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LABORATORY SCALE CONCEPT VALIDATION AND EVALUATION OF COMPROMISING PLANT NODAL INTEGRITY AS A MEANS TO INCREASE BALE DENSITY

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THESIS

A thesis submitted in partial fulfillment of the requirements
for the degree of Master of Science in Biosystems and Agricultural
Engineering in the College of Engineering at the University of Kentucky

By

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Lexington, Kentucky

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ABSTRACT OF THESIS

LABORATORY SCALE CONCEPT VALIDATION AND EVALUATION OF COMPROMISING PLANT NODAL INTEGRITY AS A MEANS TO INCREASE BALE DENSITY

Transportation costs represent a significant role in the economics of packaged hay and biomass crops. The material's low bulk density limits transportation efficiency. Density is currently limited by the ability of the baling twine to withstand the expansion forces generated by the baled material shortly after it is ejected from the bale chamber. It was hypothesized that compromising the structure of the plant, particularly the plant nodes could reduce the amount of energy stored in the material as it is compressed and thereby reduce the material's elastic response to compression. Literature pertinent to the biomass material's behavior in compression was reviewed. Bulk samples of switchgrass and miscanthus were subject to uniaxial compression, and the required pressure needed to obtain a target density of 256 kg/m^3 was compared on a wet and dry density basis. Both switchgrass and miscanthus showed a statistically significant decrease in the required compression pressure, and the interaction between the moisture level and required pressure was also significant. Existing models for the pressure density relationship of compressed bulk material were evaluated for suitability. Individual nodes and internode sections were subject to radial compression and the apparent modulus of elasticity and maximum contact stress were determined.

KEYWORDS: Biomass densification, Energy crops, Baling, Stress relaxation, Apparent modulus of elasticity

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To my wife Allie, and parents David and Sharon, I couldn't have done it without you.
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CHAPTER 1: INTRODUCTION

1.1 Introduction

The growing demand for renewable and sustainable energy sources spurred by increasing fossil fuel prices, the push towards energy independence, and the cultural shift to a life cycle conscience society has opened the door for energy from biomass to become possible on a large scale. This is evident from the Energy Independence and Security Act (EISA) of 2007 (Congress 2007), which mandated that 36 billion gallons of renewable fuel be produced by 2022. To meet this mandate a variety of resources need to be utilized. McLaughlin, De La Torre Ugarte et al. (2002) noted that although grain is currently the primary feed stock for ethanol production, its expansion will be limited by prices and competing interests in the food and animal feed sectors. In fact, the mandate requires 16 billion gallons of cellulosic biofuels, that can be made from a variety of crop residues and dedicated energy crops such as miscanthus and switchgrass. These feedstocks can also be utilized by co-fired power plants to produce electricity and lower CO2 emissions by co-firing biomass with coal.

In practice, most harvested forage materials and biomass feedstocks from crop residues and dedicated energy crops are packaged for transport 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 (Hunt 1983; Afzalinia 2005), but there are several major hurdles to using biomass as a feasible energy source on a large scale. Perlack, Wright et al. (2005) identified a need for more efficient harvest equipment, and other concerns that need to be addressed include improving the enterprise's profit margin and net energy balance of the system. Steps need to be taken to reduce costs and make it an economically lucrative venture to producers. This is especially important for dedicated energy crops such as switchgrass and miscanthus, where transportation concerns to the processing facility can limit where these crops can be grown. A large portion of the costs with biofuels are associated with biomass harvest, transport, and storage. The transportation costs of delivering biomass to a biorefinery can become significant as transportation costs increase linearly with distance. Conversely, with increased bulk density the costs can be decreased (Peleg 1980). Kumar and Sokhansanj (2007) showed that energy consumption associated with transportation of biomass to a processing plant using 1814 dry tonnes/day of biomass was equivalent to 4.8% to 6.3% of the total energy content of the switchgrass.

The optimal transportation configuration depends on a number of factors including proximity to and the size of the processing plant. Trucking is the primary method to move biomass materials due to the remote location, and wide distribution of the biomass sources. This is used in conjunction with any other transportation method for transport over longer distances (Steffe 1996). The ideal material bulk density for transportation of baled biomass by truck is limited by the mass and volume capacity of the tractor trailers used. It was noted by Lötjönen and Paappanen (2013) that bale density should be maximized to decrease the per unit transportation cost. The gross vehicle weight allowed on the National System of Interstate and Defense Highways and most state roads is limited to 36,287 kg (80,000 lbs) (23CFRPart658.17) (Federal Highway Administration 2013). Assuming a typical 13.7 m (45 ft) steel trailer pulled by a light road tractor with a day cab, a common configuration for short haul trucking, has a combined weight of 13.61 t (30,000 lbs); this leaves approximately 22.68 t (50,000 lbs) for payload. This number can vary depending on the specific tractor-trailer combination. Although other studies have used the range of 19.96 t to 21.78 t (44,000 – 48,000 lbs) (Lanning, Dooley et al. 2007), the higher weight capacity was assumed, as it represented the highest density requirement.

By looking at the example of 0.91 m X 1.22 m X 2.44 m (3 ft X 4 ft X 8 ft) mid-sized square bales, which are a good candidate because of their advantages in handling and stacking, it can be estimated that 30of these bales can be hauled in a single load. This results in a required bale density of approximately 256 kg/m^3 (16 lbs/ft^3) to reach the trailer's capacity by weight; this was also noted as the ideal density for transport by Miles and Miles Jr (1980). The bulk density of a bale varies considerably based on a number of factors including moisture content and crop, but with current baling technology, bale density typically ranges from 150-220 kg/m^3 (alfalfa) for round balers to 200 kg/m^3 for large square balers (Hunt 1983; Kemmerer and Jude 2010). Lötjönen and Paappanen (2013) found an upper limit for dry density of 200 kg/m^3 for large square bales and 180

kg/m^3 for round bales of reed canary grass. This lower density causes trucks to "cube out" i.e. reach volume capacity before reaching the weight limit.

The current typical density of baled biomass results in approximately14% of the trailer's capacity being unused (assuming an upper limit on density of 220 kg/m^3) which represents a significant inefficiency within a proposed biomass industry in the Commonwealth of Kentucky alone. The Commonwealth is estimated to have the potential to produce 5.4 million metric tons (dry) of residue and energy crops annually (Executive Task Force on Biomass and Biofuels Devolpment in Kentucky 2009). This would require 236,000 truck trips per year at the optimal density and an additional 33,000 truck trips per year would be required with the existing density. In the study of the feasibility of a billion ton annual supply of biomass for bioenergy Perlack, Wright et al. (2005) found that agricultural lands can sustainably provide 446 million dry tons of crop residues and 377 million dry tons of perennial crops. On a national level, the trucking requirements for biomass would be substantial and optimizing bale density could significantly impact transportation requirements.

Baling is just one technique that can be used to increase the bulk and energy density of biomass, with other methods including compacting, cubing, pelleting and briquetting. All of these packaging methods require high energy inputs for densification, require extra processing steps, and result in densities exceeding 400 kg/m^3. If increasing truck transportation efficiency is the only goal, there is no need to increase the density above what can be transported; therefore increasing bulk density in the bale form is the most practical method for improving transportation logistics.

