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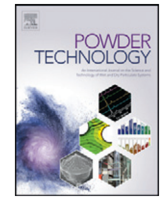

Fundamental mechanical properties of ground switchgrass for quality assessment of pellets

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ABSTRACT

Pelletization is one of the promising technologies for biomass densification. Many studies have been conducted to determine the optimum conditions for pelletizing. However, no relationship between the mechanical properties of the ground biomass and pellet quality has been published. The goal of this research was to develop and validate a predictive relationship between mechanical properties of the ground biomass in early stages of densification (<100 kPa) and the quality metrics of pellets. Switchgrass was ground with two different screen sizes (3.175 mm and 6.35 mm) and conditioned at two different levels of moisture content (17.5%, and 20%, w.b.). Hydrostatic triaxial compression (HTC) tests were performed using the Cubical Triaxial Tester (CTT) to determine bulk modulus, compression index, and spring back index below 100 kPa. Pellets were formed with ground biomass using a farm-scale pellet mill and diametral tensile strength, axial compressive strength, pellet density, and durability were determined. Regression equations between pellet quality and mechanical property having an R^2 value higher than 0.80 were selected for prediction. The validation against quality of pellets, which were formed at an alternate condition, confirms that the strength quality metrics of switchgrass pellets can be predicted using size reduced materials' bulk modulus and spring-back index.

1. Introduction

The biomass bulkiness, i.e. low bulk density, of biomass is one of the major barriers in its effective utilization as a biofuel. Loose, cut biomass has bulk density of less than 150 kg/m^3 depending on the particle size [1], for example, 60–120 kg/m^3 for switchgrass. For the efficient use of bio-feedstock as an energy or animal feed source, it is very important to form a densified product of biomass, which will not only provide a product of higher energy density or nutritional quality but will also result in a higher bulk density than in the original form. Pelletization is one of the promising technologies for the densification of biomass [2]. However, pelletization generally lacks quantitative control over the raw material, which is in ground form. For reliable and efficient production of densified biomass with improved quality, it is important to study the relationship between mechanical properties of a ground bio-feedstock, such as compressive properties, and quality metrics of densified product. From handling and transportation considerations, densities of individual pellet and bulk pellets, durability, and strength are important quality attributes [3], where durability is a measure of the friability of the pellets and strength refers to both the impact and compressive resistances. The bulk density and durability are properties of a bulk sample of densified biomass, whereas the pellet density and crushing strength are considered properties of individual pellet [4]. Those properties are significantly affected by physical and chemical properties of the feedstock, moisture content, particle size distribution of grind, temperature and applied pressure during the pelleting process [3,5,6]. To date, some research has been performed to determine these properties and factors affecting them, however, there are no standardized criteria for acceptable levels of pellet quality.

Measurements of various properties for both the biomass feedstock as brought to a biomass densification processing facility and the quality of the densified product will allow further understanding of promising methods and approaches for efficient densification systems and reliable products. The fundamental mechanical properties of a ground bio-feedstock are its genuine signature, which can be utilized to develop the relationship with the quality parameters of pellets. Fundamental mechanical properties of ground bio-feedstock materials can be determined with the cubical triaxial tester (CTT) by measuring elastic, elastoplastic, and rate-dependent responses of selected granular materials [7,8]. The CTT is capable of measuring the true 3D stress–strain behavior of granular materials over a wide range of compression and extension conditions without the confounding effect of die-wall friction [7,9]. CTT has been successfully used in the characterization of fundamental mechanical properties of various granular and powdered materials [8,10–12].

A few researchers studied the mechanics of densification of bio-feedstock and worked to identify the factors affecting the pelletization process [3,5,13–15] including constituents of the feed, moisture content, particle size and its distribution, preconditioning temperature/

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preheating of grind, added binders, and densification equipment variables. However, these studies do not address characteristics of densified biomass in terms of the ground biomass's properties, e.g., Mani et al. [13], Shaw and Tabil [16], and Adapa et al. [14] characterized the mechanical properties of pellets in relation to the densification process of biomass affected by the above-mentioned physical factors. However, these studies did not consider ground biomass' mechanical properties. Moreover, based on the literature reviewed, there are no identified or quantified relationships between the mechanical properties of ground biomass and the parameters related to pellet quality. Therefore, to be able to control the quality of biomass pellets systematically, there is a need to identify the characteristics of densified biomass pellets and develop the relationships of these pellet characteristics with the intrinsic mechanical properties of ground biomass. This fundamental approach lays the foundation for rational basis of how and why of the mechanics of pellet formation. Additionally, such an approach will bridge the knowledge gap between the quality of pelletized biomass and mechanical properties of the ground biomass feedstock and provide deeper insights of the mechanics of pelleting. Therefore, the goal of this research is to develop relationships between mechanical properties of ground biomass and resulting characteristics of pellet quality for a selected biomass, switchgrass.

Switchgrass is a perennial grass native to the tall-grass prairies, which has received much attention as a model herbaceous energy crop in the U.S. [17]. Attributes of switchgrass desirable as a bioenergy cropping include its demonstrated long-term (>10 year) high productivity across many environments, suitability for marginal land, relatively low water and nutrient requirements, and positive environmental benefits [17]. The hypothesis of this research, that there exists a direct and positive correlation ($R^2 > 0.80$) between the fundamental mechanical properties of ground biomass and pellet qualities, was tested at a significance level of $\alpha = 0.05$. Toward that end, four specific objectives were formulated, which are: 1) to measure the physical and mechanical properties of the ground switchgrass, 2) to measure the mechanical properties and quality metrics of switchgrass pellets, 3) to develop the predictive relationship(s) among the mechanical properties of the ground switchgrass and the properties of resulting pellets using statistical analysis, and 4) to validate the predictive relationships using conditions other than those used to develop the predictive relationships.

