Physical and mechanical properties of selected forage materials

S. Afzalinia[1]* and M. Roberge[2]

[1]Department of Agricultural Engineering Research, Agricultural Research Center of Fars Province, P.O. Box: 73415-111, Zarghan, Shiraz, Iran; and [2]Department of Agricultural and Bioresource Engineering, University of Saskatchewan, 57 Campus Drive, Saskatoon, Saskatchewan S7N 5A9, Canada. *Email: sja925@mail.usask.ca

Afzalinia, S. and Roberge, M. 2007. **Physical and mechanical properties of selected forage materials**. Canadian Biosystems Engineering/Le génie des biosystèmes au Canada **49**: 2.23-2.27. The static coefficient of friction of alfalfa, barley straw, wheat straw, and whole green barley on a polished steel surface was determined. Four levels of moisture content were considered for alfalfa and barley straw, while the coefficient of friction was measured at one level of moisture content for wheat straw and whole green barley. Coefficient of internal friction of alfalfa and barley straw was determined at four cut lengths. Both coefficients of external and internal frictions at each of the moisture contents and cut lengths were determined using five levels of normal pressures. Results of this study showed that the static coefficient of friction increased with an increase in material moisture content from 12.0 to 45.7% (wb) for alfalfa and barley straw. This coefficient ranged from 0.15 to 0.26 and 0.14 to 0.27 for alfalfa and barley straw, respectively. The static coefficient of friction for wheat straw at 10% moisture content (wb), and whole green barley at 51% moisture content (wb) were 0.13 and 0.21, respectively. Cut length had no significant effect on the coefficient of internal friction of barley straw and had a slight effect on the coefficient of internal friction of alfalfa. The static coefficient of friction of alfalfa on a polished steel surface was a quadratic function of material moisture content, while the relationship between the coefficient of friction of barley straw on a polished steel surface and material moisture content was best expressed by a linear equation. **Keywords:** coefficient of friction, adhesion coefficient, cohesion coefficient.

Le coefficient de friction fut déterminé respectivement pour de la luzerne, de la paille d'orge/blé et de l'orge (pour ensilage). Quatre niveaux de teneurs en eau furent considérés pour la luzerne et la paille d'orge alors que le coefficient de friction fut mesuré à un seul niveau de teneur en eau pour la paille de blé et pour l'orge (ensilage). Le coefficient de friction interne de la luzerne et de la paille de blé fut déterminé pour quatre longueurs de hachage. Les deux coefficients de friction (interne et externe) pour chaque teneur en eau et longueur de hachage furent déterminés en utilisant cinq niveaux de pressions normales. Les résultats de cette étude démontrent que le coefficient statique de friction a augmenté avec l'augmentation de la teneur en eau à partir de 12.0% jusqu'à 45.7% (b.h.) pour la luzerne et la paille d'orge. Ce coefficient a varié de 0.15 à 0.26 pour la luzerne et de 0.14 à 0.27 pour la paille d'orge. Le coefficient statique de friction pour la paille de blé à 10% de teneur en eau et l'orge (pour ensilage) à 51% de teneur en eau furent de 0.13 et 0.21 respectivement. La longueur de hachage n'a pas eu d'effet significatif sur le coefficient de friction interne de la paille de blé et peu d'effet sur le coefficient de friction interne de la luzerne. Le coefficient statique de friction de la luzerne contre une paroi métallique polie est une fonction quadratique de la teneur en eau alors que la relation entre le coefficient de friction de la paille d'orge contre une paroi métallique polie et la teneur en eau est linéaire.

INTRODUCTION

Compressing forage materials into high-density packages is necessary to reduce handling and storage costs and facilitate storage operation. Making such packages requires a comprehensive knowledge of the physical and mechanical properties of these materials and their mechanical behavior under pressure. Accurate data of physical and mechanical properties of forage materials such as coefficients of internal and external friction are needed for designing forage material harvesting and handling systems. These data are also needed as input to the analytical and numerical models of the forage material compaction process. For instance, modeling of the baling process requires some physical and mechanical properties of the baled materials. Therefore, this study was conducted to provide sufficient input data for the analytical and numerical models of pressure distribution and pressure-density relationships in a large square baler.

