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Effects of pelletization conditions on breaking strength and dimensional stability of Douglas fir pellet

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HIGHLIGHTS

- The compression behaviour of Douglas fir particles was investigated.
- Temperature, pressure and stress relaxation were significant to the pellet's mechanical properties.
- Walker, Jones, Kawakita and Ludde were the best compaction models for Douglas fir.
- The best pelletizing conditions for Douglas fir with a particle size of 1.19 mm was 100 °C, 126 MPa and 30 s relaxation time.

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ABSTRACT

The compression behavior of Douglas fir ground particles using a heated piston–cylinder unit was investigated. A complete randomized design (CRD) of experiment with three factors (die temperature, applied pressure and relaxation time), three levels and five replicates were studied. From the analysis of variance (ANOVA) with $\alpha = 0.05$, all of the three pelletization factors were significant parameters to the maximum breaking strength and the relaxed pellet density. The significant factors to the initial pellet density of pellets were the die temperature and the applied pressure. Three out of five compaction models of Walker, Jones, Kawakita and Ludde were well described to the compression behavior of Douglas fir ground particles with R^2 values between 0.90 and 0.99. The optimum processing condition to produce the best quality of Douglas fir pellets was 100 °C die temperature, 126 MPa applied pressure and 30 s relaxation time.

1. Introduction

Douglas fir (*Pseudotsuga menziesii,* L.) is one of the many abundant species of coniferous softwood in the western coast of North America. It is widely used for structural timber, lumber, and furniture; meanwhile, the wood processing generates substantial amounts of residual by-products such as sawdust and shavings. The recovered Douglas fir sawdust and shavings are good candidates for producing fuel pellets for energy production, in replacement of coal. Douglas fir ground particles with a mean particle size of 1–2 mm can be pelletized into Douglas fir pellets with a 6–8 mm diameter and 12–25 mm length [1,2]. It was found that the wood pellets longer than 13 mm decreased the average burning temperature of a pellet stove by 31% and the flue gas temperature by 25% [3]. Because of this, Douglas fir pellets with a shorter length are preferred for efficient combustion.

Douglas fir pellets are required to be handled and stored safely in order to minimize risks for health and safety. The biodegradation of the wood pellets diminishes the mechanical properties and will contribute to mass loss during storage and transportation [4]. Consequently, the major limitation of using Douglas fir pellets as fuel is low durability. Durability is defined as the weight percentage of the remaining unbroken wood pellets to the total sample size of the wood pellets after tumbling, according to the European standard EN 15210-1 [5]. The durability of wood pellets is well correlated with the hardness values measured from the material properties testers [6]. In essence, the durability of Douglas fir pellets is highly dependent on the compression behavior of the ground particles.

Extensive research has evaluated the pelletization mechanisms of Douglas fir ground particles with or without pre-treatments [7–9]. The compression behavior of biomass ground particles were studied in different models [8,10–13]. Jones [14], Heckel [15], Cooper and Eaton [16], Kawakita and Ludde [17] and Panelli and Filho [18] models were studied to determine the pressure–volume and the pressure–density relationship of barley, canola, oat and wheat

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straw. Mani et al. reported that the Heckel and Cooper–Eaton model are the most applicable compaction models to describe the compression mechanism of cellulosic agricultural materials [19]. The Kawakita–Ludde model was proposed to describe the compression behavior of soft and fluffy materials [17] and works best only for a limited species of agricultural biomass (barley, canola, oat and wheat). Adapa et al. [10] and Tabil and Sokhansanj [20] reported that the Cooper–Eaton, Heckel and Panelli–Filho models were best fitted with the compression data of alfalfa. Walker's model was used to describe the compression behavior of non-metallic powders [11,21,22]. There is limited research studying Walker's model on woody and agricultural biomass. Adapa et al. [10] attempted to use the Walker model to describe the compression behavior of fractionated alfalfa. However, a good fit was not obtained compared to other compaction models. Comoglu [22] reported that the two most commonly used compaction models; Heckel [15] and Kawakita and Ludde [17], failed to relate the densification behavior of wood to their physical and mechanical properties.

The objective of this research is to study the effect of pelletization conditions (die temperature, applied pressure and stress relaxation) on the pellet's mechanical strength and dimensional stability. A complete randomized design (CRD) of experiment with three factors, three levels, and five replicates is introduced. In addition, this research evaluates the fittings of different compaction models for Douglas fir pellets. The experimental results could be further applied to study the continuous pelletizing process with an automated control system.

