Assessment of a new laboratory die pelleting rig attached to a texture analyzer to predict process-ability of wood pellets. Energy consumption and pellet strength

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ABSTRACT

This article presents a laboratory die pelleting rig that was made to compare the pellet-ability of wood raw materials at low cost. It was found that the normal stresses at incipient flow and the yield stresses were correlated with the energy consumed by an industrial pellet press. It was not possible to calculate the stresses producing ductile failure in pellets from the diametrical compression tests.

INTRODUCTION

The use of biomass as energy supply has increased rapidly in the last years due to the increased prices of alternative fuels. Densification of biomass to pellets gives several advantages like easier combustion, transportation and standardisation. Wood pellets can be used as a substitute for oil based heating systems and can also be co-combusted in coal combustion plants. Therefore pellets are likely to have an important role in the increased biomass demands for energy.

The market for wood pellets is increasing rapidly. This has increased the interest for several new virgin - and residue feedstocks from forestry and agriculture. It is expected that using new raw materials which have different rheological characteristics, will change the process performance (e.g. energy consumption[1] and throughputs).

When considering new feedstocks for pelleting, different properties should be investigated, like the chemical and thermochemical properties.

Pelleting can be regarded as a kneading, compressing, heating and forming process where rheological transformations in the material take place[2]. For example, heated ground wood is able to deform plastically when stresses are applied towards a die hole as it softens in the range of the glass transition[3]. The pelleting process can be classified as a high pressure agglomeration process. Typically these products feature high strengths immediately after discharge, low product porosity and small voids[4, 5].

Rheological properties like compressibility (i.e. compacting stress – density relationships), compactibility (i.e. the ability of a material to form strong compacts) and resistance to flow, influence pelleting performance and product quality[2].

Rheological behaviour of compressible powders is more complex to deal with than that of incompressible solids. Therefore more sophisticated production planning and process controls are required. That includes knowledge about how the raw materials responds to the applied stresses during compaction and pellet release, keeping in mind crack prevention[2].

Quick laboratory tests at low costs, to characterize or to rank the pellet-ability of different mixtures of raw materials is of great interest, since manufacturing pellets in an industrial scale requires large volumes of raw materials which give high costs. Therefore a new laboratory die pelleting rig has been developed. The equipment is able to perform pelleting experiments under controlled settings like compressing stress, speed and temperature.

The main goal of this research is to find whether the information given by the die pelleting rig used to produce single pellets, can be used to estimate the pellet-ability of a sample. For this reason, raw materials with different characteristics are analyzed in both an industrial process and in the new laboratory die pelleting rig. It was used ground Scots pine (*Pinus sylvestris*) wood dried at two different temperatures and stored for two different periods of time.

MATERIALS AND METHODS

Preparation of the wood samples for pelleting

The effects of two different drying methods using low (LT) and high (HT) temperature were investigated on both newly felled material (Fresh, stored for 3 months) and material stored in a chip pile for 11 months (Stored). The chip pile was 6 m high and had a diameter of 10 m. All materials were harvested from identical neighbouring stands with a site index of F 14^6. This resulted in four different assortments:

(i) Newly felled material dried at low temperature (75°C), LT Fresh.
(ii) Newly felled material dried at high temperature (450°C), HT Fresh.
(iii) Material stored for 11 months dried at low temperature (75°C), LT Stored.
(iv) Material stored for 11 months dried at high temperature (450°C), HT Stored.

For the industry scale experiments, all materials were dried to a moisture content between 7 and 13 % w.b., which is suitable for the Sprout Matador M30 industrial pellet press and the specific die ring (also called matrix) that was used in the plant. The raw materials used for the experiments in the laboratory die pelleting rig, were further conditioned in a climatic cabinet for about 5 days with a temperature of 20 °C and 50 % relative humidity, to make a smaller moisture contents range. After the conditioning process, a moisture content between 9-10% w.b. was achieved for all assortments.

To produce pellets in the laboratory die pelleting rig with a similar particle size distribution compared to the original pile of material, the samples were separated using sampler dividers. A 50 kg bag taken from the process stream was divided several times until obtaining approximately 7 ml of sample volume, which is the volume of the compressing channel (ref. Fig. 1) in the laboratory die pelleting rig.