Bale density is influenced by many factors including: bale size, shape, crop, moisture content, travel speed, and baler settings (density control, stuffer settings, etc.). The primary limitations on increasing density in square bales are the baler plunger pressure (approximately 345 kPa), the number of knotters, and the ability of the bale twine to resist the rebounding forces found in bales shortly after formation. It was hypothesized that the structure of plant stems, specifically the nodes, store energy when the material is compressed and this results in the rebounding forces that cause the twine to fail. This was illustrated by the high-pressure concentrations at the nodes shown in Figure 1-1 when uniaxially compressed to a pressure of 78 kPa. The pressure range shown on the film was from 500 kPa (blue) to greater than 2500 kPa (red). It was proposed that by preprocessing the material through a set of processing rolls prior to entering the bale chamber, the node structure of the plant can be comprised, which in turn will reduce the material's ability to elastically store energy, and reduce void space in the bulk material. This results in lower pressure requirements on the plunger to produce high-density bales, and it reduces the energy stored in the bale that produces rebounding forces that cause baling twine to fail.

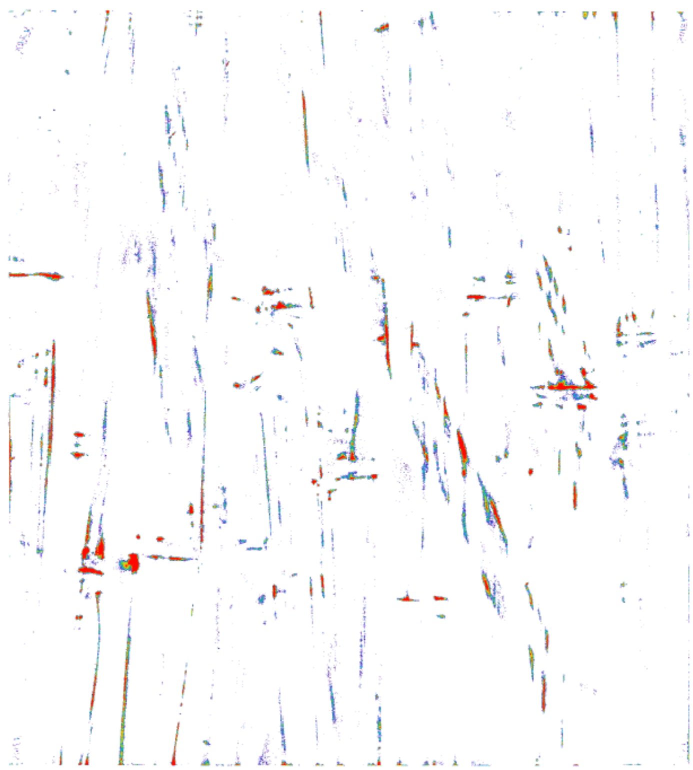


Figure 1-1: Internal pressure distribution of a bulk sample that resulted from uniaxial compression, shown on pressure sensitive film (Tekscan Inc., South Boston, MA). Total applied pressure was 78 kPa, the film pressure range was from 500kPa (blue) to greater than 2500 kPa(red)

1.2 Project objectives

The overall goal of this project is to evaluate the feasibility of compromising the plant nodes as a method to produce high density bales, and specifically examine how this affects the pressure density relationship when the bulk material is placed under uniaxial compression. Specific objectives are:

1. Quantify the change in the bulk deformation characteristics of switchgrass (*Panicum virgatum*) and miscanthus (*Miscanthus giganteus*) at two moisture contents (nominally 10 and 20%) due to crushing the plant nodes within the crop material;
2. Model the behavior of switchgrass and miscanthus under bulk compression using existing forage compression models that would account for processed material and examine the normalized stress relaxation behavior; and
3. Determine the material properties of switchgrass and miscanthus node and internode sections, including bioyield, apparent modulus of elasticity, and maximum contact stress, using parallel plate compression tests.

1.3 Organization of thesis

Chapter 1 introduces the thesis; background information and justification of the need for this research was presented. This chapter also outlines specific objectives for this thesis. Chapter 2 contains a review of pertinent literature relating to the behavior of forage material in compression and of methods to produce high-density bales. Chapter 3 explains the methodology used to complete the objectives, specifically the experimental design, test procedure, and data analysis. Chapter 4 presents the results from the experiments outlined in Chapter 3 and outlines significant findings. Chapter 5 discusses the implications of the results and Chapter 6 discusses future work. The appendix presents pertinent information not presented in the body of the text as well as extended tables and graphs of individual tests.

CHAPTER 2:LITERATURE REVIEW

This thesis evaluated the feasibility of increased bale density as a method to improve the commercial potential of forages and biomass feedstocks. Bale density is highly correlated with handling and transportation costs. These topics have been well documented for forage crops and in many studies dealing with biomass supply and logistics, thus relevant information was reviewed only in brief to provide context for the rest of the project. Additionally, the principles and practical considerations of bale formation that impact the assumptions and conclusion of this project are reviewed.

Significant research has been conducted regarding the pressure density relationship of forage material, especially in closed dies as it pertains to pellet and wafer formation. The proposed models were reviewed along with previous studies that applied the models to bale formation and recompression.

The proposed material processing requires the structure of the plant stem to be crushed in a manner that can be approximated as radial compression, therefore relevant information from studies regarding engineering properties of the plant material as it pertains to failure in radial compression is also reviewed.

2.1 Transportation costs

As previously stated, the transportation of the feedstock from the field to the processing plant has numerous costs associated with it, including costs in terms of dollars and energy. De and Assadi (2009) accounted for the monetary costs in the examination of co-firing biomass in coal plants by assuming a biomass distribution density around the plant and determining the total distance that would need to be traveled annually to supply the plant. Kumar and Sokhansanj (2007) evaluated the feasibility of supplying switchgrass to a biorefinery with a capacity of 1814 dry tonnes per day (200 tons). Energy expended in the transportation of the biomass was estimated at 4.8% to 6.3% of the total energy content of the material. At an assumed yield of 11 dry metric tons/ha, the plant required a transportation range of 77 km and the analysis showed transport costs increased or decreased with plant size because of further travel distance to supply larger facilities.

Steffe (1996) examined transport scenarios for supplying agriculture residues and wood chips for conversion to biofuels or direct combustion to produce electricity. The study examined standalone trucking; and trucking in combination with rail, ship, and pipeline transportation. The study noted that the low density of baled biomass often made volume the limiting factor for transportation, and found rail transport was economical after 500 km. Shipment via pipeline and ship were economical after 1500 km and 3000 km, respectively.

2.2 Bulk density range

The bulk density range of forage material depends on a number of factors including crop type, packaging format, field conditions, moisture content, and equipment operating parameters. The bulk density ranges from 65 kg/m^3 for loose cut hay (Kepner, Bainer et al. 1978) up to 700 kg/m^3 for pelleted switchgrass (Sokhansanj, Mani et al. 2009). The range in bulk density for switchgrass in a variety of formats is summarized in Table 2-1.

Table 2-1: Bulk density of switchgrass packaged in a variety of forms (adapted from (Sokhansanj, Mani et al. 2009)

Form of Biomass	Shape and Size Characteristics	Density (kg/m^3)
Chopped biomass	20-40mm long	60-80
Ground particles	1.5mm loose fill	120
Baled biomass	round or large squares	140-180
Briquettes	32mm diameter X 25mm thick	350
Cubes	33mm x 33mm cross section	400
Pellets	6.24 mm diameter	500-700

It is apparent from Table 2-1 that although chopping or grinding is frequently required before final processing; these steps lowered the bulk density and in turn limited the effective transportation range. Kumar and Sokhansanj (2007) examined multiple scenarios and found transporting chopped or ground material was more expensive than trucking bales. Cubing is a method of packing that has not been widely accepted because it requires very low moisture content at the time of harvest and it has large equipment costs (Kepner, Bainer et al. 1978). Though higher density formats are better suited for longer range transportation, briquettes or pellets are not commonly made on farm. This leaves round or square bales as a primary candidate for transportation.

