Pre-treatment of Biomass By Rolling - A Combined Experimental and Numerical Analysis

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ABSTRACT: Pre-treatment of bulk straw material by rolling is studied as a possible method to prepare for subsequent biogas production. A combined experimental and theoretical study is presented. A pilot rolling mill with a double screw feeder is designed and constructed for crushing of bulk straw. Experiments show that the roll speed and the roll reduction should be chosen within a specific range depending on the injection screw speed to avoid blocking or insufficient compaction. A mechanical testing procedure of the bulk straw material including closed die compaction testing as well as simple upsetting of pre-compacted billets of straw is carried out based on which a mathematical model for the yield surface is determined fitting to a geological cap model for porous material similar to the Drucker-Prager spherical cap model. An experimental test campaign is carried out to determine the feasible process window for pre-treatment of wheat straw by roll pressing varying the feed, the roll gap, the roll speed and the moisture content of the bulk straw.

Keywords: Pre-treatment of biomass, roll pressing of straw, process window

1 INTRODUCTION

In the production of biogas from straw and manure it is considered important to pre-treat the straw in order to open the outer shell of the straw to allow an efficient reaction between microorganisms and the interior straw material mainly consisting of cellulose and hemi-cellulose. A number of different methods to pre-process biomass exist, including chemical as well as mechanical processing. Alternatively the two processes can be combined or biological microorganisms can be used.

The most common mechanical processes are milling and cutting. As an alternative the present paper studies pre-treatment by rolling. The mechanical process of rolling is not novel, it has existed for more than a century, and is tonnage wise the most important metal processing method applied to reduce plate thicknesses. Additionally rolling has been used for agglomerating bulks and powders into larger particles. Roll pressing used for bulks and powder agglomeration has been applied in the pharmaceutical industry for tabletting, easier and dust free handling, and in biomass briquetting of straw and wood. Roll pressing is also widely used within the mineral industry for breaking down minerals into smaller particles on High Pressure Grinding Rolls. Other agglomeration applications of roll presses include salts, sugar, food, kernels, clay, chemicals and charcoal [1].

Each industry and application has different ways of designing and controlling the roll press, the feeding and the control. Based on the application, roll presses used for breaking down materials are distinguished from those used for agglomeration.

1.1 Industrial biomass machines for briquetting and agglomeration

Roll presses used for briquetting or agglomerating and pressing biomass typically consist of a feeding mechanism and compacting rollers. The feeding can be either passive using gravity, or active using screws for continuous feeding. The performance of the feeding and rolling mechanism depends on the mechanical material properties, which must be considered when choosing and designing the mechanisms [2].

Gravity feed systems rely on flood-loaded chutes to feed roll presses. They are limited in force and require a large roll diameter, and they are most suitable for easy flowing and permeable solids [1]. The primary advantages are low energy consumption, use of wide rolls, and the ability to handle lumpy solids.

In order to obtain higher feed pressures and more consistent flow through the press, screws can be used for feeding. As screws are capable of reaching considerably higher pressures than gravitational feeding, a smaller roll diameter is needed, but higher feed pressure makes the process more susceptible to material changes and pressure build-ups [3], which increases the complexity of control. The screw is superior to the gravitational feed when requiring a uniform quality of for example briquettes or agglomerated material, as it offers more flexibility and possibilities in controlling the feeding. The screw however feeds in a circle, whereas the cross section of the rolling inlet has a rectangular interface, leading to a non-uniform processing of the material, which can be accommodated for by multiple parallel feeding screws [3]. When using a single screw, two common ways of designing the system, is by feeding a chute, in which the screw is placed, or placing the screw at the outlet of the chute. In order to ensure more homogeneous material feed, two screws can be used, although it increases the complexity of control.

1.2 Mineral comminution industry

In the mineral industry, machines are applied for comminution by breaking material into smaller pieces. Machines designed for the mineral crushing industry are intended for operating conditions requiring high pressures exerted onto materials of high hardness resulting in extensive wear. These machines are applied for crushing cement, clinker and ore minerals as a pre-treatment prior to ball milling. The roll is used for creating inter-particle breakage. Energy consumption in subsequent ball milling is thereby greatly reduced [4].
Commercial machines from FL Smidth, Köppern, Outec, KHD Humboldt Wedag and other manufacturers are all based on the same basic principles. The feeding is in commonly gravitational and controlled by feed gates, but can also be screw fed.

