Internal Shear Stress for Sugarcane Bagasse

Abstract
This paper presents internal shear-stress results at preshear conditions for sugarcane bagasse using a modified direct-shear device. The relationship between normal stresses and shear stress was measured at three moisture content levels. Statistical analysis is shown for the Mohr envelope as a linear trend line with R² greater than 0.97, obtaining larger cohesion and shearing coefficients (c, µ) at the lowest moisture content than at high moisture content: C = 0.207 N/cm² and µ = 0.729 for 8.7% moisture content; C = 0.105 N/cm² and µ = 0.598 for 28.6% moisture content; C = 0.097 N/cm² and µ = 0.596 for 63.5% moisture content.

List of Symbols
- $A_R$: actual area at failure
- d: upper cell displacement
- C: cohesion
- F: horizontal load
- $F_f$: friction force between cells
- L: failure length plane
- S: separation between cells
- W: normal load
- $\phi$: angle of shearing resistance
- $\sigma$: normal stress
- $\tau$: shearing stress
- $\mu$: shearing resistance coefficient

Introduction
The sugarcane bagasse is a lignocellulosic fiber produced as residue from sugarcane factories. This bulk material is composed of individual particles, each one is thin and long and of different diameters. Sugarcane bagasse is a low-density, highly compressed material and the particles tend to interlock. In the last few years there has been growing interest in the use this material as fuel or animal feed and for this reason the mechanical properties of the product are important. A basic characteristic to be determined is the limiting stress function that defines cohesion and angle of internal friction. These characteristics are useful for determining free-flow parameters for hopper design, as described by Jenike [1].

The limiting stress function in geotechnical engineering for rigid materials was described by Mohr and Coulomb and is accepted to be a linear function defined as follows:

$$\tau = \mu \sigma + C, \text{ or } \tau = \tan \phi \sigma + C \quad (1)$$

Where $\tau$ denotes the shearing strength on failure plane, $\mu$ denotes shearing resistance coefficient, $C$ denotes bulk material cohesion, $\phi$ denotes angle of shearing resistance and $\sigma$ denotes normal stress on failure plane.

There is a lack of research using the Mohr envelope description in agricultural fibrous materials like a sugarcane bagasse. This is due to problems of performing tests using conventional devices for granular materials like Jenike cells [1], Schulze cells [2], or Peschel cells [3]. Some parameters of shredded agricultural materials are reported by Ussrey [4] on quasi-whole rice stalks arranged in parallel position. Negi [5] reported internal shear test on chopped corn silage. Berhardt [6] reported internal shear failure tests on sugarcane bagasse; he measured only tensile strength values on 0.05-0.068 N/cm². See Table 1.

As described by Escamilla-Martinez [7] and Berhardt [6], there is not an easy way to measure the mechanical properties of fibrous agricultural residues using typical devices. For this reason a modified direct shear device was designed to investigate internal shear stresses on sugar cane bagasse.

Materials and Methods
Sugarcane bagasse from a Mexican sugarcane factory with 55% moisture content was used as the test material. This material was dried naturally to the sun. Then it was tested at three levels of moisture content obtained artificially by the addition of water. Moisture content was measured as suggested by ASAE-

<table>
<thead>
<tr>
<th>Table 1. Internal shear test for fibrous agricultural materials</th>
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<tbody>
<tr>
<td><strong>Author/ bulk material</strong></td>
</tr>
<tr>
<td>---------------------------</td>
</tr>
<tr>
<td>Ussrey: Rice stalks residues</td>
</tr>
<tr>
<td>Negi: Silage Corn</td>
</tr>
<tr>
<td>Silage Grass</td>
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<tr>
<td>Berhardt: Sugarcane bagasse</td>
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S358.2 standard at the following levels: 8.7, 28.6 and 63.4% w.b. Bulk density related to each moisture content was 70, 100, 120 kg/m³ respectively. The shear device used for the tests consisted of two square 16x16 cm boxes and 5 cm deep [7], Figure 1; the upper box is movable and slides over the fixed lower box. In the shear direction and sliding plane there is a separation between the shell boxes (S, Figure 1). The system also includes a data acquisition system in order to capture the upper cell displacement and corresponding shear load increase on the failure plane. Seven points were measured (τ, σ): for 8.3% moisture content, each point was repeated three times. For the other moisture content levels there were two repetitions. The normal loads tested were: 59.8, 151.0, 243.3, 335.5, 448.3, 535.6 and 618.0 N.