Although most research work in the field of the coefficient of friction of agricultural materials is related to grains, some literature was found regarding the static coefficient of friction, adhesion coefficient, and cohesion coefficient of forage materials. Coefficients of friction of grains and forage materials are significantly affected by material moisture content. Brubaker and Pos (1965) showed that increasing moisture content of grains increased the static coefficient of friction on all structural surfaces except teflon. Bickert and Buelow (1966) found that the sliding coefficient of friction of shelled corn on steel and plywood surfaces and barley on a steel surface was a linear function of material moisture content. Lawton and Marchant (1980) reported that material moisture content had a significant effect on the coefficient of internal friction of all seeds tested; the coefficient increased with an increase in moisture content. Thompson and Ross (1983) reported that the coefficient of friction of wheat grain on a steel surface increased with increasing moisture content from 8 to 20%, but at 24% moisture content, it decreased. Zhang et al. (1994) found that the coefficient of friction of wheat on a corrugated steel surface increased with an increase in moisture content.

Ling et al. (1997) stated that the static and sliding coefficients of friction of wood ash increased with an increase in ash moisture content. Chandrasekar and Viswanathan (1999) showed that the coefficient of friction of arabica and robusta (coffee) parchments on various surfaces increased with an increase in moisture content in the range of 9.9 to 30.6% (wb).

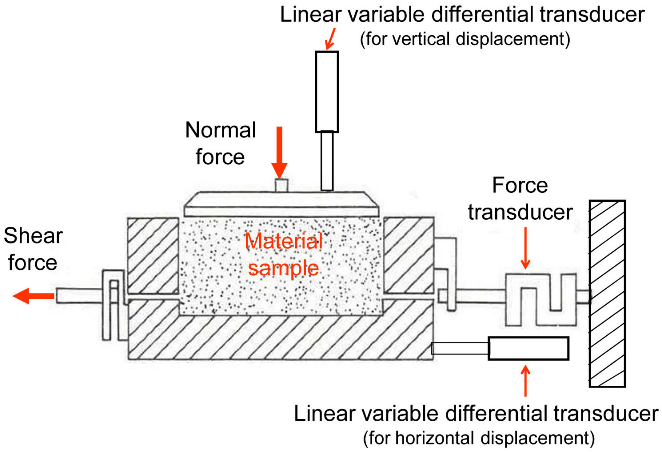

Fig. 1. Schematic of the shear box used in this study (redrawn from Moysey and Hiltz 1985).

Aviara et al. (1999) reported a range of 0.41 to 0.98 for the coefficient of static friction of guna seeds in the moisture range of 4.7 to 39.3% (db). Jha (1999) found the ranges of 0.596 to 0.82 and 0.493 to 0.684 for the static coefficient of friction of makhana on galvanized iron and stainless steel, respectively, within the moisture content range of 5 to 20% (db). Nimkar and Chattopadhyay (2001) reported a static coefficient of friction range of 0.344 to 0.625 for green gram over different material surfaces within the moisture range of 8.39 to 33.40% (db). Balasubramanian (2001) showed that coefficient of friction of raw cashew nut on different surfaces increased with an increase in moisture content within the range of 3.15 to 20.05% (db). Mani et al. (2003) stated that moisture content had a significant effect on the coefficient of friction of corn stover grind on a galvanized steel surface. Parde et al. (2003) showed that the sliding coefficient of friction of buckwheat was significantly affected by moisture content.