1.3 Rolling of porous material

Johanson [6] was among the first to propose a theoretical analysis of rolling of granular solids. The analysis adopts the flow criterion by Jennike and Shield [7] for granular materials, which is based on intergranular Coulomb friction in an isotropic, compressible and cohesive material obeying the effective yield function. Johanson [6] describes the rolling of granular material by defining an "angle of nip" $\alpha_{nip}$ such that for any angular position $\theta \geq \alpha_{nip}$, the rolls move faster than the material, so that slip occurs along the roll surface; for any $\theta \leq \alpha_{nip}$, no relative motion occurs between the granular solid and the rolls. When the nip angle $\alpha_{nip}$ and the bulk density at the position $\theta = \alpha_{nip}$ are known, the maximum density and pressure extended on the material at $\theta = 0$ can be calculated, provided the pressure-density relation is known. This can be determined by close die compaction tests.

![Figure 1: Rolling model by Johanson [6]](image1)

In their comparison of various modelling methods for analysis of powder compaction in rolling Dec et al. [8] describes the slab method analysis developed by Kuhn and Downey [9]. They find good agreement between calculated and measured pressure distribution in the roll bite when rolling lignite.

Cunningham et al. [8,10] have established a 2D FE model for analysis of powder compaction in rolling using ABAQUS finite element code. Their material model for microcrystalline cellulose powder is based on Drucker-Prager’s spherical cap model and a series of tests using diometric compression, simple upsetting and closed die compression. Their rolling analysis identifies two slip zones namely one at the entry of the roll gap, another at the exit. In between these two zones a major zone of sticking friction is located. This is an agreement with analysis on skinpass rolling of steel by Kijima and Bay [11], where high friction prevails as in the case investigated by Cunningham. Their results on calculated pressure and friction distribution are in good agreement with experimental measurements by themselves as well as others [12]. Cunningham et al. [10] calculates the increase of relative density with increasing reduction and feed pressure. Maximum density appears at the centre

line where $\theta=0$. Contact with the rolls exceeds beyond this point due to expansion of the bulk powder caused by stress relaxation in the relieve zone.

Guigon and Simon [13] have designed a laboratory roll press design with screw feeder and studied the influence of a forced feed system on compaction when rolling monohydrate lactose with 0.5% magnesium stearate. Fixing the screw feeder speed at seven different levels from 10.4 rpm to 45 rpm experiments were carried out with varying roller speed to the upper and lower limits allowing compaction. The lower limit of roller speed appeared, when over-compaction occurred, whereas the upper limit was set by no throughput. Their results indicate that the throughput is only determined by the screw feeder, no matter the roller speed.

1.4 Objective of present work

The present paper describes a custom built, pilot rolling mill intended for crushing of straw as a pre-treatment of biomass. Mechanical properties of the bulk straw material data are obtained by experimental testing of pre-compacted straw and by closed die compaction. An experimental test campaign carried out on the rolling mill establishes the appropriate process window, within which the rolling is stable and efficient.

2 DESIGN OF ROLLING EQUIPMENT

Figure 2 shows the custom built, pilot rolling mill situated at TK Energy, one of the industrial partners in the project. Figure 3 shows a schematic of the equipment. It is a 2-high mill with roll diameter $D_{roll} = 695$ mm and roll width $w = 95$ mm. It is fed by two horizontal screws, an Ø300 mm dosing screw located above and before the injection screw, which is Ø180×500 mm on its cylindrical part but with a conical end, which fits into a conical housing of length 400 mm with end opening Ø95 mm. The end of the conical housing is mounted close to the roll gap, which is variable in size (2 ≤ $h_1$ ≤ 12 mm). The speed of rotation of the dosing screw can be varied within the range $2 \leq n_{d,roll} \leq 30$ rpm whereas the injection screw speed can be varied in the range $15 \leq n_{inj} \leq 150$ rpm. The roll speed is variable in the range $3.5 \leq n_{roll} \leq 30$ rpm.

The dosing screw controls the feed rate, whereas the injection screw compresses the material and controls the feed pressure.

![Figure 2: Custom built rolling mill for crushing of straw](image2)
A mathematical model of the mechanical properties of bulk straw is required in order to model the rolling pretreatment process. Since this is chosen to be performed in the program LS-DYNA a material model available in this code has been selected. As such the geologic cap model named MAT_025 in LS-DYNA [14] has been chosen as one of the most flexible models able to model isotropic, porous materials, which means that anisotropy of the bulk straw is neglected for reasons of simplicity. The yield surface according to the model is plotted in the \( I_1 - \sqrt{J_2} \) space in Figure 4 where:

\[
I_1 = \sigma_{11} + \sigma_{22} + \sigma_{33} = 3p
\]

is the first invariant of the stress tensor, \( p \) is the hydrostatic pressure and:

\[
\sqrt{J_2} = \frac{1}{\sqrt{2}} s_{ij} s_{ij}
\]

where \( s_{ij} \) is the deviatoric stress tensor. It should be noted that all normal stresses \( \sigma_{ij} \) are defined as positive in compression. The failure envelope is given by:

\[
F_e = \alpha - \gamma \exp(-\beta \times I_1) + \theta \times I_1
\]