2.3 Principles of square baling

A variety of sizes and shapes of balers are available on the market today. These range from small square balers, round balers, mid-size, and large square balers. 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 shed water, which makes them better suited for unprotected storage. Alternatively, mid to large square bales have advantages in stacking and do not require the baler to stop to tie and eject the bale. As previously discussed, the mid to large size square bale was the focus of this research, thus only these principles were discussed.

The cut material is fed into the baler by the pickup. For large inline balers, the crop then moves into 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 pushed 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 can be controlled hydraulically. The converging sides put lateral pressure against the material which creates resistance to the material being pushed through the baler. The following equation from Srivastava, Goering et al. (1993) gives the required plunger force based on the convergence of the bale chamber.

$$Fc = \frac{E_h * y}{d_c} L_c * w_c * f_h \qquad \text{Equation 2-1}$$

Where:

F_c= the compressive force applied by the plunger, N

E_h= effective modulus of elasticity of the material, kPa

y= total convergence of the baler, mm

d_c= depth of the bale chamber, m

L_c= length of the converging section, m

w_c= width of the bale chamber, m

F_h= coefficient of friction between the hay and the bale chamber

Kemmerer and Jude (2010) demonstrated that as switchgrass bale density approached 200 kg/m^3 (at 12.5% moisture content) that large square balers begin to encounter problems with the strength of the twine. Increasing the strength of the twine and/or increasing the amount of twine on a baler would be cost prohibitive.

2.4 Standards for baling twine

The standard that regulates twine used in automatic balers is ANSI/ASAE S315.3. The purpose of this standard was to provide specifications for twine used in small and large square balers. It covers sisal and polyolefin twine, and ensures the twine provides satisfactory performance in a knotter and adequate durability in handling and storage (ANSI/ASAE 2002). It outlines the testing procedures to meet these requirements, but more relevant to the topic at hand it provides the minimum acceptable knot strength. It can be seen that polyolefin twine for use in large square balers is required to have a minimum knot strength of 1.29 kN (ANSI/ASAE 2002). Currently twine has a maximum knot strength of approximately 2.67 kN (Donaghy's Industries).

2.5 Behavior of forage materials in compression

When subjected to constrained uniaxial compression, the bulk density of the forage material is directly related to the applied pressure. Biological materials exhibit a non-linear viscoelastic or viscoplastic response dependent on the compressive force, loading rate, orientation, and duration of compression (Faborode and O'Callaghan 1989; Kaliyan 2008). Several stages can be seen within this compression cycle. Initially, the particles are loosely spaced and a large amount of airspace exists between the stems. The low pressure portion of the compression cycle causes viscous deformation, where the loose particles are rearranged and packed close together, reducing the amount of void space in the bulk material (Stage 1 Figure 2-1). The force requirement for this stage was dependent on the loading rate. As the pressure further increased, the individual particles in the bulk material undergo elastic and plastic deformation (Stage 2). Once the maximum displacement was reached, if the load was removed (unconstrained final displacement), the material rebounded and part of the deformation was recovered. If the material was constrained in the final position, the energy stored would produce the rebounding forces against the constraints. This rebounding force is hysteretic in nature, as the particles rearrange and further reduce void space, and after a short time the forces settle asymptotically to a final value. At this point, it was theorized that energy stored to produce the rebounding force is due to the elastic part of the bulk deformation.

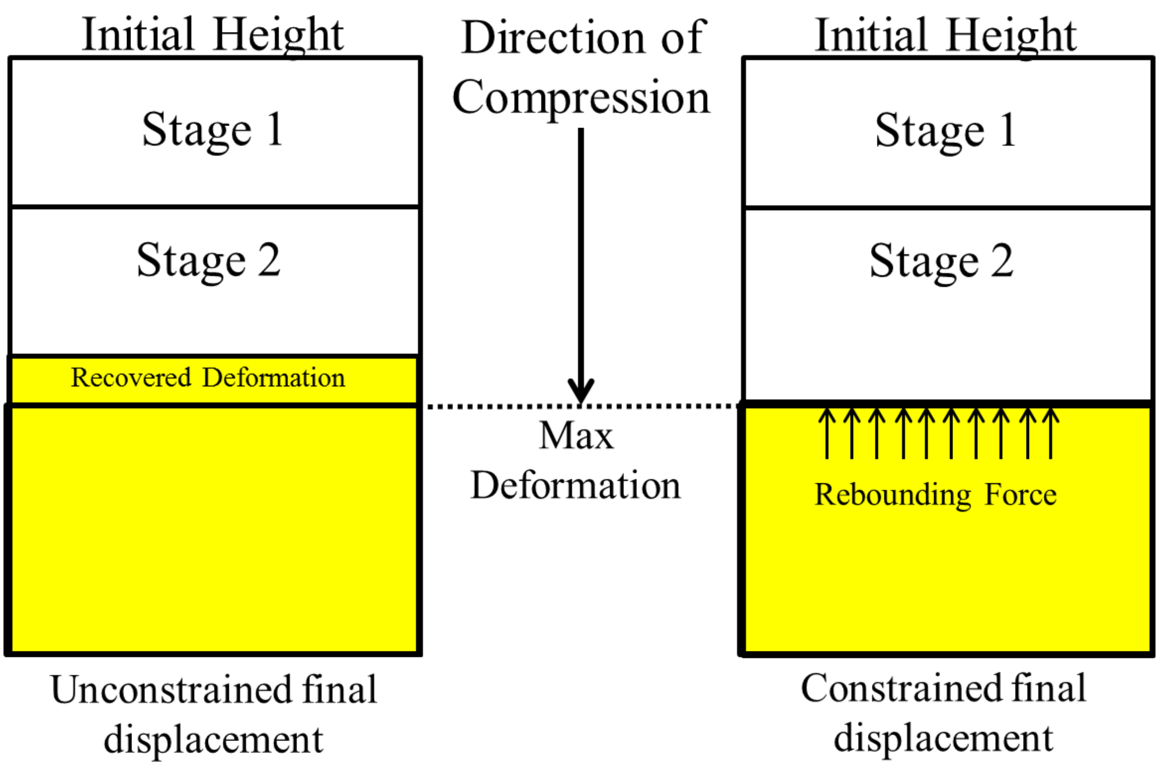


Figure 2-1: Behavior of viscoelastic/plastic material under uniaxial compression.

2.5.1 *Models for predicting behavior in compression*

The behavior of agricultural materials subject to compression has been studied extensively and numerous models have been proposed to describe the pressure density relationship. The majority of these models takes the form of a simple power law (Equation 2-2) or variations of an exponential function (Afzalinia 2005). Some of these models were developed using the density range commonly encountered during baling or bale densification, but the focus of many of the models was compression to significantly higher densities.

$$P = b_0 * \rho^{b_1} \qquad \text{Equation 2-2}$$

Where:

P= pressure, kPa

ρ= bulk density of the material

b_0 and b_1=regression coefficients

O'Dogherty and Wheeler (1984) studied straw wafer formation in closed dies with a diameter ranging from 25-75mm. It was determined from Equation 2-2 that the model coefficients of $11.2X10^{-6}$ for b_0 and 2 for b_1 were sufficient to model the behavior for the density range of 150-400 kg/m^3. At higher densities, a logarithmic power law provided a better fit. Talebi, Tabil et al. (2011) found that Equation 2-2 could be used to relate the applied pressure to density for hay below 500 kg/m^3.

