MODELLING OF THE MECHANICAL BEHAVIOUR OF HEAVILY OVER-CONSOLIDATED BAGASSE

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Abstract

A BETTER UNDERSTANDING of the behaviour of prepared cane and bagasse, and the ability to model the mechanical behaviour of bagasse as it is squeezed in a milling unit to extract juice, would help identify how to improve the current process, for example to reduce final bagasse moisture. Previous investigations have proven that juice flow through bagasse obeys Darcy’s permeability law, that the grip of the rough surface of the grooves on the bagasse can be represented by the Mohr-Coulomb failure criterion for soils, and that the internal mechanical behaviour of the bagasse is critical state behaviour similar to that for sand and clay. Current Finite Element Models (FEM) available in commercial software have adequate permeability models. However, no commercially available software seems to contain an adequate mechanical model for bagasse. The same software contains a few material models for soil and other materials, while the coding of hundreds of developed models for soil and other materials remains confidential at universities and government research centres. Progress has been made in the past 10 years towards implementing a mechanical model for bagasse in finite element software code. This paper builds on that progress and carries out a further step towards obtaining an adequate material model. The fifth and final loading condition outlined previously, shearing of heavily over-consolidated bagasse, is outlined.

Introduction

A better understanding of the mechanical behaviour of prepared cane and bagasse during the crushing process, coupled with a milling model incorporating a material model that can reproduce that behaviour, is seen as the most promising avenue to make a sizeable, step improvement to the crushing process.

Improvements could be made, for example, to reduce bagasse moisture or increase extraction. With a generally increased interest in cogeneration in Australia, and a move towards cane diffusers overseas, the efficient dewatering of bagasse becomes more important.

The ability to model the mechanical behaviour of bagasse as it is squeezed in a milling unit to extract juice would help identify how to improve the current process to reduce final bagasse moisture.

Previous investigations have demonstrated that juice flow through bagasse obeys Darcy’s permeability law (Kent and McKenzie, 2003), that the grip of the rough surface of the grooves on the bagasse can be represented by the Mohr-Coulomb failure criterion for soils (Plaza and Kent, 1997), and that the internal mechanical behaviour of the bagasse is critical state behaviour similar to that for sand and clay (Plaza, 2002).
Friction behaviour of bagasse with boundaries can be defined by a combination of the material model and explicitly defined maximum values of coefficient of friction. Current Finite Element Models (FEM) available in commercial software have adequate permeability models (they use Darcy’s permeability law). However, an adequate material model for bagasse is currently not available.

Plaza (2010) noted that a model described by de Souza Neto et al. (2008), with further modifications described in previous work, was likely to progress towards achieving an adequate material model for bagasse. By coding such a model into a subroutine attached to a commercial FEM package, it would be possible to modify any part of the predicted material behaviour, while being able to track and understand the internal workings of the code, and still use the solution procedures of a commercial FEM package. This avenue is seen as the best pathway towards achieving an adequate model for bagasse.

The current paper builds on the model of de Souza et al. and follows on the predictions of simple loading cases of compression, unloading, reloading, and shearing of normally consolidated bagasse (Plaza, 2011). If the material model can simulate the stresses and strains in simple mechanical tests on bagasse, it is more likely that the loads and torques in a milling unit, or the movement and deformation of bagasse in a pressure feeder chute or a roll groove, can be predicted adequately.

This paper concerns the last loading case needed to cover all likely cases—the shearing of a heavily over-consolidated bagasse sample. This behaviour is likely to occur for example, after the bagasse exits the pressure feeder, travels along the pressure feeder chute and contacts the feed roll and top roll surfaces. At these rough roll surfaces, the friction coefficient of the bagasse is likely to exceed a value of 1.0 (Plaza et al., 2002) so modelling the shearing behaviour of the bagasse has relevance to the roll contact angle that can be used for reliable feeding.

The model and shearing of heavily over-consolidated bagasse

The Modified Cam Clay model with beta modification and tension capability (de Souza Neto et al., 2008), with separately defined shapes for the yield surface (which defines the yield points) and the potential surface (which defines the deformation at yield, that is, the ratio between the shear deformation and the volume deformation) was further modified by Plaza (2010, 2011) and then tested against the following four loading conditions on bagasse:

- initial loading in compression
- unloading in compression
- reloading in compression
- shearing of normally consolidated bagasse.

The predictions were compared with compression and shear measurements from a modified direct shear test (Plaza, 2002). Either a single element model, or a multi-element finite element model (FEM) using a software package such as ABAQUS (Anon., 2009), can be used for the four loading conditions as the behaviour throughout the test sample is expected to be uniform (in the same manner as is established for soil).

The fifth and final loading case, the shearing of heavily over-consolidated bagasse, is the most challenging of the five cases to simulate. There are many reasons for this:

- Near yield, some of the sample is likely to fail while the rest does not (in the same manner as occurs in the case of soil). Once this happens, a single element model is no longer adequate to carry out the remainder of the simulation, and a multi-element finite element model is required.
• The behaviour of the bagasse is elastic until yield is reached, and little is known, for example, about the value of Poisson’s ratio ($\nu$) for bagasse. The ratio of the lateral stress developed to the stress being applied ($K_o$) for the over-consolidated condition is not known to have been measured, and its value is likely to change as shearing progresses.