2. Methodology

Two important parameters, particle size and moisture content, were considered for preconditioning the material, which forms the basis of the design of experiments. Two screen sizes; 3.175 mm and 6.35 mm, were used for size reduction and thus two different sets of particle size distributions of material were obtained. A size reduction machine (Munson SCC-10, Utica, New York), which uses shear cutting mechanism, was used for reducing the size of the as-received test material (Fig. 1). For this study, switchgrass was collected from a farm located at Julian, Pennsylvania (PA), USA, which was harvested in November 2011. The moisture content of the size-reduced, i.e., ground, switchgrass was measured by the oven drying method according to the ASABE S358.2 standard [18]. The moisture content was calculated using the following equation:

$$\text{Moisture content} = \frac{(\text{weight before drying} - \text{weight after drying})}{\text{weight before drying}} * 100(\%\text{w.b.}). \quad (1)$$

The ground switchgrass was conditioned by spraying water to achieve the required moisture content on a wet basis (w.b.). The initial moisture content of the received switchgrass was 3.8 ± 0.2% (w.b.) and of the ground switchgrass was 3.6 ± 0.3% (w.b.). After size reduction, the ground switchgrass was conditioned at two different moisture contents, i.e., 17.5% and 20% (w.b.). The water was mixed using manual Mini-Inversina (Bioengineering AG, Switzerland) capable of giving 360° motion in the mixer. Several trial runs were performed to determine the mixing duration and based on these runs, the mixing was performed at 80 rpm for 2 min. To obtain one batch of conditioned switchgrass of 500 g, 100 g of sample was mixed at a time in the mixer. The conditioned material was kept covered for 24 h for moisture equilibration. Based on the review of literature and preliminary runs performed, (1) two moisture content levels considered for conditioning of materials were 17.5% (w.b.) and 20.0% (w.b) and (2) number of replicates for each treatment, which is included in Table 1. Linear regressions were performed between the mechanical properties of the ground switchgrass and pellet quality using Minitab (Version 16.1.0.0, State College, PA). Based on the results, the correlation ($R^2 > 0.80$) between the mechanical properties of the ground switchgrass and pellet quality metrics were established. For the validation of the developed relationships, switchgrass ground with 6.35 mm was conditioned at 18.75% (w.b.), different from the test conditions noted above, to form pellets and the quality of pellets was tested.

2.1. Physical properties of ground switchgrass

The particle size distributions of the ground switchgrass were determined using a Ro-tap sieve shaker according to the ASABE S319.3 standard [19]. Per the standard, a sample size of 100 g was used to determine the particle size distribution. U.S. Standard Sieve numbers 5 (nominal opening size 4.0 mm), 7 (2.81 mm), 10 (2.0 mm), 14 (1.4 mm), 18 (1.0 mm), 25 (0.71 mm), 35 (0.5 mm), 45 (0.353 mm), 60 (0.25 mm), 80 (0.176 mm), 120 (0.125 mm), 170 (0.088 mm), and 230 (0.062 mm) plus a pan were used for this analysis.

The measurement of particle density of the ground switchgrass was performed with a Multipycnometer (Quantachrome Instruments, MVP · 2, Boynton Beach, Florida) using helium as the pressure medium. Based on volume–pressure relationship, the volume of the sample of the

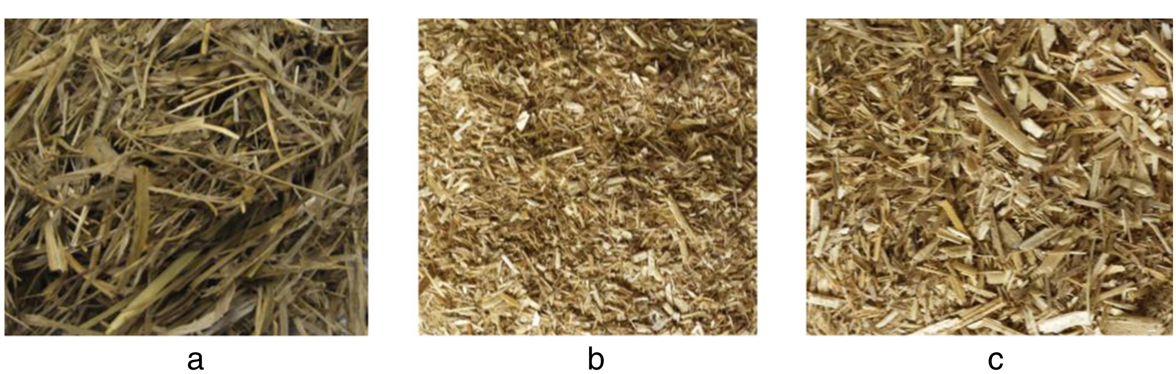

Fig. 1. Photographs of a. as received switchgrass (3.8 ± 0.2% wet basis (w.b.) moisture content), b. ground switchgrass with 3.175 mm screen size (3.6 ± 0.3% w.b.), and c. ground switchgrass with 6.35 mm screen size (3.6 ± 0.3% w.b.).