Faborode and Ocallaghan (1986) derived Equation 2-3 which models the pressure density relationship using the uncompacted bulk density. Using Equation 2-4, Equation 2-3 can be restated in terms of the compression ratio, r_c, as shown in Equation 2-5. This model relies on the assumptions of a constant compression rate, as well as uniform sample loading and lateral pressure variation.

$$P = \frac{b_0 * \rho_0}{b_1} * \left[e^{b_1 * \left(\frac{\rho}{\rho_0} - 1\right)} - 1\right] \qquad \text{Equation 2-3}$$

Where:

P=applied pressure, kPa

ρ_0=initial bulk density, kg/m^3

ρ= compressed density, kg/m^3

b_0 and b_1= regression coefficients

Frequently a compression ratio is defined:

$$r_c = \frac{\rho}{\rho_0} \quad \text{Equation 2-4}$$

That results in Equation 2-3 being rewritten as:

$$P= \frac{b_0 * \rho_0}{b_1} * \left[e^{b_1 * (r_c - 1)} - 1\right] \quad \text{Equation 2-5}$$

Hofstetter and Liu (2011) applied several of these models in the recompression of small square bales (36 cm x 46 cm) of corn stover, Indiangrass, switchgrass, and wheat straw. Tests were performed at three compression rates: 106.7 mm/sec, 50.8 mm/sec, and 2.54 mm/sec. Figure 2-2 shows the compression behavior and the data fit using the power model, along with Equation 2-3 for corn stover with the 106.7 mm/sec compression rate.

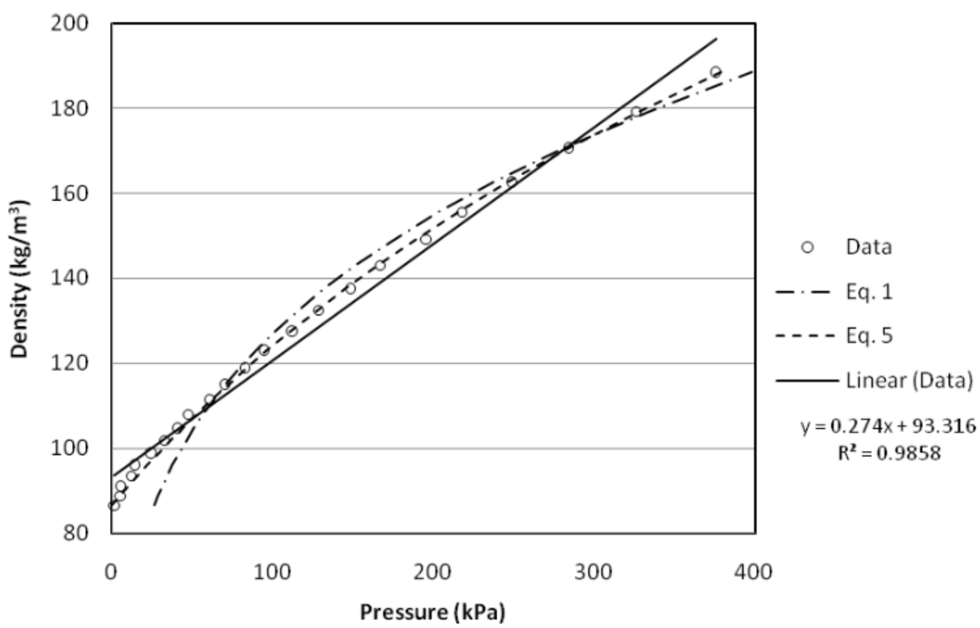


Figure 2-2: Sample compression data for corn stover compressed at 106.7 mm/sec (Hofstetter and Liu 2011). Eq. 1 is the power model and Eq. 5 corresponds to Equation 2-3 in this thesis.

Tabil, Talebi et al. (2011) studied the compression and relaxation behavior of timothy hay over a range of moisture contents with an applied pressure range of 5.58 to 14.88 MPa. The simple power law model (Equation 2-2) was best suited to describe the pressure density relationship at densities above 500 kg/m^3 and Equation 2-3 provided the best fit below 500 kg/m^3. The coefficient b_0 was also found to have a linear correlation with moisture content.

Pitt and Gebremedhin (1989) studied the pressure density relationship of alfalfa and grasses as it applied to silo capacity, and proposed a modification to Equation 2-3 seen in Equation 2-6, which used the dry density of the forage material.

$$P = b_0 * \left[e^{b_1 *(\rho-\rho_0)} - 1\right] \qquad \text{Equation 2-6}$$

Where:

P= applied pressure, kPa

ρ= dry density kg/m^3

ρ_0= uncompacted dry density kg/m^3

b_0 and b_1=regression coefficients

Bilanski, Graham et al. (1985) proposed Equation 2-7, which incorporated the fact that the bulk density does not increase indefinitely, but asymptotically approached some final value as the applied pressure goes to infinity.

$$(\gamma_{max} - \gamma)/(\gamma_{max} - \gamma_o) = e^{-P/k} \qquad \text{Equation 2-7}$$

Where:

P=applied pressure, MPa

γ= instantaneous bulk density, kg/m^3

γ_{max}=maximum bulk density, kg/m^3

γ_o = initial bulk density, kg/m^3

k= model coefficient

Afzalinia and Roberge (2013) studied the pressure density relationship in a large cubic baler for alfalfa and barley straw. The study instrumented the plunger with strain gauges to measure the applied force and determined the density by weighing and measuring the bale volume. The effects of baler settings (flake size and density) were examined. Several previously developed models were evaluated, and Equation 2-8 was proposed as an alternative to model the pressure density relationship.

$$\gamma = \gamma_o + (A + BP + CP^2)(1 - e^{-DP}) \qquad \text{Equation 2-8}$$

Where:

P=compression pressure, MPa

γ= instantaneous bulk density, kg/m^3

γ_o = initial bulk density, kg/m^3

A,B,C,D= model coefficients

2.5.2 Rheological models

Rational models predict the material's behavior based on the laws of physics and many of these models are based on the science of rheology. Figure 2-3 illustrates many of the rheological models already developed. The process of bale formation was modeled as a nonlinear viscoelastic process. This behavior can be modeled using various combinations of spring elements to represent the elastic component of the deformation, along with dashpots to represent the viscous components.

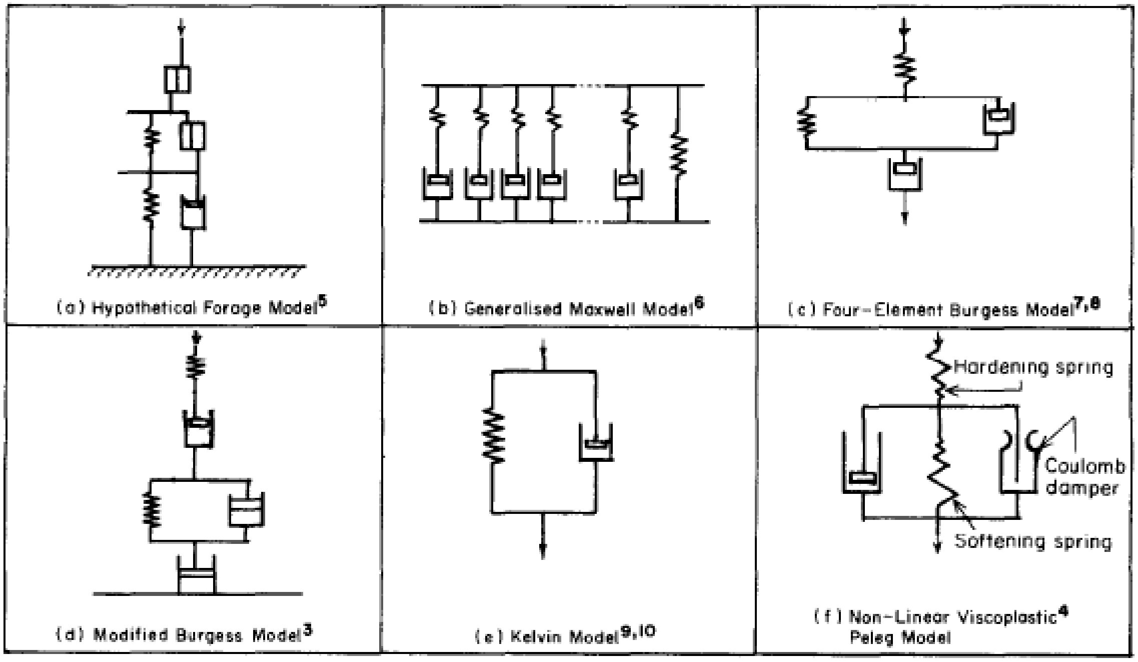


Figure 2-3: Some rheological models for the compaction of fibrous agricultural materials (Faborode and O'Callaghan 1989)

