute of Technology, Silsoe College, Silsoe, UK

Hansen R (2008). Industrial Hemp Profile. Agriculture Marketing Resource Center, Iowa State University, Iowa, USA. (http://www.agmrc.org/commoditiesproducts/fiber/industrial_hemp_profile.cfm)

Lo T Y; Cui H Z; Leung H C (2004). The effect of fiber density on strength capacity of bamboo. Materials Letter, **58**, 2595-2598

McRandal D M; McNulty P B (1980). Mechanical and physical properties of grasses. Transactions of the ASAE, **23**(2), 816-821

Mohsenin N N (1986). Physical properties of plant and animal materials. Gordon and Breach, NY, USA

Oke B O; Kaul R N; Mittal J P (1984). Physical and mechanical properties of sorghum (*Sorghum bicolor*) stalk harvested at various intervals after grain maturity. Agricultural Wastes, **11**, 31-45

Prasad J; Gupta C P (1975). Mechanical properties of maize stalk as related to harvesting. Journal of Agricultural Engineering Research, **20**(2), 79–87

Persson S (1987). Mechanics of cutting plant material. ASAE publications, Michigan, USA

Qingxi L; Yitao L; Caixia S; Boping T (2007). Research on the physical mechanics properties of the rape stalk. An ASABE meeting presentation paper No. 076136, ASABE, Minneapolis, Minne., USA

Skubisz G (1980). The dependence of the Young modulus of winter wheat stalk in various phenological phases. University of Agricultural Science, vol 37, pp. 1–9, Godollo, Hungary

Steel R G D; Torrie J A (1980). Principles and Procedures of Statistics, A Biometrical Approach, 2nd edition, McGraw-Hill Inc, Montreal, QC, Canada