Design Features. Industrial pellet press and die pelleting rig

The industrial pellets were produced in a Sprout Matador M30 pellet press with a nominal production capacity of 3.5 tonne h^{-1} of wood pellets. The pellet press had a common construction; a rotating die ring (or matrix) and pressing rollers. A die ring with

die holes of 8 mm in diameter and 60 mm pressure length was used (see Fig. 1). The pellet press, is an industrial equipment located at Møre Biovarme AS's which is a pellet factory in Sykkylven, western Norway (see Fig. 2). The material was fed into the production line immediately before the hammer mill, and was stored in a bin prior to the pelleting process.

The laboratory die pelleting rig used in this study is the same as the one used by Salas-Bringas et al.[7], except for the die (Fig 1). The laboratory die pelleting rig, have a barrel with a channel of 9.5 mm along the centre. The cylindrical channel has the same 9.5 mm diameter as the entry diameter to the die hole of the industry pellet press. Both die holes (industrial pellet press and laboratory die pelleting rig) have 8 mm in diameter (see Fig. 1), but the length of the die hole in the laboratory die pelleting rig was 48.7 mm shorter because it was not possible to produce flow using the 60 mm length with the maximum pressure of 72 MPa that can be achieved using a 9.4 mm diameter rod and 5 kN force. 5 kN is the maximum force given by the Lloyd LR 5K Plus texture analyzer which was used in this study.

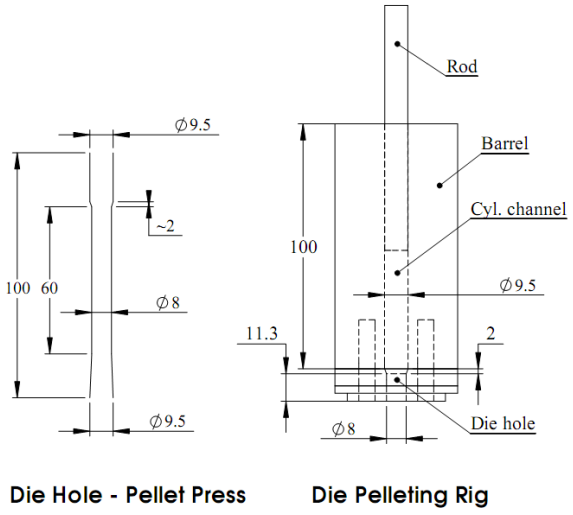

Figure 1. Die hole used in the Sprout matador M30 industrial pellet press (left), and laboratory die pelleting rig (right). Dimensions are in millimetres.

Figure 2. Industrial pelleting line used for the experiments.
Source: Møre Biovarme AS.

Grinding effect of the pellet press

To quantify the grinding given by the pellet press, pellets were added into water to be disintegrated. After that, the disintegrated pellets were dried to the moisture content recommended by the standard method for sieving[8]. The disintegrated pellets and raw materials taken from the pellet press inlet, were sieved to determine whether differences in particle size distribution existed or not. Standard methods were followed[8]. The procedure was repeated three times. The results are shown in Fig. 3.

Determination of energy consumption in the industrial pellet press

The experiments were performed using a pre-warmed die ring. For each test, the pelleting process was run for approximately four minutes until steady state was achieved. The duration of each test was about 20 minutes, corresponding to approximately 750 kg of pellets. The average electrical power recorded from the pellet press and the throughputs during steady state production were used to calculate the energy consumption (power/throughput). For each of the four materials, three replicates were made, resulting in 12 separate pelleting tests. The volumetric flow rate was kept constant through a screw conveyor during all tests.

The raw materials used in the laboratory die pelleting rig were collected from the product stream at the entry of the industrial pellet press during steady conditions. The samples were cooled at ambient room temperature and stored in a freezer in sealed plastic bags.

For the analysis of pellet strength, pellets were collected from the product stream at the pellet press outlet during steady state production. Only the pellets made from the raw materials having moisture contents in the range 9-10% w.b. were used for the strength analysis.