2.5.3 *Stress relaxation*

Due to the fact that viscoelastic materials often exhibit nonlinear behavior when subject to large deformations, along with the difficulty that arises when measuring mechanical properties of biological materials, (Peleg 1980; Steffe 1996) recommends representing the data as a normalized stress fit to Equation 2-9. Talebi, Tabil et al. (2011) state that model coefficients define the relaxation curve’s shape characteristic and can be used to compare different materials. The regression coefficient, k_2, represents the theoretical asymptote of the normalized stress and can be an index of how solid the compact material is (Mani, Tabil et al. 2006).

$$\frac{\sigma_o t}{\sigma_o - \sigma(t)} = k_1 + k_2 t \qquad \text{Equation 2-9}$$

Where

σ_o = initial stress, kPa

$\sigma(t)$ = stress at time t, kPa

k_1 and k_2=constants

The relaxation has also been characterized using percent relaxation. Tabil, Talebi et al. (2011) found the percent relaxation in hay using Equation 2-10. The study found the percent relaxation to be affected by maximum pressure and moisture content, which ranged from 28.8%-53.7% for low quality hay.

$$Percent\ relaxation = \frac{100 * F_o - F_e}{F_o} \qquad \text{Equation 2-10}$$

Where:

$F_o =$ initial force at t=0, kN

F_e= force after some specified time, kN

2.6 Effects of moisture content

Moisture content has been shown to impact the mechanical properties and the density of baled material. It has been shown, for alfalfa, that higher moisture leads to more dry matter per bale, for a given baler density setting (Burrough and Graham as cited by Kepner, Bainer et al. (1978)). However, Kepner, Bainer et al. (1978) also cite the works of Nation who found that moisture content had no effect on dry density of clover/rye grass mix.

Nazari Galedar, Jafari et al. (2008) studied a variety of engineering properties for alfalfa stems over a moisture content range of 10-80%. The results indicated an increase in moisture content resulted in a decrease in: tensile strength, bending stress, elastic modulus, and modulus of rigidity. However, the shear stress and shear energy increased with moisture content. Tavakoli, Mohtasebi et al. (2009) found that higher moisture content samples had significantly reduced bending stress and Young's modulus. The addition of moisture was shown to increase E_h and f_h in Equation 2-1, for alfalfa (Kepner, Bainer et al. 1978; Srivastava, Goering et al. 1993).

2.7 Friction forces and lateral pressure

As the bulk material is compressed the force is transmitted through the bulk material, a portion of the energy is expended by inter-particle friction, and a portion of the stress is exerted laterally against the container sidewalls. This, combined with the coefficient of friction between the material and the wall, represents a component of the system's resistance to deformation. Faborode and O'Callaghan (1986) suggested the Cauchy number, which represents the dimensionless ratio of the inertia to elastic forces, could be used to relate these forces to the ram speed and die geometry.

The ratio of transverse to axial strain is commonly quantified using Poisson's ratio. O'Dogherty (1989) cites several works by Mewes who found the lateral pressure ranged from 10-50% of the applied axial pressure for straw. Pitt and Gebremedhin (1989) used 0.5 for Poisson's ratio for hay and grasses in silos. Le Lievre and Jofriet (1984) conducted triaxial tests on alfalfa silage, and assumed an approximate value for Poisson's ratio to be 0.3. Wang, Tabil et al. (2009) assumed a value of 0.4 for timothy hay nodes. Anazodo and Chikwendu (1983) developed an equation for Poisson's ratio for radially compressed corn cobs. The equation predicted a value of 0.29 and was compared to the photographically measured value of 0.35.

The influence of moisture content, velocity, chop length, and surface finish on the coefficient of friction for forage material has been well documented. ASABE standard D251.2 (ASAE 2003) provides the static and sliding coefficients of friction for chopped grass, corn, hay, and straw against various surfaces. The standard shows a general trend of increasing sliding coefficient of friction with the addition of moisture, with the value leveling out in the upper moisture content range. Sliding friction ranged from 0.2 to 0.3 for alfalfa against stainless steel in the moisture range of interest. Both the material chop length and velocity in the range of interest had no discernable effect. Shinners, Koegel et al. (1991) studied the effect of velocity, lateral pressure, and moisture content and on the coefficient of friction. The study reports no interaction effect between the normal pressure and moisture content. In the moisture and lateral pressure range of interest, a friction value of 0.278, for alfalfa against iron oxide coated steel, was reported.

2.8 Mechanical properties of biological materials

The hollow internode section of grass stems is weaker than the node sections, which results in the node determining the stem strength (Srivastava, Goering et al. 1993). Recent interest in energy crops has led to a number of studies examining the biomechanical properties of these crops to assist in the design of harvest and processing equipment. Liu, Mathanker et al. (2012) conducted experiments to examine the cutting force, shear strength, tensile strength, and bending strength of miscanthus to aid in the design of harvesting and size reduction equipment. The cutting force was examined at the first and second internode and the maximum cutting force was found to range from 54.6 N/mm to 83.0 N/mm, depending on the blade type. It was also found that the biomechanical properties vary according to the node location on the stem. The modulus of elasticity in bending for miscanthus stems increased from 4,600 to 11,300 MPa as the internode number increased from the first to the seventh. Liu, Mathanker et al. (2012) hypothesized this phenomenon was due to the presence of a core in the upper nodes that provided extra support.

Yu, Womac et al. (2006) studied the ultimate shear and tensile strength of switchgrass internode sections. The study indicated that the variety of switchgrass had an effect on these properties. Alamo switchgrass had higher ultimate tensile and ultimate shear strength, 97.8 and 20.5 MPa, respectively. For comparison, Kanlow had an ultimate tensile and ultimate shear strength of 89.7 and 17.9 MPa, respectively. Moisture content was also found to influence the ultimate tensile strength, but it was found that shear stress was not significantly affected.

ASAE/ASABE (2000) S368.4 is the standard for compression tests of biological materials. This standard was developed for the testing of food materials with a convex shape but can be applied to other biological materials. The standard is geared toward tests using a UTM to produce force deformation curves and defines the bioyield point as the point where an increase in deformation produces a decrease or no change in the force. The standard also defines the apparent modulus of elasticity for different loading configurations. The standard uses apparent modulus of elasticity because biological materials exhibit viscoelastic or viscoplastic behavior, which results in strains that cannot be fully recovered. The equation for the conventional modulus of elasticity was based on

Hertz theory for contact stress, which assumes elasticity. It is noted in the standard that the equations are still useful when comparing viscoelastic materials when the deformation and loading rates are similar for all tested samples. The equation for the apparent modulus of elasticity, when using parallel plates, is given in Equation 2-11. The apparent modulus of elasticity is only valid before the inflection point on the force deformation curve.

$$E = \frac{0.388F(1-\mu^2)}{D^{3/2}}\left[K_u\left(\frac{1}{R_u}+\frac{1}{R'_u}\right)^{1/3} + K_L\left(\frac{1}{R_L}+\frac{1}{R'_L}\right)^{1/3}\right]^{3/2} \qquad \text{Equation 2-11}$$

