FE14 DETERMINING THE MATERIAL PROPERTIES FOR HEAVILY OVER-CONSOLIDATED BAGASSE THROUGH PARAMETER ESTIMATION

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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, there are opportunities to decrease bagasse moisture from a milling unit. Also, the behaviour of bagasse in chutes is poorly understood.

Previous investigations have shown 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.

Progress has been made in the last ten years towards implementing a mechanical model for bagasse in finite element software. The objective has been to be able to simulate simple mechanical loading conditions measured in the laboratory, which, when combined together, have a high probability of reproducing the complicated stress conditions in a milling unit. This paper reports on the successful simulation of part of the fifth and final (and most challenging) loading condition, the shearing of heavily over-consolidated bagasse, and determining material property values through the use of powerful and free parameter estimation software.

Introduction

The crushing of prepared cane and bagasse in a milling unit to remove sugar and water involves large deformations with decreases in volume by a factor of seven. The compression pressures range from a few kilopascals at the feed (Donnelly) chute to as much as 20 000 kPa at the delivery nip. The roughened surface on the roll grooves is able to sustain large shear stresses in order to feed the material through the roll nips.

A better understanding of the mechanical behaviour of prepared cane and bagasse (shown in Figure 1) 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 and a move towards cane diffusers, the efficient dewatering of bagasse becomes more important. For example, it has been shown that bagasse subjected to shearing will shrink or expand in volume at the same confining pressure, depending on its previous stress history (Plaza *et al*., 2000). If the bagasse expands, it will suck in additional juice and vice versa. The detail of the behaviour is therefore of interest, particularly at the delivery nip in order to express more juice and/or reduce re-absorption.

Also, the behaviour of bagasse in chutes is poorly understood. For example, the values of the friction coefficient may be significantly higher than those quoted in the literature. Plaza *et al*. (2002) reported large values of the coefficient of shear for highly over-consolidated bagasse (such as bagasse that has exited a roll nip into a pressure feeder chute). The implication is that these values could lead to higher loads in the chute. However, higher throughput may be achieved if better grip is achieved on the surface of the next roller.

Fig. 1 – Prepared cane and final bagasse.

This paper follows on from previous experimental tests which 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). The Mohr-Coulomb failure criterion and the critical state behaviour were measured using modified direct shear tests as shown in Figure 2. The geometry was specially designed to cope with the large deformations and to minimise the juice pressure developed.

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. The measurements available from direct shear tests provide a means with which to develop a material model for bagasse. 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 is 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.

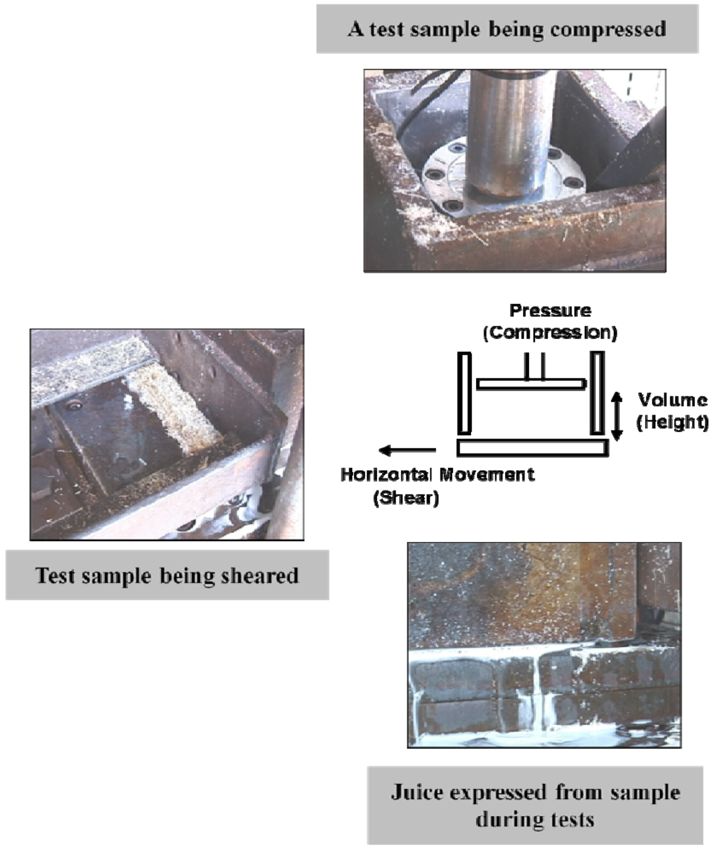

Fig. 2 – Direct shear testing of prepared cane and bagasse.