Laboratory die pelleting rig. Determination of the resistance to flow and yield stress

The resistance of the wood samples to flow through the laboratory die pelleting rig was performed by fully loading the compressing channel with wood (7 ml) and then pre-compressing the sample until 1.4 MPa was reached. A second full load was then performed to have sufficient material to fully cover the channel of the die hole and to produce flow for enough time. After the second load, the test started using a compressing speed of 2 mm s^{-1}. When the rod was almost completely inside the cylindrical channel, at 1.5 mm above the barrel, the test was stopped. This procedure was used in all stress-relaxation tests to quantify the viscous (fluid) and elastic (solid) nature of the wood samples. Temperature was set to 110 °C which is above the glass transition temperature of the lignin binder[3, 9] and below its melting point[10].

Changes in pressure during a relaxation time of 1.5 minutes were continuously recorded. The pressure at the end of the recording time was used as ΔP_{min} (ref. Fig. 5). Three tests were performed for each material to obtain an average ΔP_{min}.

The yield stress (τ_0) of a material in this system can be determined using the stress relaxation test. The yield stress is calculated from a force balance equation as follows[11, 12]:

$$\tau_0 = \frac{\Delta P_{min} R}{2L} \quad (1)$$

where R is the die radius, 4 mm, and L the die length, 11.3 mm (see Fig. 1).

The source of error for this type of tests is that the normal stress at the side walls of the channel reduces from top to bottom[5, 7] due to friction. It is possible to obtain small differences in normal stress from the rod to what is actually experienced by the wood material at the entry of the die hole (at 11.3 mm, from bottom to top). For this reason, in these tests at the moment of the relaxation time, the rod was set to stop at about 1.5 mm above the die entry.

Prediction of process-ability

The evaluation of the laboratory die pelleting rig as a method to estimate the industrial pellet-ability of wood materials was done by a comparative plot of the results given by the normal stress at incipient flow, versus the energy consumed by the pellet press in the industrial trial. It was also performed a comparison between the yield stress and the energy consumed by the industrial pellet press. It is hypothesized that the rheological properties (x-axis, Fig 9 and Fig. 10) affect the energy consumption in the industrial pellet press (y-axis).

Pellet strength

The mechanical strength of the wood pellets was analyzed by measuring the maximum peak force registered during a diametrical compression, as similarly used and described by Salas-Bringas et al[7].

It was planned to measure the mechanical strength of the pellets from the laboratory die pelleting rig after the stress relaxation test. However, as observed from Fig. 6, the bottom side of the pellet was irregular and less dense than the opposite side. Additionally, it was not possible to cut this end properly and make a cylindrical

pellet without damaging the sample. This shaping problem made it difficult to separate the samples and analyse and to compare their mechanical strength with the pellets produced in the industry. Consequently, the strength of the 9.5 mm pellets produced with a blank die[7] in the same laboratory die pelleting rig, using the same four raw materials and temperatures[7], are shown in this article together with the strength from the 8 mm diameter pellets produced in the industrial pelleting line.

Data analysis

To determine significant differences between different groups, it was used one-way ANOVA and Tukey's test.

RESULTS AND DISCUSSIONS

Preparation of the wood samples for pelleting

An important challenge when using the laboratory die pelleting rig, is to achieve a representative raw material sample, since the quantities of wood used is small. For example, the 7 ml of raw material used for one flow test, should have a particle size distribution, moisture content, etc., that represents the pile of the raw material used in the industrial pelleting process.

Grinding effect of the pellet press

It was found higher amounts of the fraction smaller than 0.5 mm from the disintegrated pellets than from the raw material taken from the pellet press inlet ($p<0.05$). This result demonstrates a grinding effect in the pellet press. The other fractions remained with no significant differences ($p>0.05$).