Material and surface type also have considerable effect on the coefficient of friction. Richter (1954) determined the static and sliding friction coefficients for chopped hay, chopped straw, and corn and grass silages on a galvanized steel surface. He reported the static and sliding coefficients of friction for chopped hay and straw ranging from 0.17 to 0.42 and 0.28 to 0.33, respectively. The researcher also reported the ranges of 0.52 to 0.82 and 0.57 to 0.78 for the static and sliding coefficients of friction of corn and grass silages, respectively. White and Jayas (2001) reported that increasing moisture content had no significant effect on the sliding coefficient of friction of canola meal pellets on plywood, steel-troweled concrete, and steel surface while sliding coefficient of sunflower meal pellets on plywood, steel-troweled concrete, and wood-floated concrete increased with an increase in moisture content. Olajide and Ade-Omowaye (1999) found that the static coefficient of friction of locust bean seed varied from 0.36 on glass to 0.62 on plywood at a moisture content of 6.42% (db). Olajide et al. (2000) showed that the static coefficient of friction of Shea nut kernels on different surfaces varied from 0.36 to 0.52 at moisture content of 4.35% (db). Parde et al. (2003) reported that the sliding coefficient of friction of buckwheat was considerably affected by cultivar type and surface type.

Normal pressure, shear rate, particle size, and relative humidity are other parameters which may have an influence on the coefficient of friction. Snyder et al. (1967) showed that normal pressure and relative humidity had a slight effect on the coefficient of friction of wheat grains on various metal surfaces. The value of the coefficient increased with increasing relative humidity in the range of 25 to 85%. Zhang et al. (1994) found that increasing normal pressure in the range of 9.73 to 70.53 kPa with the moisture content ranging from 11.9 to 17.7% (wb) decreased the coefficient of friction of wheat on a corrugated steel surface. Ling et al. (1997) reported that both the static and sliding coefficients of friction decreased with an increase in ash particle size. Molenda et al. (2000) showed that the coefficient of friction of soft red winter wheat on corrugated and smooth galvanized steel surfaces increased with an increase in shear rate and decreased with an increase in normal pressure.

A limited number of research works related to the coefficients of adhesion and cohesion was found in the literature. Tabil and Sokhansanj (1997) reported cohesions of 2.19 and 2.51 kPa for alfalfa ground using 3.2 and 2.4 mm hammer mill screen sizes, respectively. Mani et al. (2003) showed that the adhesion coefficient of corn stover grind on a galvanized steel surface was not affected by moisture content.

Data of physical and mechanical properties of alfalfa, barley straw, wheat straw, and whole green barley were required as input to the analytical and numerical models of the compaction process of these materials in a large square baler. Therefore, this study was conducted to determine some physical and mechanical properties of alfalfa, barley straw, wheat straw, and whole green barley. Thus, the objectives of this study were:

1. to determine the static coefficient of friction of alfalfa, barley straw, wheat straw, and whole green barley on a polished steel surface;
2. to determine the coefficient of internal friction of alfalfa and barley straw at different cut lengths;
3. to evaluate the effect of moisture content on the coefficient of friction of alfalfa and barley straw on a polished steel surface; and
4. to determine adhesion and cohesion coefficients of alfalfa and barley straw.

MATERIALS and METHODS

Friction, adhesion, and cohesion coefficients

In this research, the coefficients of adhesion and cohesion, the coefficient of internal friction, and the coefficient of friction of selected forage materials on a polished steel surface were measured in the laboratory using a shear box apparatus (Fig. 1). This apparatus consisted of a sample box for holding the material samples, a force transducer to record the frictional force, two linear variable differential transducers (LVDT) to measure the sample horizontal and vertical displacements, a linkage to apply the normal force to the sample, and an electrical motor to provide a relative motion for the variable half of the sample box with respect to its fixed half. The sample box was 100 mm square with a thickness of 18 mm and depth of 37 mm. The coefficients of friction and adhesion were measured for alfalfa, barley straw, wheat straw, and whole green barley on a polished steel surface. The steel surface was polished using M-Prep conditioner A and silicon-carbide paper. In the case of alfalfa and barley straw, four levels of material moisture content were considered [12.0, 22.0, 31.0, and 42.2% (wb) for alfalfa

Table 1. Static coefficient of friction and adhesion coefficient for alfalfa on a polished steel surface at different moisture contents.