Where

E=apparent modulus of elasticity, Pa

D= deformation, m

μ=Poisson's ratio

F=compression force, N

R_u, R'_u= radii of curvature of sample in contact with upper plate, m

R_L, R'_L= radii of curvature of sample in contact with lower plate, m

K_u, K_l=constants

Equation 2-12 was derived by Sherif, Segerlind et al. (1976) to estimate the modulus of elasticity of a cylinder compressed between two parallel plates. These equations are based on the assumptions of Hertz contact theory and are geared toward the testing of agricultural materials.

$$E = \frac{8F(1-\mu^2)}{\pi D} * Z^2 F \qquad \text{Equation 2-12}$$

Where:

E=apparent modulus of elasticity, Pa

D= average diameter, m

μ=Poisson's ratio

F=compression force per unit length, N/m

Z=R/b which is the ratio of the original radius to half the contact width, m/m

The Z ratio was determined based on the ratio of the total deformation (Δ) to the original diameter from Equation 2-13, using a trial and error method. The ratio of deformation to the original diameter was drawn from experimental data.

$$\frac{\Delta}{D} = \frac{1}{2Z^2}\left[\ln(2Z) + \frac{1}{2}\right] \qquad \text{Equation 2-13}$$

The equation for half the contact width, b, was given by:

$$b^2 = 4RKF \qquad \text{Equation 2-14}$$

Where:

$$K = \frac{1 - \mu^2}{\pi E} \qquad \text{Equation 2-15}$$

Wang, Tabil et al. (2009) examined the apparent modulus of elasticity of timothy stem nodes through uniaxial compression tests. This was to evaluate the suitability of recompressing bales to high pressures in order to disinfest bales from Hessian fly pupa for shipment from Canada to Japan. This study made use of a modified form of Equation 2-12, by using the length of the cylinder (L) and the total force applied to calculate E for the whole sample:

$$E = \frac{8F(1 - \mu^2)}{\pi DL} * Z^2 F \qquad \text{Equation 2-16}$$

This study also determined the maximum contact stress, S_{max} (Pa), using Equation 2-17. The study grouped nodes by position on the plant (top, middle, and bottom) and also by three diameter categories. The apparent modulus of elasticity was higher in high moisture content samples and decreased with increasing node diameter. The maximum contact stress also decreased as the node diameter increased.

$$S_{max} = \frac{2F}{\pi LB} \qquad \text{Equation 2-17}$$

Moiceanu, Voicu et al. (2012) studied the crushing strength and shear stress of miscanthus internode sections. This study utilized 20 mm internode sections between parallel plates, and reported the break and yield force. The materials were crushed at a rate of 50 mm/min. No major conclusions could be drawn from the data because of the large variation in the results. NIKLAS (1998) stated the nodal diaphragms function as spring like joints that store strain energy when the stems flex, and release this energy when bending forces are removed. This research was conducted to examine the plant material's response to bending stress, but it is rational to assume that the same holds true for the material placed under compression.

CHAPTER 3: MATERIALS AND METHODS

3.1 Test material origin and harvest

The switchgrass (Alamo) and Miscanthus (Miscanthus x giganteus) used in these studies were harvested at the University of Kentucky's North Farm, Lexington, KY. The sample material was harvested in late winter 2011 using a disk mower and was laid into swaths with no further processing to preserve the structural integrity of the material. The material was bundled by hand and placed in storage until use.

3.2 Objective 1: Evaluate the feasibility of crushing nodes as a way to increase bale density

The overall goal of this objective was to quantify the change in the bulk deformation characteristics of the crop material that resulted from crushing the plant nodes. This objective was completed through the use of uniaxial compression tests on a universal testing machine (UTM). The feasibility of crushing nodes as a way to increase the bale density was evaluated using two crops, switchgrass (*Panicum virgatum*, Alamo variety) and miscanthus (*Miscanthus giganteus).* The treatment structure for each crop was a factorial with a minimum of three replications. The factors considered were intact material and processed material. The processed material was crushed using sheet metal rollers to completely compromise the node. Each factor was evaluated at two moisture levels. The lower level was the equilibrium moisture content of the material during indoor storage (9-10%), and the higher level was the same material rewetted to 20%; as this moisture content was assumed to be representative of the upper bound for realistic baling operations. A smaller subset of material was harvested prior to plant senescence and was at a naturally high moisture content (approximately 50%). The primary metric developed to evaluate changes in the material's response to compression was the required pressure to reach the ideal transportation density. The material was examined on both a wet and dry density basis.

3.2.1 Processing methods

The material used as 'ideal' processed material was run through sheet metal rollers with the gap between the rollers adjusted to be as narrow as possible and still allow the crop to feed. This gap was approximately 4.76 mm for miscanthus and 1.6 mm for switchgrass. The material was always processed at the low moisture content level.

Figure 3-1: Switchgrass nodes being crushed using sheet metal rollers

The crushing efficiency of the sheet metal rollers was determined by counting three random samples of approximately 100 nodes for each crop. The nodes were classified as cracked, crushed, or intact.

3.2.2 Sample preparation

The processed and control samples were cut into 10 cm (4 inch) particles using a table saw and weighed out into plastic containers. The only exception was the preliminary tests that utilized material cut to 33 cm (13 inch). The lower moisture level consisted of material kept in dry storage and had a moisture content of 8-12%. The higher moisture level was nominally 20% and the samples were rewetted from the dry material. The moisture content of 20% was used since it would represent the upper bound for safe baling operations. For rewetted samples, the average moisture content was determined from 3-5 random grab samples using an Ohaus moisture analyzer (Ohaus Corporation, Parsippany, NJ) and the required amount of water was added to the sample.

Unpublished work by Jackson (2010) showed a strong correlation between the moisture analyzer and the oven dried standard ANSI/ASAE (May2012) (r^2>0.9), therefore this method was deemed sufficient to reduce sample preparation time. The wetted samples were sealed in containers and placed in cold storage for 2-3 weeks to allow the moisture to equilibrate within the stalks. After testing, all rewetted samples were oven dried at 104°C for 24h in accordance with ANSI/ASAE (May2012). Although the sample mass was determined using the moisture analyzer results, the final density reported was based on the oven standard. Low moisture content samples that had been in storage for an extended period showed little variability in moisture, therefore it was considered sufficient to use the moisture analyzer results in the final density calculations.

3.2.3 Test apparatus

The test apparatus consisted of a rigid box and sample container. The apparatus is shown in Figure 3-3 below and in schematic form in the appendix. The box had a door that allowed the sample bin to slide into the compression chamber. The purpose of this was to facilitate quick and easy loading and unloading of samples. The sample bin fit tightly inside the rigid outer frame. The apparatus accommodated a sample of 35.2 cm X 35.2 cm X 25.4 cm (13.88 X 13.88 X 10 inches). The intent was to accommodate the largest sample size possible and the final dimensions were constrained by the test bed dimensions and travel of the UTM. The test apparatus was designed to have negligible deformation at the expected maximum pressure of 345 kPa (50 psi), which is the maximum expected plunger pressure that a baler could produce. The design assumed 100% of the pressure was exerted laterally on the container walls. After preliminary testing, the platen in contact with the bulk material was slightly undersized (34.9 cm X 34.9 cm) to prevent friction and material binding on the sidewall.

3.2.4 Preliminary testing

Preliminary testing was conducted using a SATEC Systems universal testing machine (UTM) model 120 HVL with 530kN (120 kips) capacity (SATEC Systems Inc., Grove City, PA). The data acquisition was performed using Partner™ Universal Materials Testing Software. The compression length was determined by observing the displacement read out and manually switching the machine into neutral once the desired compression was achieved. Because of equipment limitations, only the compression phase and not relaxation was measured in the preliminary tests.