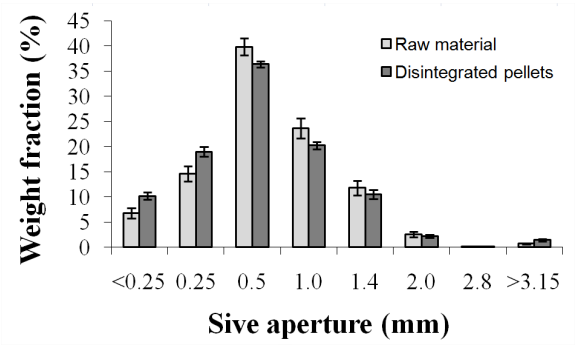

Figure 3. Particle size distribution of the raw materials and disintegrated pellets. Averages were calculated using all samples (LT Fresh, HT Fresh, LT Stored and HT Stored). The error bars represent ± standard error. Statistical differences ($p<0.05$) within a sieve aperture only occurred in the finer fractions (0.25 mm and <0.25 mm)

The grinding effect is probably a consequence of the shearing environment. In pellet presses the product in under stresses, strains and friction mostly in the gap rollers-die ring, in the nip area, as well as in the die hole[13]. In the Sprout Matador M30 pellet press used in the study, the gap between the rollers and the die ring was approximately 2 mm.

Determination of energy consumption in the industrial pellet press

The material expected to have the smallest amount of extractives required more energy (see Fig. 4). This might be due to less lubricant effect due to less extractives. The energy consumption was significantly higher when pelleting stored materials ($p<0.05$). However, drying methods did not produce significant differences ($p>0.05$).

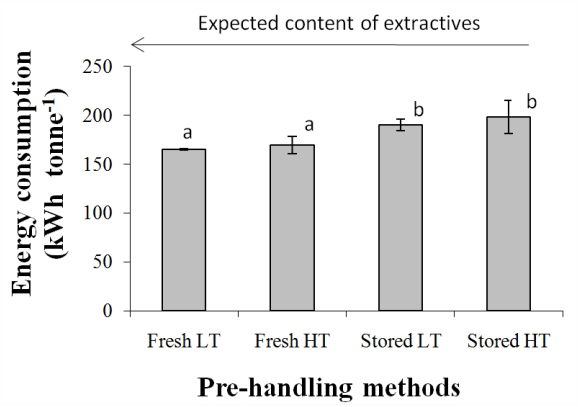

Figure 4. Average energy consumption obtained in the M30 Sprout matador pellet press for the four pre-handling conditions. The error bars represent ± standard error. Different letters indicate significant differences ($p<0.05$).

Laboratory die pelleting rig. Determination of the resistance to flow and yield stress

It was not possible to produce a continuous flow in the laboratory die pelleting rig during a long period due to the small quantity of sample used. Since the laboratory die pelleting rig had a limitation of 72 MPa, the material could not be pre-compressed more than two times. Compressibility information for the raw materials used in these experiments can be found in Salas-Bringas et al.[7]

Fig. 5 indicates the different regions and how the data was used. A first region of compression shows how the normal stress increases exponentially. A second region of plastic flow is initiated where the curve start to decrease the slope, the maximum normal stress was obtained in this region, where the incipient flow is produced. The curve then rapidly decays as the test is stopped to measure the minimum normal stress at the end of the relaxation part of the test.

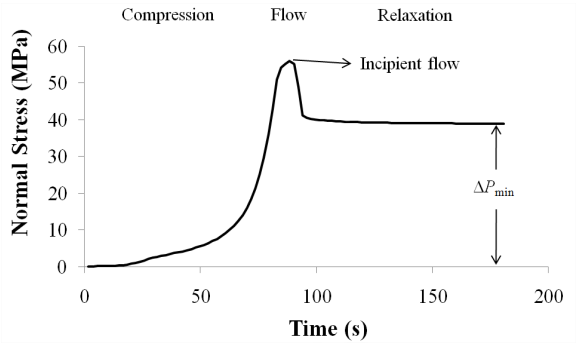

Figure 5. Example of a stress relaxation curve for one of the samples (HT Stored). The plot shows the viscoelastic behaviour of the wood materials.

Fig. 5 shows that the wood samples when compressed present a viscoelastic solid nature since the curve decay to an equilibrium stress higher than zero (shown by a $\Delta P_{min} > 0$). Consequently, these materials exhibit a solid behaviour at stresses below τ_0, and the presence of a viscous behaviour can be noticed at higher stresses ($> \tau_0$).