**Test procedure.** First, the friction force (Ff) between upper and lower cells without any load was measured. Later, the upper and lower cells were aligned one over the other and the sample was manually loaded into the shear boxes. Then, a selected normal load W was applied over the sample and a horizontal force applied to displace the upper cell to produce shear stress (see Figure 1). The data acquisition system recorded displacement (X-axis) versus horizontal load (Y-axis) and displayed it in real time as shown on Figure 2. Testing was stopped when the maximum value was observed.

**Calculation procedure.** Normal stress and shear stress were calculated as follows:

$$\sigma = \frac{W}{A_r} \quad (2)$$

$$\tau = \frac{(F - F_f)}{A_r} \quad (3)$$

Where W is the normal load, F is the horizontal load, Ff is the friction force between cells and, A_r actual area at failure time.

**Results**

Actual area A_R was determined by the equation:

$$A_r = 16L_f = 16(22.5 - d) \quad (4)$$

Where d is the upper cell displacement and 22.5 is a length measured during tests related to the shell box thickness and the influence of fiber interlocking on points A and B as seen on Figure 1.

As expected for bulk solids, the failure occurred at a high displacement distance from the initial position of the upper cell. The failure took place within a defined range. For this set of test, the displacement value (d) ranged from 4.7-7.2 cm, as shown in Figure 2.

Figure 3 shows the results for sugarcane bagasse at 8.7, 28.6 and 63.4% moisture content w.b. A simple regression analysis for normal load, σ, and shear stress, τ, indicate a linear trend line with R² greater than 0.97 at 8.7% moisture content. It also shows similar behavior between 28.6 and 63.5% moisture content.

As shown in Figure 4, there is a general inverse relationship between normal moisture content and cohesion where the highest Cohesion (C) occurs at the lowest moisture content. Figure 5 illustrates the results for the Internal Friction Coefficient (µ) at each level. The highest µ occurs at the lowest moisture content.

**Discussion**

The results of this investigation indicate that the Mohr envelope is a linear function for sugarcane bagasse for moisture content from 8.7 to 63.7%. This behavior is also reported by Negi [5] on corn silage and by Ussrey [4] on rice stalk residues with high moisture content (60.5 to 67.2%). Values measured for internal friction coefficient (µ) at high moisture content are greater in sugarcane bagasse than in rice stalks or corn silage. This is because of the larger contact area between particles on sugarcane bagasse than on rice stalks or chopped corn silage. The cohesion values (C) reported...
by Ussrey [4] and by Negi [5] are higher than those obtained in sugarcane bagasse. This could be caused by obstruction on the shear line produced by the shear device. At high moisture content, the fibers are flexible and shear strength is reduced. This is verified on sugarcane bagasse where low moisture content shows higher values for μ and C, and vice versa.

**Conclusion**

Internal shear tests on sugarcane bagasse at three levels of moisture contents demonstrated that for each case there was a linear trend as predicted by the Mohr envelope. These functions were described by the following relationships:

\[ \tau = 0.729\sigma + 0.207 \text{ [N/cm}^2\text{]} \]

with \( R^2 = 0.9728 \) for 8.7% moisture content; \( \tau = 0.5984\sigma + 0.105 \text{ [N/cm}^2\text{]} \]

with \( R^2 = 0.9711 \) for 28.67% moisture content; and \( \tau = 0.5963\sigma + 0.097 \text{ [N/cm}^2\text{]} \)

with \( R^2 = 0.978 \) for 63.4% moisture content. The general behavior of cohesion was seen to decrease as the moisture content increased; the same behavior was observed for the internal friction coefficient. This study also verified that there was less shear strength at high moisture content.

**References**


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Fig. 1. Special shear device for fibrous agricultural materials
Fig. 1. Dispositivo de corte directo modificado, [7].

Fig. 2. Typical shear cell data for sugarcane bagasse
Fig. 2. Curva típica de comportamiento de la fuerza horizontal durante el corte, [7].

Figure 3. Mohr envelope for sugarcane bagasse at three moisture content levels
Fig. 3. Envolvente de Mohr para bagazo de caña a tres contenidos de humedad, [7]

Figure 4. Relationship between moisture content and cohesion
Fig. 4. Relación entre el contenido de humedad y la cohesión en bagazo de caña, [8].

Figure 5. Relationship between moisture content and internal friction coefficient
Fig. 5. Relación entre el contenido de humedad y el coeficiente de fricción interno en bagazo de caña, [8].

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