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), was modified by Plaza (2010) to have 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) and then tested (Plaza, 2010, 2011) 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 (ν) 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 shown that, when bagasse is unloaded, the plot of specific volume (or void ratio) versus the natural log of applied pressure is linear over a significant pressure range (Plaza, 2002), the elastic behaviour was modelled using the following equations (Plaza, 2012):

$$K = \frac{\sigma_s\,(1+e)}{\kappa}$$ eq.1, (Naylor and Pande, 1981**)**

$$E = 3\,K\,(1-2\nu)$$ eq.2, (Naylor and Pande, 1981; Muir Wood, 1990)

$$G = \frac{E}{2\,(1+\nu)}$$ 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, ν is Poisson's ratio, κ is the slope of the elastic unloading-reloading line when void ratio is plotted against the natural log of applied pressure, e is void ratio and σ_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 β_1 (beta modification for the shape of the yield surface) and the potential surface is defined by ψ (the dilation angle) and β_2 (beta modification for the shape of the potential surface). The slope of the normal compression line is denoted by λ. 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 λ, κ, and M have been relatively well determined from experimental data. The values of ν and p_t are estimates from data which show a large variation, and for ν may have been measured when the bagasse was not behaving elastically. The values of β_1, ψ, and β_2 were, at best, guesses.

Table 1 – Critical state parameters used in simulation of shearing of heavily over-consolidated final bagasse

λ	κ	ν	M	β_1	p_t (kPa)	ψ	β_2
0.93	0.169	0.3	1.1	0.6	6.0	1.1	0.75

The predictions for shear stress and specific volume, compared to the measured values and reproduced from Plaza (2012) are shown in Figure 3 and Figure 4 respectively.

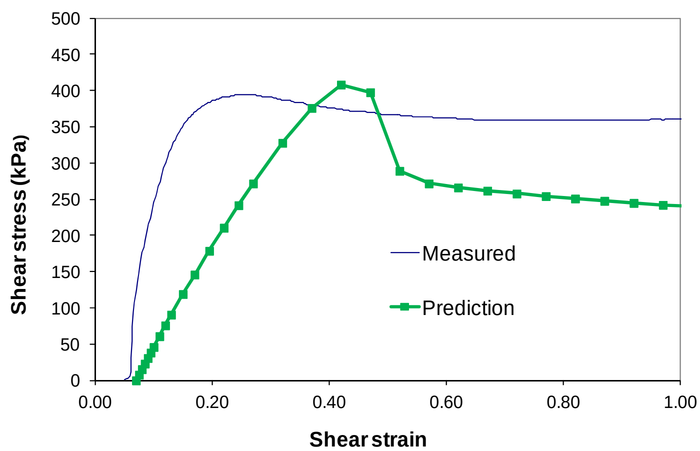

Fig. 3 – Comparison of predictions with measured data of shear stress for shearing a heavily over-consolidated final bagasse sample.

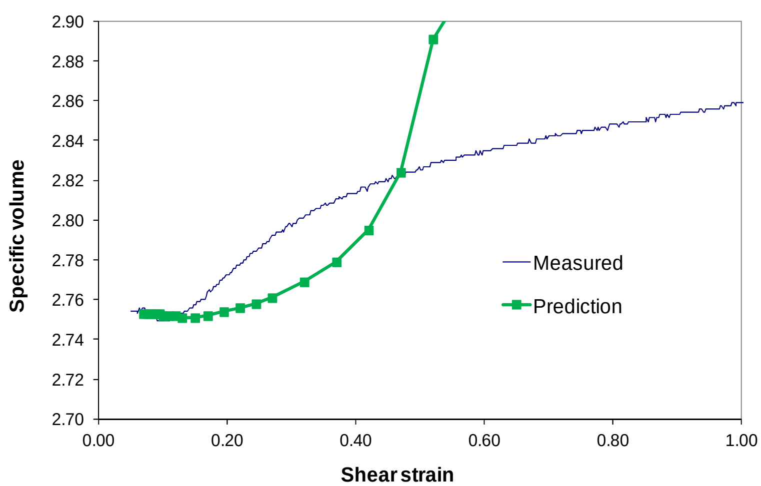

Fig. 4 – Comparison of predictions with measured data of specific volume for shearing a heavily over-consolidated final bagasse sample.

