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Research Paper

Effect of stem crushing on the uniaxial bulk compression behaviour of switchgrass and miscanthus

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The bulk density with current baling technology is too low to utilise the full transportation capacity. For square bales, bulk density is limited by the pressure generated by the baler, density settings, and the ability of baling twine to withstand the expansion forces shortly after ejection from the bale chamber. This study explores crushing the stem on the pressure required to compact the material and the rebounding forces generated after compression. Uniaxial compression tests were conducted on bulk samples of switchgrass at three moisture levels (nominally 10%, 20%, and 45%) and miscanthus at two moisture levels (nominally 10% and 20%) to evaluate crushing. The pressure required to compress the material to 256 dry kg m^{-3} and the materials' stress relaxation behaviour were used as evaluation metrics. Crushing the material resulted in a significant decrease in the compression required for both crops. The peak stress was reduced from 577 to 441 kPa (a decrease of 23.6%) and from 581 to 365 kPa (a decrease of 37.2%) for switchgrass and miscanthus, respectively. Moisture level was also significant for both crops at the 10% and 20% moisture level with the low moisture material requiring higher pressures to reach the target densities. The final pressure after 5 min of relaxation was significantly lower for crushed material by 37.6% for miscanthus and 24.2% for switchgrass. However, this result from the reduction in peak stress at the end of the compression cycle, and relaxation behaviour was more affected by moisture level than by processing treatment.

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Nomenclature

σ_o	Initial stress (kPa)
$\sigma(t)$	Stress at time t (kPa)
F_e	Force at a specific time (kN)
F_o	Initial force at time zero (kN)
k_1	Coefficient in stress relaxation (s)
k_2	Coefficient in stress relaxation (–)
Crushed	Processing treatment that crushed the plant stem
Green	Moisture content of approximately 46% wet basis
High moisture	Moisture content of approximately 20% wet basis
Intact	No processing performed
Low moisture	Moisture content of approximately 9.5% wet basis
R^2	Coefficient of determination
UTM	Universal testing machine

1. Introduction

In order for a biomass supply system to work at its optimum point, the packaging format and capacity of transport equipment should be matched. In practice, most harvested forage materials, biomass feedstocks from crop residues, and dedicated energy crops are packaged in the field into round or square bales of various sizes. It has been shown that 90% of the hay and forage produced in the US is baled (Afzalinia, 2005; Hunt, 2001), but there are several major hurdles with biomass harvest, transport, and storage that need to be addressed before it is feasible on a large scale (Richard, 2010). Hess, Wright, and Kenney (2007) identified a need for more efficient harvest and transportation equipment as a concern that must be addressed to improve the profit margin and net energy balance of the system. This is especially important for dedicated energy crops such as switchgrass and miscanthus, where transportation distance may limit the selection/location of a processing facility. The transportation costs of delivering biomass to a biorefinery are composed of fixed costs and variable operating costs that increase linearly with distance (Sokhansanj et al., 2009). Conversely, increasing bulk density can decrease these costs (Larasati, Liu, & Epplin, 2012). Kumar and Sokhansanj (2007) showed energy consumption associated with transportation of biomass to a processing plant was equivalent to 4.8%–6.3% of the total energy content of the switchgrass.

1.1. *Principles of square baling*

Balers available on the market today can produce bales in a variety of sizes and shapes. These include various sizes round bales and square bales that can be generalised as small, mid-size, and large. Optimal equipment selection depends on the size of the operation and intended end use of the material. Round balers have lower power requirements and the bales' shape allows better protection from rain, which makes them better suited for unprotected storage. Alternatively, mid to large square bales have advantages in transportation efficiency and do not require the baler to stop to tie and eject the bale. The mid to large size square bale was the intended final application of this study.

For large inline square balers, the pickup feeds the cut material into the baler where it initially collects in the pre-compression chamber. Once the pre-compression chamber is full, the stuffer is tripped, and the material is fed into the bale chamber in front of the plunger. The material is then compressed against the material already in the chamber by the plunger, creating the next flake. The density of the material is controlled by the convergence of the sides of the bale chamber, which are adjusted hydraulically. Most balers allow a density level to be set by the operator. The baler compensates for changing baling conditions such as, moisture content and crop type, by adjusting the cylinders to keep the plunger load and the bale density constant. A percentage of the maximum available plunger force is selected by the operator and the hydraulic cylinders adjust the convergence to apply a resistance equal to the requested plunger force (Afzalinia, 2005).

1.2. *Bulk density range*

Trucking is the primary method to move biomass materials due to the remote locations and wide distribution of the biomass sources. It was noted by Lötjönen and Paappanen (2013) that bale density should be maximised to decrease the per unit transportation cost. The optimum bulk density for transportation of baled biomass by truck is the point where the tractor-trailer reaches its capacity by both mass and volume. This value can vary depending on the specific tractor-trailer combination evaluated and local regulations. Miao, Phillips, Grift, and Mathanker (2013) suggested 224 kg m^{-3} as the maximum biomass density for truck transportation in the USA; however, this number does not account for inefficiencies in stacking due to bale geometry. Lacy and Shinners (2016) used 240 kg m^{-3} as the target density for recompressed round bales. For this study, the target density was taken as 256 kg m^{-3}, which should ensure the maximum load was achieved in most locations in the United States.

The bulk density of a bale varies considerably based on a number of factors including: bale geometry, operating parameters of the baler (travel speed, density control, stuffer settings, etc.), moisture content, and crop. With current baling technology, bale density typically ranges from 150 to 200 kg m^{-3} (Afzalinia & Roberge, 2013; Kemmerer & Liu, 2012; Lötjönen & Paappanen, 2013; Shinners, Boettcher, Muck, Weimer, & Casler, 2010). The primary limitations on increasing density in square bales are the baler plunger pressure (approximately 350 kPa in a New Holland BB960 (Afzalinia & Roberge, 2013)), the number of knotters, and the ability of the bale twine to resist the rebounding forces found in bales shortly after formation. Kemmerer and Liu (2010) were able to produce large square switchgrass bales with a density of 180 kg m^{-3} at 80% plunger load, and encountered baling twine failure above this point. Lötjönen and Paappanen (2013) found an upper limit for dry density of 200 kg m^{-3} for