The cap surface is given by:

\[
F_c = \frac{1}{R} \left[ X(\kappa) - U(\kappa) \right]^2 + \left[ I_1 - U(\kappa) \right]^2
\]

\( X(\kappa) \) is the intersection between the cap \( f_2 \) surface and the \( I_1 \) axis:

\[
L(\kappa) = \begin{cases} 
\kappa & \text{if } \kappa > 0 \\
0 & \text{if } \kappa \leq 0
\end{cases}
\]

The volumetric plastic strain:

\[
e_{V}^p = \ln \frac{\rho_i}{\rho_0}
\]

where \( \rho_0 \) and \( \rho \) are the initial and current straw densities, is given by the following hardening law:

\[
e_{V}^p = W \left[ 1 - \exp\left[-D(X(\kappa) - X_0)\right]\right]
\]

The tension cut-off surface \( f_3 \) is described by:
where $T$ is the maximum hydrostatic tension the material can sustain.

3.2 Testing of mechanical properties

Testing of the mechanical properties of bulk straw were performed by Closed Die Compaction (CDC) tests as well as simple upsetting (SI) between plane, overhanging tool plates of pre-compacted straw billets at different densities made by pre-compaction in closed die, see Figure 5. The test billets were all prepared by pre-compacting the material to one of the following five densities: $\rho = 800; 900; 1000; 1100; 1200$ kg/m$^3$ in the closed die. The closed die was a steel tube of inner diameter $\varnothing 51$ mm, and the billets were made by pouring a certain amount of straw at a time into the tube, compacting this to a relative low density (<200 kg/ m$^3$) then pouring additional material in, until a final height of app. 70 mm with required density could be achieved.

![Figure 5: Schematic of a) Simple upsetting test, b) CDC test.](image)

The radial stress in the simple upsetting test is zero. As regards the CDC test the radial stress can be calculated by multiplying the axial stress with a factor $\beta$: $\sigma_r = \beta \sigma_z$ where $0.3 \leq \beta \leq 0.7$ [15]. It is then possible to express $I_1$ as well as $J_2$ for the two tests as indicated in Table I.

### Table I: Radial pressure, $I_1$ and $J_2$ for simple upsetting and closed die compression.

<table>
<thead>
<tr>
<th></th>
<th>Freeform upsetting</th>
<th>Closed die compaction</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma_r$</td>
<td>0</td>
<td>$\sigma_r = \beta \sigma_z$</td>
</tr>
<tr>
<td>$I_1$</td>
<td>$\sigma_z$</td>
<td>$(1+2\beta) \sigma_z$</td>
</tr>
<tr>
<td>$\sqrt{J_2}$</td>
<td>$\frac{p_z}{\sqrt{3}}$</td>
<td>$\frac{1-\beta}{\sqrt{3}} \sigma_z$</td>
</tr>
</tbody>
</table>

The initial density of the bulk straw was approximately $\rho_0 = 400$ kg/m$^3$ and the first significant load measurement was obtained after a compaction to 800 kg/m$^3$. This corresponds to a pre-compaction: $\varepsilon_0^p = \ln \frac{800}{400} = 0.69$.

The stress ratio $\beta = 0.5$ was assumed and the constants $\alpha$, $\beta^*$, $\gamma$, $X_0$ in the material model were all assumed equal to zero, which corresponds to no material strength in hydrostatic tension. Based on these assumptions the resulting material parameters in the LS-DYNA material model were calculated as shown in Table II.

### Table II: Parameters in material model

<table>
<thead>
<tr>
<th>$\alpha$</th>
<th>$\beta^*$</th>
<th>$\gamma$</th>
<th>$\theta$</th>
<th>$W$</th>
<th>$D$</th>
<th>$R$</th>
<th>$X_0$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0.58</td>
<td>1.06</td>
<td>0.04</td>
<td>2.58</td>
<td>0</td>
</tr>
</tbody>
</table>

Figure 6 shows the density versus $I_1$, whereas Figure 7 shows the yield surface as a function of density.

![Figure 6: Density versus the first invariant of the stress tensor.](image)

Figure 7: Experimentally determined yield surface

4 EXPERIMENTAL INVESTIGATION

4.1 Control of mass flow

A number of rolling experiments with chopped wheat straw were performed. During the individual experiments, variables such as dosage rate, injection...
screw speed, roller speed, moisture content in raw material and addition of water between dosage and feeding screw have been varied.