Moisture content (% wb)	Coefficient of friction*		Adhesion coefficient* (kPa)	
	Mean	SD	Mean	SD
12.0	0.15 a	0.01	2.1 a	1.68
22.0	0.17 b	0.01	11.4 ab	6.17
31.0	0.20 c	0.01	14.9 b	4.78
42.2	0.26 d	0.02	9.3 ab	6.67
LSD (P = 0.05)	0.019		9.8	

* Values are averages of three replicates.
a, b, c, d - Averages with different letters are statistically different at the confidence level of 95%.

and 12.2, 20.3, 32.9, and 45.7% (wb) for barley straw] and tests were carried out at five levels of normal pressures (200, 330, 500, 600, and 735 kPa). Since parameters measured in this study would be used in the modeling of pressure distribution in a large square baler, the pressures encountered in a large square baler were used as normal pressures.

The coefficient of friction and adhesion coefficient of wheat straw and whole green barley on a polished steel surface were measured at only one level of moisture content each. The moisture contents were 10.0 and 51.0% for wheat straw and whole green barley, respectively. Alfalfa samples were selected from the first cut alfalfa of the 2003 crop, and barley and wheat straw were chosen from straw left on the field after harvesting in August 2003. A pre-calculated amount of water was sprayed on the samples to achieve the required moisture levels, and then the samples were kept in a climate controlled storage for 72 hours. The coefficient of internal friction and cohesion coefficient were determined for alfalfa and barley straw. In this experiment, forage materials were chopped into four levels of cut lengths (10, 30, 60, and 90 mm), and tests were performed at 12.0% moisture content (wb) for both materials. For each test, a sample of forage material was put in the sample box and the bottom half of the sample box was subjected to a shear force by the electrical motor at a shear rate of 0.4 mm/min for each of the aforementioned normal pressures. The frictional force was recorded by the force transducer. The horizontal and the vertical displacements were recorded by the horizontal and vertical LVDTs, respectively.

Each test was repeated three times, and a new sample was used for each test. In the case of surface friction measurement, the steel surface was cleaned after running each test to remove the residue deposited on the surface. The SAS software (SAS Institute, Cary, NC) was used to analyze the data of the experiments in the form of a completely randomized experimental design. The maximum shear stresses were plotted versus the normal pressures at each level of moisture content. The slope of the best fit line to the plotted data was considered as the coefficient of friction, and the *y*-intercept of the line was considered as the adhesion or cohesion coefficient of the sample at that moisture content based on Mohr-Coulomb's model. Mohr-Coulomb's model expresses shear stress as a function of normal stress, coefficient of friction, and adhesion or cohesion coefficients as (Lawton and Marchant 1980):

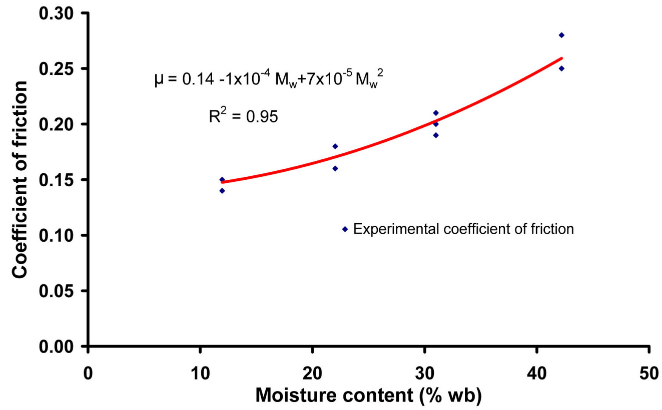

Fig. 2. Experimental and predicted coefficients of friction of alfalfa on a polished steel surface vs material moisture content.

$$\tau = C_a + \mu\sigma_n \qquad (1)$$

where:
τ = effective shear stress (kPa),
C_a = adhesion or cohesion coefficient (kPa),
μ = coefficient of external friction (decimal) and
σ_n = effective normal stress (kPa).

In the coefficient of internal friction measurement, the *y*-intercept represents the cohesion coefficient (it is shown by C) and μ is the coefficient of internal friction.