Plaza (2012) concluded that there was potential for the model to predict the shear stress and shear strain of a heavily over-consolidated final bagasse sample with good agreement.

Model modifications and the application of PEST

For the current investigation, two adjustment parameters were added to the model, f1 and f2. The role of f1 is to adjust the magnitude of the specific volume change due to the shear strain. The role of f2 is to adjust the shear stiffness. These additions were carried out as it was thought that they may be required in order to improve the agreement with measurements.

The parameter estimation package PEST (Anon., 2012) is a free set of programs with a powerful capability to provide improved understanding of a complicated model by systematically adjusting model parameters to match model predictions to provided measurements. The input and output files of the model were adjusted so that they could be used by PEST. Additional files required by PEST were created and PEST was run in 'parameter estimation mode', where PEST is asked to minimise an objective function comprised of the sum of weighted squared deviations between model predictions and their corresponding field-measured counterparts. Because the magnitude differences for shear stress are much greater than for specific volume, the specific volume deviations were multiplied by a weighting of 1000.0 during the estimation process. Because the behaviour of heavily over-consolidated bagasse is likely to be non-uniform after failure, the simulations using the single element model were only carried out to a shear strain of about 0.21. Parameters such as λ and κ, which are well defined by other loading conditions, were not allowed to be modified by PEST.

PEST carried out 121 program calls of the single element critical state model. The parameters found for a minimum objective function are given in Table 2. The predictions compared to measured values are shown in Figure 5 and Figure 6 for shear stress and specific volume respectively. It is shown that the agreement is quite good, concluding that the existing model does have the ability to simulate the shear stress and specific volume of heavily over-consolidated final bagasse. This is an important conclusion to achieve for the last of the five loading conditions.

Table 2 – Parameters for a minimum objective function for shearing of heavily over-consolidated final bagasse.

λ*	κ*	ν	M	β_1	p_t* (kPa)	ψ	β_2	f1	f2
0.93	0.169	0.06	1.45	0.71	6.0	1.57	1.03	0.74	2.0

Note: * signifies that this parameter was not allowed to be modified by PEST.

PEST can provide further information in order to understand how the parameters are interacting. For example, a parameter correlation coefficient matrix is produced as shown in Table 3. The absolute values are all quite close to 1.0, that is, there is strong correlation between the parameters, which is undesirable because it indicates that either parameter could have been varied in combination to achieve the same result. What this means is that, although a good reproduction of the measurements has been achieved, the parameters used to achieve the reproduction are not estimated accurately. The use of a separate program called SENSAN (also free, and which can produce contours of the values of the objective function to show the effect of the interaction between parameters on the objective function) is desirable.

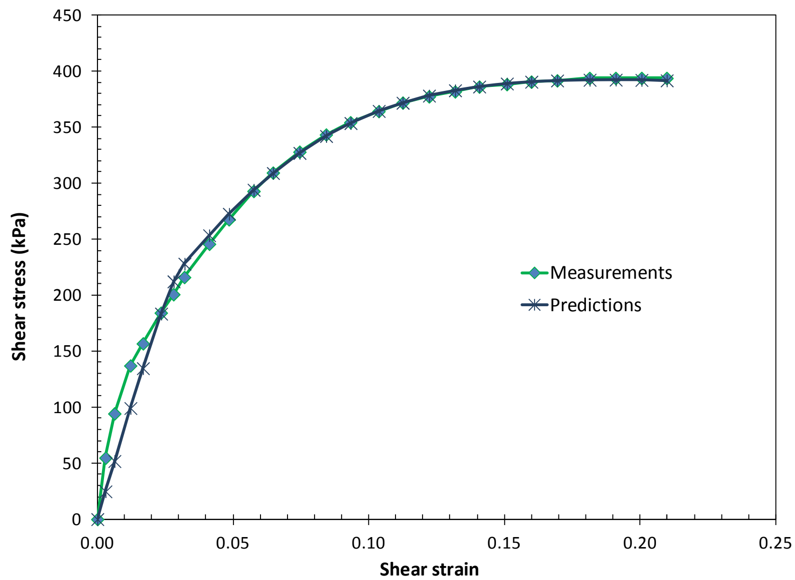

Fig. 5 – Comparison of predictions with measured data of shear stress for shearing a heavily over-consolidated final bagasse sample.