As seen in Figure 3 the dosing screw is located above the injection screw and initially with a horizontal overlap of approximately 400 mm. The purpose is that the straw should fall from last part of the dosing screw into the injection screw. The capacity of the injection screw must exceed the mass flow of the dosing screw as otherwise the material will accumulate between the two screws. This means that increasing dosage rate requires increasing injection screw speed to prevent material from accumulating in the funnel.

The rotational speed of the different parts (dosage, feed and roller) is regulated by frequency converters. It was found that even at low speeds on the rollers it was necessary to apply a high speed of the injection screw to transport enough material and build up an appropriate pressure in front of the rollers so that the bulk of straw was sufficiently compacted for subsequent crushing by the rolling process instead of just being transported through the rollers without any crushing. In practice, it was found appropriate to run with a velocity of the injection screw corresponding to an electrical frequency between 90 and 150 Hz. Unfortunately, the motors are power-limited in the frequency range 50 - 150 Hz. This means that a higher feed rate provides a lower available torque. As an example a reduction of the injection speed was found appropriate to run with a velocity of the injection screw corresponding to an electrical frequency between 90 and 150 Hz. This situation is named clogging in the following.

If material flow is increased a higher pressure will be built up in front of the rollers. As this pressure rises, the injection screw requires a larger torque. If the injection screw is able to deliver this torque, the operating conditions will remain stable. If the torque limit of the motor, however, is exceeded, the frequency converter will lower the speed to protect it from overload. If dosing is not stopped in time, the high pressure in front of the rollers will stop rotation of the injection screw and / or the rollers. This situation is named clogging in the following.

If friction between straw and rolls is small, it is usually the injection screw that stops, when too much straw is dosed. This is due to the pressure build up in front of the roll gap to an extent where the torque limit of the injection screw is exceeded. If friction is larger, the rollers will stop first due to the roller torque limit. Subsequently the injection screw will stop as pressure builds up in front of the rollers. Both situations are referred to as clogging.

4.2 Determination of process window
The experimental plan was to determine the window in which the rolling process could operate without clogging varying the roll gap, the mass flow and the speed of rotation of the rollers, the latter expressed as the peripheral speed of the rollers. Two roll gaps were investigated, namely 6 and 8 mm corresponding to a reduction of 94% and 92% respectively. Larger roll gap resulted in little if any crushing and smaller roll gap caused clogging.

Preliminary experiments on rolling of moist straw showed it possible to run with larger mass flow than with dry straw. It was decided to investigate this further by filling the dosage system with dry straw and then in selected experiments spray the straw with a water mist between the dosing screw and the injection screw, see Figure 3. In these experiments, three nozzles were applied and a water supply of approximately 1 kg/min was provided. Referring to Figure 8 and Figure 9 the limits for dosing of dry straw and wet straw were found in this way. The mass flow indicated in the figures is based on dry straw water from the dosing system containing app. 15% water. The figures shows the successful experiments for the dry as well as the wet straw with green markers whereas clogging is shown with red markers. The added water corresponds to between 12 and 26% for 6 mm gap and 9 to 13% for the 8 mm gap implying a total water content of 24-35% for 6 mm gap and 22-25 for 8 mm gap. The percentages are for maximum mass flow achieved at the different roller speeds.

Figure 8 and Figure 9 show that higher mass flow is possible with wet than dry straw and that increased roller speed increases the maximum mass flow in case of wet straw, whereas the influence of roller speed on mass flow in case of dry straw seems rather insignificant.

![Figure 8: Mass flow vs. roller speed for experiments with 6 mm roller gap.](image1)

![Figure 9: Mass flow vs. roller speed for experiments with 8 mm roller gap.](image2)

For the case of 8 mm roll gap a special experiment was carried out rolling first wet straw with high mass flow / density by water spraying the dosed material. After running through a stable period, water spraying was stopped to investigate how the process developed. It turned out that clogging occurred stopping the rolls and injection screw when dry straw entered the rollers.
When comparing the mass flow with the roller speed and the area of the roll gap the characteristic maximum density of the material in the roll gap can be determined, see Figure 10 and Figure 11. It is noticed that the density may rise up to 1200-1400 kg/m³ and that higher densities are obtained with 8 mm roll gap than 6 mm in the high end range of roller speed (145-190 mm/s). Aiming at larger densities by increasing the dosage further is not possible due to clogging.