RESULTS and DISCUSSION

Friction, adhesion, and cohesion coefficients

Results of the static coefficient of friction of alfalfa on a polished steel surface showed that alfalfa moisture content had a significant effect on the coefficient of friction such that the coefficient of friction increased with increasing moisture content; however, the rate of increment was larger for the higher moisture contents than that of the lower moisture contents (Table 1). This result was in good agreement with the results reported for alfalfa and similar materials in the literature (Shinners et al. 1991; Mani et al. 2003 ; Ling et al. 1997). The relationship between the coefficient of friction of alfalfa on a polished steel surface and alfalfa moisture content was best expressed by the quadratic equation:

$$\mu = 0.14 - 1\times10^{-4} M_w + 7\times10^{-5} M_w^2 \qquad (2)$$

where M_w = moisture content (% wb).

The experimental and predicted data of coefficient of friction of alfalfa on a polished steel surface versus moisture content is shown in Fig. 2. The coefficient of determination and the standard error of the model fitness were 0.95 and 0.01, respectively. The adhesion coefficient of alfalfa on a polished steel surface increased with an increase in moisture contents from 12.0 to 31.0% and decreased at a moisture content of 42.2% (Table 1). The lower adhesion coefficient at 42.2% moisture content could be related to the lubrication of the steel surface by water released from the moist materials under pressure. Comparison of the results was not possible as no

Table 2. Static coefficient of friction and adhesion coefficient for barley straw on a polished steel surface at different moisture contents.

Moisture content (% wb)	Coefficient of friction*		Adhesion coefficient* (kPa)	
	Mean	SD	Mean	SD
12.2	0.14 a	0.02	5.9 ab	3.98
20.3	0.18 b	0.01	11.2 a	1.29
32.9	0.22 c	0.02	3.1 ab	5.96
45.7	0.27 d	0.02	0.8 b	7.98
LSD (P = 0.05)	0.027		10.2	

* Values are averages of three replicates.
a, b, c, d - Averages with different letters are statistically different at the confidence level of 95%.

Table 3. Static coefficient of internal friction and cohesion coefficient for alfalfa with 12% moisture content at different cut lengths.

Cut length (mm)	Coefficient of internal friction*		Cohesion coefficient* (kPa)	
	Mean	SD	Mean	SD
10	0.44 a	0.00	27.9 a	1.27
30	0.43 a	0.03	27.1 a	11.23
60	0.44 a	0.02	23.9 ab	8.94
90	0.48 b	0.01	10.5 b	5.40
LSD (P = 0.05)	0.027		14.5	

* Values are averages of three replicates.
a, b - Averages with different letters are statistically different at the confidence level of 95%.

literature was found regarding adhesion coefficient of alfalfa. However, some studies related to the effect of moisture content on adhesion coefficient of some other forage materials have been reported. For instance, Mani et al. (2003) reported that moisture content had no significant effect on adhesion coefficient of corn stover grind.

Results of the static coefficient of friction of barley straw on a polished steel surface revealed that material moisture content had a significant effect on the coefficient of friction, which increased with an increase in moisture content (Table 2). The coefficient of friction for barley straw was in the range of 0.14 to 0.27 at moisture contents of 12.2 to 45.7% (wb). The relationship between the coefficient of friction of barley straw on a polished steel surface and material moisture content was best expressed by the linear equation:

$$\mu = 0.1006 + 0.0037\, M_w \quad (3)$$

The coefficient of determination and the standard error of the model fitness for barley straw were 0.93 and 0.013, respectively. Figure 3 shows the experimental and predicted data of coefficient of friction of barley straw on a polished steel surface versus moisture content. The adhesion coefficient of