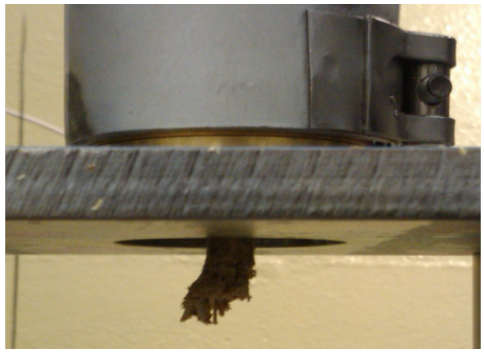

Figure 6. Flow of Pine Scots through the laboratory die pelleting rig.

No significant effects ($p>0.05$) on the stresses at incipient flow were present due to the different drying temperatures (ref. Fig. 7). However, significant higher ($p<0.05$) stresses at incipient flow were found for the stored material compared to the fresh material. This might be explained by the

viscous nature of the extractives. which evaporate during storage [14].

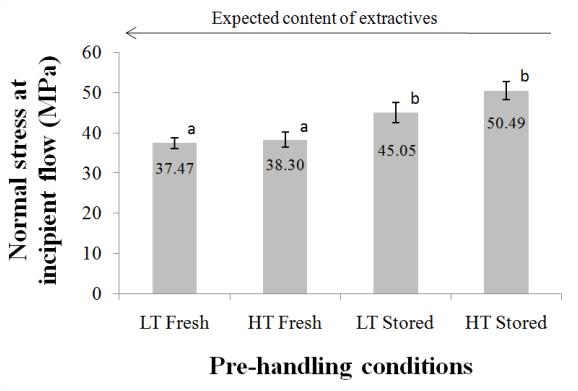

Figure 7. Average (n = 3) normal stresses at incipient flow (MPa) for the materials pre-handled by the four conditions. Different letters indicate significant differences ($p<0.05$). The error bars represents ± the standard error.

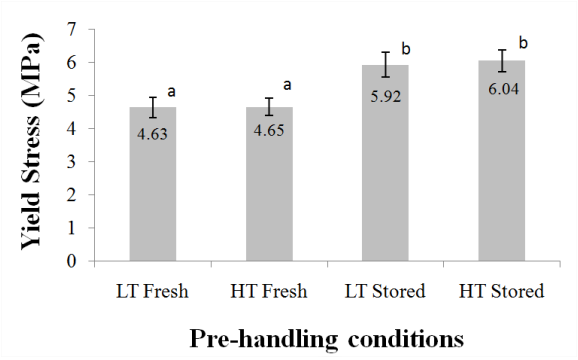

Figure 8. Average (n = 3) yield stresses (MPa) for the four pre-handling conditions. Different letters indicate significant differences ($p<0.05$). The error bars represents ± the standard error.

Significantly larger yield stresses were found for the stored raw material ($p>0.05$). This might be due to less extractives. However no differences were found between the different drying methods. This is in accordance with the results given by the normal stresses at incipient flow and by the energy consumption used by the industrial pellet press.

Prediction of process-ability

The data used in Fig. 9 and Fig. 10 are the raw data of Fig. 3, Fig. 7 and Fig. 8.

A significant positive correlation was found between normal stress at incipient flow and the energy consumption used in the industrial trial (Fig 9). It also was a significant positive correlation between yield stress and energy consumption used (Fig 10).

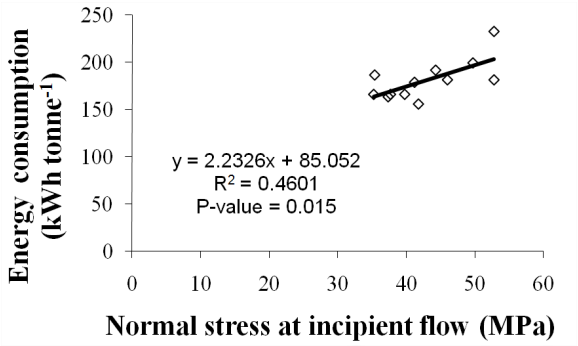

Figure 9. Correlations between energy consumption in the pellet press and the normal stresses at incipient flow in the laboratory die pelleting rig.

The above commented relationships indicate that it is possible to predict energy consumption in an industrial pellet press from measurements done with the laboratory die pelleting rig. The R^2 values were 46 and 61 % respectively (Fig. 9 and Fig. 10). Still new studies have to be done in order to validate the models. However, comparisons of process-ability among raw materials can be made by comparing the different resistances to flow, when no energy predictions are required.