Maximum theoretical density of wheat straw can be calculated from the weighted densities of the relative mass percentages of the chemical components. For wheat straw with 15% water content the maximum theoretical density becomes approximately 1550 kg/m³. In this calculation the effect of compacting mixed molecules is not taken into account. Nor is the compressibility of solids taken into account [16].

In Figure 8 representing the high reduction with 6 mm roll gap the limiting mass flow before clogging in case of wet straw is seen to be almost proportional with the rolling speed. The added mass of the water spray is not included in the mass flow. According to Figure 10 the maximum density range is 1200-1400 kg/m³ (without the contribution from the added mass from the water spay). If rolling is performed close to this limit, the straw output is crumbled. If the mass flow and the density are reduced the straw becomes more coherent and the output is plate formed. This occurs at densities between 750 and 1000 kg/m³. At even lower densities the straw becomes looser again. The reason that the straw crumbles at the highest densities is that it breaks down into smaller pieces by fracture and crushing of the straw stalks, which results in less coherence. Running with large mass flow results in large pre-compaction of the bulk straw before rolling. As long as clogging is avoided this will lead to improved crushing of the slab during rolling and thereby finer particles and crumbling, which is the objective of the roll pressing operation. The issue is therefore to run with as high density as possible but still ensuring that clogging does not occur.

Reduced mass flow and density diminishes the decomposition and the cohesion of the output increases. This may possibly be due to moist lignin that has been heated above the glass transitions temperature, Tg (similar to wood pellets). $T_g_{lignin} = 53 – 63 \, ^\circ\text{C}$ [17], which makes the straws stick together in form of a plate. The plate, however, has only little strength. Lower mass flow / density causes decreasing cohesion as the straw does not heat up as much and the pressure is less (compare pellets and lignin that bind). After the straw plate has left the roll gap, it expands to a thickness of about 5 times the height of the roll gap.

![Figure 10: Density vs. roller speed with 6 mm roller gap.](image)

![Figure 11: Density vs. roller speed with 8 mm roller gap.](image)

![Figure 12: Density vs. stress for closed die compaction test.](image)

![Figure 13: Density vs. Stress for simple upsetting test.](image)
Comparing the curves in Figure 12 for wet and dry straw it is seen that the stress-density curves are almost coinciding. This is probably due to the fact that the relative location between the individual straws is not changed during CDC testing. It is anticipated that this fact implies mechanical interlocking and limited effect of interior lubrication between straws. According to Figure 12 the density for dry straw reaches a maximum of approximately 1600 kg/m$^3$. This is slightly above the maximum theoretical density. Furthermore, the two curves intersect each other. Both of these observations may be explained by uncertainties in the measurements and poor calibration of the zero position for the measurements. Setting the curve for dry straw lateral with 3% removes the intersection and the “too high density” calculation.

The density curve for wet straw shows the density of 15% wet straw without taking into account the influence of the additional 11% of water for wetting.

Comparing the curves in Figure 13 a large difference is noticed between wet and dry straw. This is probably due to the less confined deformation in simple upsetting, which allows relocation of individual straws during deformation. In this case the lubricating effect of the additional water is significant. In good correspondence with this observation it is noticed from Figure 8 and Figure 9 that the maximum possible mass flow increases with water lubrication.

During handling of the straw for both CDC tests and simple upsetting tests significant differences between wet and dry straw were observed. Figure 14 shows the amount of straw compacted to a single billet, the individual billets before and after upsetting. All billets and the pile of loose straw have the same straw mass of 60 gram. The added water is 6 gram, which is not added to the total mass in the density calculations. The wet billets have clearly expanded significantly more than the dry billets. During simple upsetting large difference was furthermore observed as regards the collapse. In case of wet straw the collapse was continuously progressing with a significant diameter increase, whereas the collapse in case of dry straw was almost instantaneously like an explosion with hardly any diameter increase.

5 CONCLUSIONS

Pre-preparation of bulk straw for biogas production has been studied using roll pressing as a crushing operation. Wet straw is significantly easier to roll than dry straw. Rolling wet straw densities up to 1400 kg/m$^3$ can be achieved whereas the maximum density for dry straw was significantly lower with the available torque in the system.

In closed die compaction of straw a density close to the theoretical maximum of 1550 kg/m$^3$ can be achieved at a pressure of 100-150 MPa if the billet is low (25 mm). Higher billets will probably not be possible to compact to such densities due to die friction, unless compaction is performed stepwise.

Whereas the load displacement curves for wet and dry straw in closed die compaction are very similar, this is not the case in simple upsetting, where wet straw has much lower stress response. Collapse furthermore occurs at much lower stresses and density.

6 REFERENCES

7 ACKNOWLEDGEMENTS

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