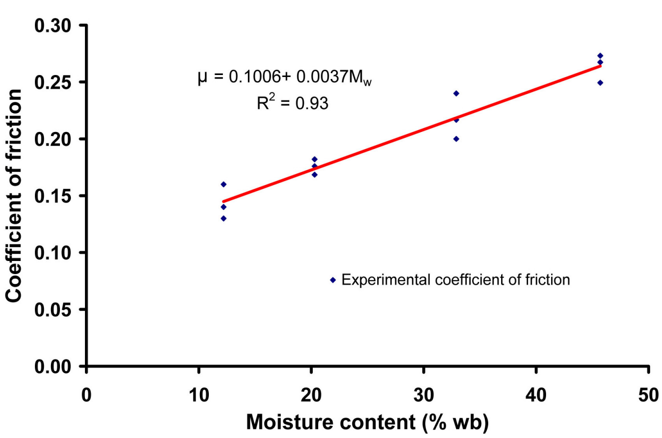

Fig. 3. Experimental and predicted coefficients of friction of barley straw on a polished steel surface vs material moisture content.

barley straw on a polished steel surface was affected by material moisture content, which increased with an increase in moisture content from 12.2 to 20.3% and decreased when moisture content increased from 20.3 to 45.7% (Table 2). Again, lubrication due to released water from moist material under pressure could explain the reduction in adhesion coefficient at high moisture contents.

The static coefficient of friction of wheat straw and whole green barley on a polished steel surface was 0.13 and 0.21 when measured at 10.0 and 51.0% moisture content, respectively.

Table 3 shows the results of the coefficient of internal friction of alfalfa at different material cut lengths. No significant difference between coefficients of internal friction was observed at all cut lengths except 90 mm. The coefficient of internal friction at 90-mm cut length was slightly higher than the coefficients of other cut lengths. The results of this study were not compared as no literature was found regarding coefficient of internal friction of alfalfa. These results also showed a significant difference between the cohesion coefficient of alfalfa at 90-mm cut length and the coefficients at 10 and 30-mm cut lengths (Table 3). The adhesion coefficient remained relatively constant when cut length increased from 10 to 30 mm and decreased with an increase in cut length from 30 to 90 mm. Tabil and Sokhansanj (1997) reported cohesion coefficients of 2.19 and 2.51 kPa for alfalfa grinds using 3.2 and 2.4-mm screen sizes, respectively. Results of their study showed a slight increase in cohesion coefficient as particle size increased; however, it should be noted that alfalfa grinds might have different properties compared to chopped alfalfa. The reduction of the cohesion coefficient at the larger cut lengths in the present study could be related to the reduction of contact area between the particles at larger cut lengths.

Results also showed that material cut length had no significant effect on the coefficient of internal friction and cohesion coefficient of barley straw. However, the cohesion coefficient slightly increased with an increase in cut length from 10 to 30 mm and decreased for the cut lengths varying from 30 to 90 mm (Table 4).

Table 4. Static coefficient of internal friction and cohesion coefficient for barley straw with 12% moisture content at different cut lengths.

Cut length (mm)	Coefficient of internal friction*		Cohesion coefficient* (kPa)	
	Mean	SD	Mean	SD
19	0.30 a	0.01	34.4 a	8.38
30	0.30 a	0.02	36.1 a	6.59
60	0.31 a	0.01	29.7 a	5.19
90	0.32 a	0.02	26.0 a	4.42
LSD (P = 0.05)	0.027		11.9	

* Values are averages of three replicates.
a - Averages with different letters are statistically different at the confidence level of 95%.

CONCLUSIONS

The following conclusions were drawn from the results of this research:

1. The coefficient of friction of alfalfa and barley straw on a polished steel surface increased with an increase in material moisture content from 12.0 to 45.7% (wb). This coefficient ranged from 0.15 to 0.26 and 0.14 to 0.27 for alfalfa and barley straw, respectively.
2. Coefficients of friction for wheat straw at 10% moisture content and whole green barley at 51% moisture content were 0.13 and 0.21, respectively.
3. Cut length had no significant effect on the coefficient of internal friction of barley straw and had a slight effect on the coefficient of internal friction of alfalfa.
4. The static coefficient of friction of alfalfa on a polished steel surface was a quadratic function of material moisture content (r^2 = 0.95), while the relationship between the coefficient of friction of barley straw and material moisture content was best expressed by a linear equation (r^2 = 0.93).

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