The initial tests conducted utilized material cut to 33 cm, in a consistent manner using a fine tooth table saw or paper cutter to fit into the sample container. Material was oriented by alternate handfuls in a random orientation with the stems placed horizontally to provide consistent results while closely modeling realistic sample orientation. This is similar to a crisscross orientation method used by Talebi, Tabil et al. (2011). This procedure can be seen in Figure 3-2. This method allowed for longer particle length (more nodes) and repeatability, but was not necessarily representative of actual baling.

Figure 3-2: Loading long particles alternating stem to tip

For these initial experiments, a constant starting volume of material was used. The sample container was filled to the top with material and weighed. Based on the mass of the sample and the physical dimensions of the sample container the required compression stroke to reach the target wet density of 256 kg/m^3 was determined. The starting sample mass was inconsistent between tests due to differences in the moisture content and changes in the processed material through the sheet metal rollers which resulted in a higher initial density.

These tests were conducted utilizing the 2X2 factorial discussed below, but due to these tests only achieving the target density on a wet basis, the results can only be compared on the wet density basis. After this point, these experiments are referred to as the long particle length because subsequent experiments utilized shorter randomly oriented particles.

3.2.5 Uniaxial compression test procedure

The preliminary test results were difficult to analyze due to the interaction between wet density and moisture content. It was decided to conduct additional tests using a constant mass of 2.27 kg dry matter, resulting in a variable initial density that ranged from 70-80 dry kg/m^3 for switchgrass and 80-95 dry kg/m^3 for miscanthus. In order to examine changes in the material's bulk deformation characteristics caused by compromising the plant nodes, samples of intact and 'ideal' processed material at various moisture levels were subjected to uniaxial compression inside a rigid container using a SATEC Systems UTM (SATEC Systems Inc., Grove City, PA). This system allowed for a longer compression stroke and computer control of the load stages and rates.

The methods outlined for these experiments were based on the methods shown in previous works by (Watts and Bilanski 1991; Hofstetter and Liu 2011; Talebi, Tabil et al. 2011). The material was cut into 10 cm lengths with a table saw and randomly dropped into the sample container such that the particle orientation was random. Two crops, miscanthus and switchgrass, were used in this study. The effect of node crushing was analyzed with a 2X2 factorial (2X3 for switchgrass) comparing intact and 'ideal' processed material run through sheet metal rollers and different moisture levels. The crop moisture levels examined were: storage equilibrium (8-12%), rewetted from storage equilibrium to 20 % (nominally), and additionally for switchgrass, green high moisture (45-50%) material.

Figure 3-3: Compression chamber and sample bin on SATEC universal testing machine

The tests were conducted in several loading stages. The first stage, pre compression, was only required for switchgrass. An additional loading box (Figure 3-4) was placed on top of the compression chamber to pre compress the sample to the top of the rigid container. Due to the low bulk density of loose switchgrass, this step was necessary to keep the mass of the sample consistent between crops and to increase the final sample height, reducing edge effects. The pre-compression was completed manually raising the hydraulic ram until the bottom of the platen was level with the top of the rigid container. The level was measured using a standard tape measure, and the readings were taken consistently from the same location on the sample container to a steel square extended from the top of the platen. It was assumed the bulk material would behave similarly to dry soil when subjected to loading and unloading (in this case not necessarily unloading, but stress relaxation), which follows essentially the same stress strain curve once the stress becomes greater than the maximum stress from the initial loading (Lambe and Whitman 1969).

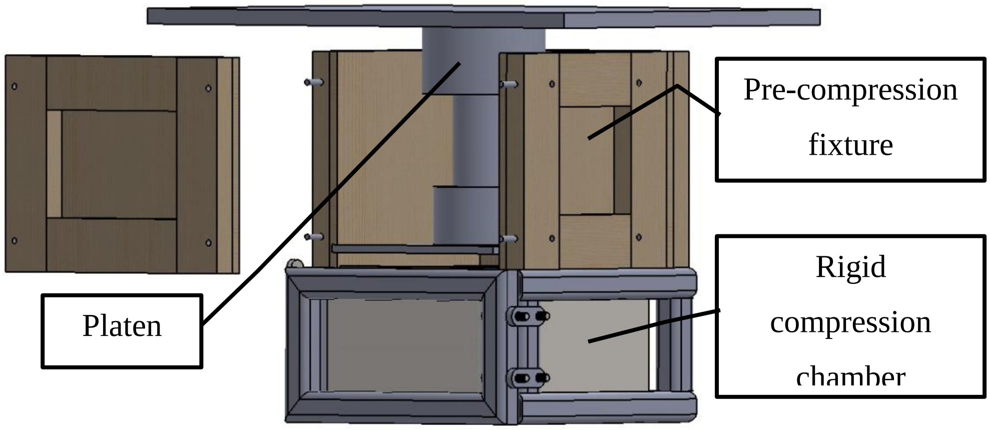


Figure 3-4 Schematic form of the pre-compression fixture used to compress the sample to the starting height (25.4 cm), after initial compression the upper portion was removed and platen readjusted

Once the pre-compression chamber was removed and the platen readjusted, the second stage was the compression phase where the material was compressed from 25.4 cm to 7.1 cm. This distance resulted in a final dry bulk density of 256 kg/m^3 throughout the sample. Previous work has shown the pressure required to produce a bale of a certain density varied with compression speed (Kaliyan 2008; Hofstetter and Liu 2011). It was not feasible to use a compression rate high enough to approach what would be seen in an actual baling operation; therefore a loading rate of 1.5 mm/s (3.54 in/min) was used. This is consistent with what was reported by Talebi, Tabil et al. (2011). The final stage of testing examined force relaxation in the material after the target density was achieved. To ensure accurate readings and prevent pressure bleed off in the UTM's hydraulics the loading rate was set extremely slow 0.025 mm/h (0.001 in/hr). This ensures that a constant displacement could be assumed over the duration of the test. The rebounding force produced by the sample was measured for a period of 5 minutes. This time frame was chosen to capture the period where the relaxation was most pronounced based on data from Watts and Bilanski (1991). Figure 3-5 shows the measured force plotted against time for a typical experiment and the point where the loading rate changed is visible.

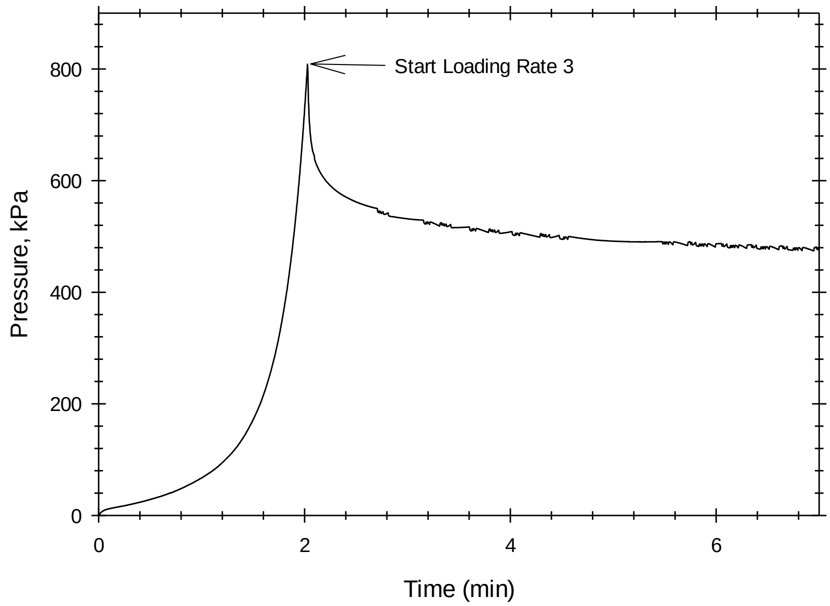


Figure 3-5 Example compression test data using crop at a moisture content of 10%.