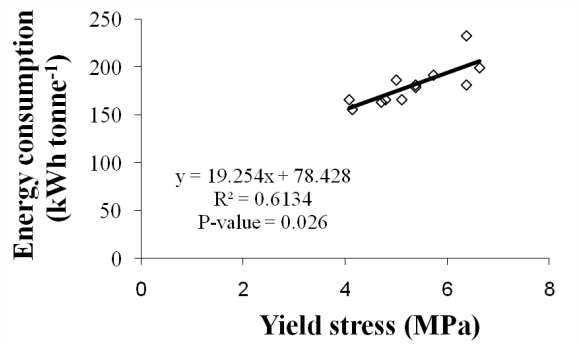

Figure 10. Correlations between energy consumption in the pellet press and yield stress determined in the laboratory die pelleting rig.

Pellet strength

It was not possible to compare strength values for the 8 mm (industrial pellet) and 9.5 mm (laboratory pellets with blank die) directly[7] since the industry pellet geometry was not possible to describe exactly, which gives errors into stress calculations. The 8 mm pellets produced in the industrial pelleting line did not have defined ends that could allow a reliable measurement of an area of stress. More research should be done to find methods to calculate pellet strength considering different diameters.

Since large plastic deformations (approximately 10% strain) occurred at the moment of ductile failure in all pellets, leaving different and random thresholds such as cracks. This implicates that the failure mechanisms (compressive stresses and tensile stresses) and stress distribution could not be well represented analytically. Additionally, the strength of these pellets is possibly anisotropic.

Pellet density affected the pellet strength, made in the laboratory die pelleting rig, significantly ($p<0.05$). Significant differences between the four raw materials were found. Detailed information about these differences can be found in Salas-Bringas et al[7]. Still, pellet density did not reduce the residual variance for the strength of the pellet made in the industrial line. The reason for this is the small range in density for this pellet and the large variance for maximum yield load for a specific density (Fig. 11).

Both types of pellets are plotted in Fig. 11. However, the plot does not consider the effect of diameter.

The pellets produced by the laboratory die pelleting rig had lower densities than the pellets produced in the industrial pelleting line. However, differences in densities cannot be directly associated to the compacting stresses without considering the changes in particle size distribution produced in the industrial pellet press. As a consequence, strength differences can be caused by different compacting stresses or by the changes in the compressibility given by the changes in particle size distributions.

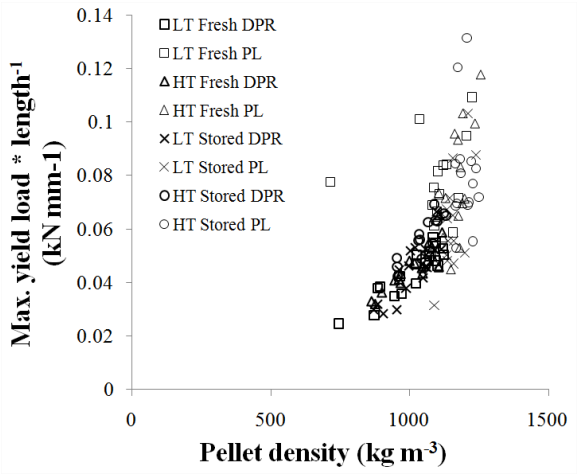

Figure 11. Physical strength of the pellets made in the laboratory die pelleting rig (DPR) and the pellets made in the pelleting line (PL).

CONCLUSIONS

Care should be taken when preparing small samples like the 7 ml samples used in the laboratory die pelleting rig, since it represents a much larger amount of material processed in the industry.

The grinding effect given by the pellet press should be considered when performing direct comparisons or predictions. However, this effect should not affect studies ranking the process-ability of raw materials.

Long storage time of the raw material produced higher normal stresses at incipient flow and higher yield stresses in the materials. Most probably this is important for the higher energy consumption when making pellets from stored wood. Drying temperatures did not change incipient flow and normal stress significantly.

Normal stresses at incipient flow, and yield stresses correlated with the energy consumed by the industrial pellet press.

Higher pellet strength was present at higher densifications.

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