• The shapes of the yield and the potential surfaces are not known.

The procedure adopted was to continue using a single element model and focus mainly on the shear stress predicted prior to the maximum value, while still monitoring the predicted change in volume. Since it is proven that, when bagasse is unloaded, the plot of specific volume (or void ratio) versus the natural log of applied pressure is linear (Plaza, 2002), the elastic behaviour was modelled using the following equations:

$$K = \sigma_s (1 + e) / \kappa \quad \text{eq.1, (Naylor and Pande, 1981)}$$
$$E = 3K (1 - 2\nu) \quad \text{eq.2, (Naylor and Pande, 1981; Muir Wood, 1990)}$$
$$G = E / (2 (1 + \nu)) \quad \text{eq.3, (Timoshenko and Goodier, 1982; Muir Wood, 1990)}$$

where $K$ is the bulk modulus, $G$ is the shear modulus, $E$ is Young’s modulus, $\nu$ is Poisson’s ratio, $\kappa$ is the slope of the elastic unloading-reloading line when void ratio is plotted versus the natural log of applied pressure, $e$ is void ratio and $\sigma_s$ is the confining stress. The parameters $K$, $E$, and $G$ were calculated from the other parameters as the simulation progressed. An alternative approach is to provide values of $E$ and $G$ from experimental data at varying pressures and over-consolidation but this alternative is far more cumbersome.

The critical state model parameters used in the modelling are also given in Table 1. It is noted that for the case modelled the yield and potential surfaces were different. The yield surface is defined by the values of $M$ (the slope of the critical state line) and $\beta_1$ (beta modification for the shape of the yield surface) and the potential surface is defined by $\psi$ (the dilation angle) and $\beta_2$ (beta modification for the shape of the potential surface). The slope of the normal compression line is denoted by $\lambda$. As per previous simulations, $P_t$ is a small tension (or cohesion) stress of 6.0 kPa. The initial vertical stress was 340 kPa, with a $K_o$ of 0.4, resulting in initial lateral stresses of 136 kPa. It is noted that the values of $\lambda$, $\kappa$, and $M$ have been relatively well determined from experimental data. The values of $\nu$ and $P_t$ are estimates from data which show a large variation, and for $\nu$ may have been measured when the bagasse was not behaving elastically. The values of $\beta_1$, $\psi$, and $\beta_2$ are, at best, guesses.

<table>
<thead>
<tr>
<th>$\lambda$</th>
<th>$\kappa$</th>
<th>$\nu$</th>
<th>$M$</th>
<th>$\beta_1$</th>
<th>$P_t$ (kPa)</th>
<th>$\psi$</th>
<th>$\beta_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.93</td>
<td>0.169</td>
<td>0.3</td>
<td>1.1</td>
<td>0.6</td>
<td>6.0</td>
<td>1.1</td>
<td>0.75</td>
</tr>
</tbody>
</table>

The predictions for shear stress and specific volume are shown in Figure 1 and Figure 2 respectively. The predictions in Figure 1 show a similar shear stress versus shear strain relationship to the experimental data. However, at low values of shear strain, the slope of the curve is under predicted. It may be that the values of the confining stress $\sigma_s$ and void ratio $e$ are not quite correct. The predictions near and after reaching the peak shear stress will likely need a multi-element model, and are affected by parameters with poorly known values. It is concluded that there is potential in
the model to predict the shear stress with good agreement. The exercise described here serves the purpose of showing that, with further investigation, it is likely that the developed model will be adequate to simulate the shear stress for heavily over-consolidated final bagasse. A comprehensive investigation using a parameter estimation package such as PEST (Anon., 2012) is likely to shed much more information on the modelling capability.

![Graph of Shear Stress vs Shear Strain](image1)

**Fig. 1**—Comparison of predictions with measured data of shear stress for shearing a heavily over-consolidated final bagasse sample.

The predicted specific volumes are a poor match for the measured values. This was the case initially for the shearing of normally consolidated bagasse (Plaza 2010, 2011) and this is seen as a readily surmountable problem. As noted previously, a multi-element model is most likely to be needed for modelling the specific volume for shearing of heavily over-consolidated bagasse.

![Graph of Specific Volume vs Shear Strain](image2)

**Fig. 2**—Comparison of predictions with measured data of specific volume for shearing a heavily over-consolidated final bagasse sample.

**Conclusions**

Improved understanding of bagasse mechanical behaviour and improved modelling capability is required to achieve further gains in a logical, structured manner. The latest mechanical
model developments have been presented in this work. An attempt has been made to model the remaining loading condition (shear stress and specific volume prediction during shearing of heavily over-consolidated final bagasse). Although not yet successful, the simulations to date indicate that the model is likely to be adequate for representing this last important loading condition with relatively minor modifications. However significant data analysis is required for this final step.

REFERENCES