2. Materials and methods

2.1. Materials

As-received Douglas fir (*Pseudotsuga menziesii* L.) with 55% (w.b.) moisture content were obtained from piles of wood chips at the Fibreco facilities in North Vancouver, B.C., Canada. The woodchips were ground into powder using a laboratory knife mill equipped with a 6 mm screen size. The particle size analysis was performed according to the ASABE S319.3 standard [23]. The mean particle size of the powder was 1.19 mm. The recovered powders from the knife mill were conditioned to 11.3% (w.b.) moisture content prior to pelletization.

2.2. Pelletization

A removable fixture and a single die pelletizing unit (MTI 50 K, Measurement Technology Inc., Atlanta, USA) was used to produce wood pellets (Fig. 1). The fixture composed of a top part and a bottom part. The top part with a 6.35 mm diameter iron rod connecting to the top flange was controlled by the crosshead of the MTI machine. The bottom part was installed with four bars at the corners to provide an accurate alignment between the rod and the die channel during vertical movement. The channel of the die is 70 mm long and 6.35 mm in diameter. The die was pre-heated by a heating tape connected to a controller. The heat supply mimics the heat generated by the friction during pelletization in the industrial pellet mill. It also ensures a uniform temperature gradient over the die. For each experimental trial, approximately 0.85 g of Douglas fir powder was fed into the die channel and compressed at 10 mm/min. The compression force and displacement data were recorded by the computer data logging system connecting to the pelletizing unit. The total energy required to produce a pellet is the total area under the force versus displacement curve. In order to study the effect of process conditions on pellet quality, a complete randomized design (CRD) of experiment with three factors, three levels, and five replicates is introduced (Table 1). Five pellets were made for each mechanical condition.

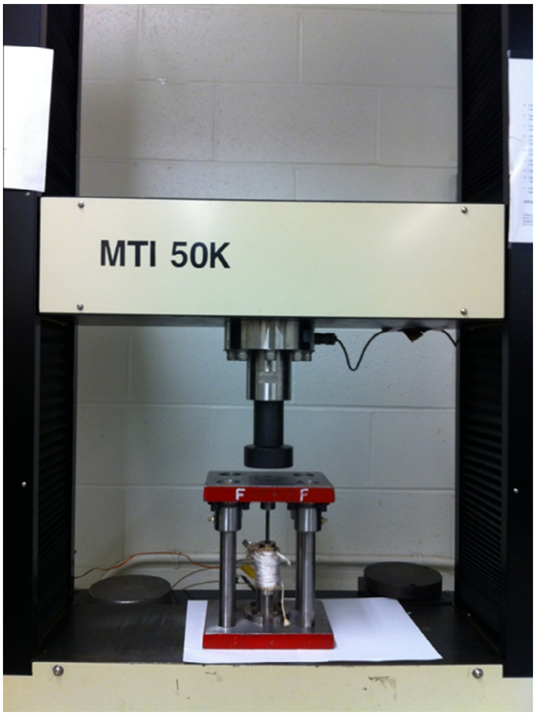

Fig. 1. Experimental setup with a MTI system and the die to produce pellets.

2.3. Stress relaxation and hardness test

The effect of the stress relaxation behavior of thermally treated Douglas fir pellets on its dimensional stability was investigated [8]. This was done by measuring the rate of decrease of residual stress in 30 s and the associated data were normalized, linearized and represented as a straight line:

$$\frac{\sigma_0 t}{\sigma_0 - \sigma(t)} = k_1 + k_2 t \tag{1}$$

where σ_0 is the initial stress, GPa, $\sigma(t)$ the stress after time t at relaxation, GPa, t is time, s and k_1 and k_2 are constants.

The viscoelastic slope, k_2, can be used to quantify the degree of plastic flow under compaction [24]. Materials with a high visco–elastic slope value, k_2, exhibit a greater degree of plastic flow under compression. This parameter was found to correlate well with forming strong pellets. For example, materials that displayed large viscoelastic slope constants formed strong tablets at low compaction temperatures [24]. The slope k_2 of the straight line must be greater than one, and from a rheological point of view, the slope can be considered as an index of how solid the compacted specimen is on a short time scale. Any large value of greater than one is an indication of the existence of stresses that will

Table 1
Design of experiment of pelletization.

Parameters[a]	Units	Low (−1)	Normal (0)	High (+1)
Die temperature	°C	70	100	130
Applied pressure	MPa	63	126	190
Relaxation time	s	5	15	30

[a] Number of measurements, $N = 5$.