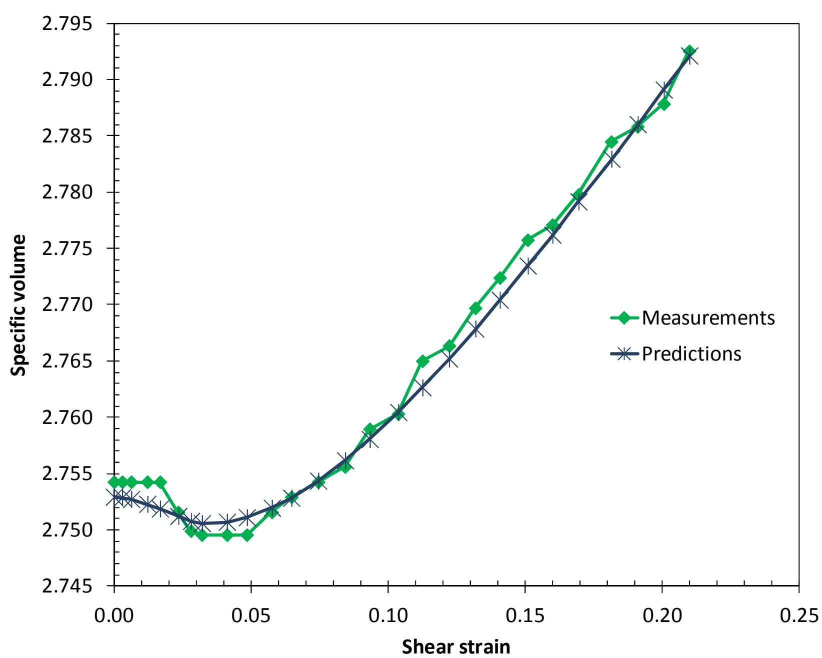

Fig. 6 – Comparison of predictions with measured data of specific volume for shearing heavily over-consolidated final bagasse sample.

Table 3 – Determined parameter correlation coefficient matrix

	M	ν	ψ	β_1	β_2	f1	f2
M	1.0	0.9331	0.9265	-0.7341	0.9383	-0.9025	0.9324
ν	0.9331	1.0	0.9989	-0.8822	0.9984	-0.9963	1.0
ψ	0.9265	0.9989	1.0	-0.8956	0.9991	-0.9961	0.9988
β_1	-0.7341	-0.8822	-0.8956	1.0	-0.8865	0.8999	-0.8836
β_2	0.9383	0.9984	0.9991	-0.8865	1.0	-0.9924	0.9984
f1	-0.9025	-0.9963	-0.9961	0.8999	-0.9924	1.0	-0.9963
f2	0.9324	1.0	0.9988	-0.8836	0.9984	-0.9963	1.0

Further work is required in order to:

1. Use a separate program called SENSAN to produce contours of the values of the objective function to show the effect of the interaction between parameters on the objective function.
2. Estimate the parameters more accurately by, for example, simultaneously matching compression, unloading, reloading, shearing of normally consolidated, lightly over-consolidated and highly over-consolidated results all in one analysis.
3. The additional parameters f1 and f2 may not be required. A further study should be carried out using PEST to confirm this.
4. There is a need to examine the heavily over-consolidated case with a FEM software package to confirm that the model behaves well under higher shear strain (ie, after yield).

Conclusions

Improved understanding of bagasse mechanical behaviour and improved modelling capability is required to achieve further gains in milling in a logical, structured manner. The latest mechanical model developments have been presented in this work. A critical state material model has been further developed in order to simulate the shearing behaviour of heavily over-consolidated final bagasse. A parameter estimation software package called PEST has been used to conclude that the existing model does have the ability to simulate the shear stress and specific volume of heavily over-consolidated final bagasse during shearing. This is an important conclusion to achieve for the last of five important loading conditions that are applicable to milling. Further work is required to improve the estimation of the values of the parameters.

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