3.2.6 Calculation of wet density and dry density

In order to make real world comparisons of the effectiveness of node crushing it was desirable to make comparisons based on the wet weight of the bale because this weight and density determines potential transportation savings. However, this was not the ideal case when the effect of additional moisture on the material's behavior in compression was examined. The addition of water, with its comparatively high density, inflates the bulk density which causes difficulty in statistical analysis. For this reason, the test parameters compressed the material to a target dry density of 256 kg/m^3 that would guarantee a wet density greater than 256 kg/m^3. The two methods of calculating density are given below:

$$wet\ bulk\ density = \frac{wet\ weight}{Volume} \qquad \text{Equation 3-1}$$

$$dry\ bulk\ density = \frac{wet\ weight\ * (1 - MC)}{Volume} \qquad \text{Equation 3-2}$$

Where: wet weight = mass of the material, kg

Volume = volume in the container under the platen, m^3

MC = wet basis moisture content, in decimal

The moisture content used to weigh out each sample before testing was determined by averaging 3-6 moisture contents for each sample as determined using an Ohaus moisture analyzer. For the higher moisture level samples, the entire sample was oven dried to determine a more accurate moisture content, and the dry bulk density in the pressure density curves was adjusted accordingly.

Two moisture levels, 10% and 20% nominally were evaluated in the study. The lower moisture content ranged from 8-12%, and was the equilibrium MC of the material stored in the lab. A higher moisture content of 20% was obtained by rewetting the dry material. Additional tests were run for switchgrass using green high moisture material that ranged from 45-50% moisture.

3.2.7 Data analysis

The data collected was organized and processed using a combination of Microsoft Excel (Microsoft Excel 2010, Microsoft Corporation, Redmond, WA) and MATLAB (MATLAB2010a, The MathWorks Inc. Natick, MA), while the statistical analysis was performed using the GLM procedure available within SAS (SAS 9.3, SAS Institute Inc. Cary, NC). There were several metrics that were easily obtainable from the uniaxial compression tests, which allowed conclusions to be drawn about the effectiveness of compromising the plant node. The mean pressure required to reach the target density and standard deviation were determined for the two crops, two treatments, and moisture content combinations. Each crop was examined separately as a 2X2 factorial (material treatment and moisture content) for significant differences (α=0.05) in the required pressure to reach the target density. Additionally, a separate analysis was conducted for the initial experiments using a constant starting volume and longer particle length, denoted in the remainder of the text as long or long particle tests. The analysis was preformed based on both wet and dry bulk density. In cases where there was significant interaction between the treatment and moisture content, main effects of each were examined using Tukey's HSD test. This method was chosen over the LSD or Bonferroni adjustment to provide more conservative results and reduce type I error.

3.3 Objective 2: Modeling the behavior of compressed bulk material

The overall goal of objective 2 was to apply existing models for compression of forage materials to switchgrass and miscanthus, evaluate the application to processed material, and model the pressure relaxation over time as the material is held constrained at a final density.

3.3.1 Modeling the pressure density relationship

The data from the compression phase of the uniaxial compression tests was fitted to the power model, the models developed by Faborode and O'Callaghan (1986) and Pitt and Gebremedhin (1989) discussed in the literature review in Equation 2-2, Equation 2-3, and Equation 2-6. New constants for the models were found using the nonlinear regression function (nlinfit) in MATLAB. The data was analyzed by crop and treatment. The moisture levels were handled by fitting all of the repetitions as one data set, and again by separating out the moisture levels. For each fit, the predicted value was graphed against the observed values and the correlation coefficients; F-Statistic, RSME, and Akaike's Information Criterion (AIC) were computed. The F statistic, however, was of no use in comparing the models because the models were not nested. Motulsky (2004) recommended using the AIC value to compare non- nested models. This statistic is based on information theory, and accounts for how well the model fits as well as the number of regression parameters. AIC can be calculated from Equation 3-3 where N is the number of data points, SS is the sum of squares and K is the number of regression parameters. The AIC value in this study was calculated using the AIC function in MATLAB. The model with the smallest AIC value has a higher probability of being correct.

$$AIC = N * ln\frac{SS}{N} + 2K \qquad \text{Equation 3-3}$$

3.3.2 Modeling the stress relaxation behavior

As discussed previously, once bulk samples reached the target density, the displacement was held constant and the stress relaxation was measured for a period of five minutes. Due to the fact that viscoelastic materials often exhibit nonlinear behavior when subjected to large deformations, and due to the difficulty that arises when measuring mechanical properties of biological materials, the data was represented as a normalized stress fit to Equation 2-9 based on the recommendations in (Peleg 1980; Steffe 1996). The regression coefficients k_1 and k_2 were fit for each crop based on treatment, moisture content, and treatments combined by moisture content; as this represented the best grouping of the data.

3.4 Objective 3 Individual node compression tests

The overall goal of objective 3 was to examine the strength of individual nodes to gain insight geared towards the future development of a system to crush nodes. Biomechanical properties including force at the bioyield point, apparent modulus of elasticity, and maximum contact stress were determined for node and internode sections of switchgrass and miscanthus via radial compression between parallel plates on an UTM.

3.4.1 Test procedure

The individual plant nodes were separated from the stem using a fine tooth saw blade (hacksaw blade). The cut locations for the nodes were determined by visually identifying where the node ends based on changes in diameter and color. The internode specimens were cut consistently at 10.16 cm to mirror the particle size used in the bulk compression tests. Descriptive measurements of the whole stem were taken including internode lengths and diameters, which were recorded prior to the separation of the node. Two measurements, taken 90 degrees apart, were taken to determine the average node diameter, and the average length was also recorded. All sample length and diameter measurements were taken using digital calipers (accuracy ±0.025mm). The material properties vary along the length of the stem, therefore, the location of each plant node was recorded. The internode samples used were taken from random locations along the stalk. The samples were tested at lab equilibrium moisture (average of 8.1% for switchgrass and 8.5% MC for miscanthus). The average temperature and relative humidity during testing was 23.9°C and 49%, respectively.

ASAE/ASABE (2000), which provides the standard for evaluating convex shaped food materials subject to uniaxial compression between parallel plates calls for a minimum of twenty samples to be tested to overcome variations in size, shape, and structure. There were 117 and 101 node samples tested for miscanthus and switchgrass, respectively, and 20 internode samples were also tested for each crop.
The individual node radial compressions tests utilized an Instron UTM model 8800R with a 5 kN load cell (Instron Industrial Products, Grove City, PA). The UTM and parallel plate set up is shown in Figure 3-6.

Figure 3-6: UTM fitted with parallel plates used in objective 3

The tests were conducted using a loading rate of 1 mm/minute; this was chosen in agreement with the loading rate reported by Wang, Tabil et al. (2009) (1 mm/min) and ASAE/ASABE (2000) which specifies a loading rate of 1.25 mm/min ±50% for seeds and grains. A loading rate of 100 mm/min (1.67 mm/s) was used by Liu, Mathanker et al. (2012) and 5 mm/min was used by Moiceanu, Voicu et al. (2012) who examined force deformation curves of miscanthus internodes. The samples were compressed to 650 N, which surpassed the failure point of all samples.

3.4.2 Data analysis

The data was processed and characteristic force deformation curves were generated for each sample using MATLAB. The bioyield point is defined in ASAE/ASABE (2000) as the point where an increase in displacement resulted in no increase or a decrease in load. Figure 3-7 below shows a representative force deformation curve for miscanthus. Miscanthus failed in a manner that was easily identified, which can be seen by examination of Figure 3-8. The bioyield and rupture was not as easily identified in switchgrass.

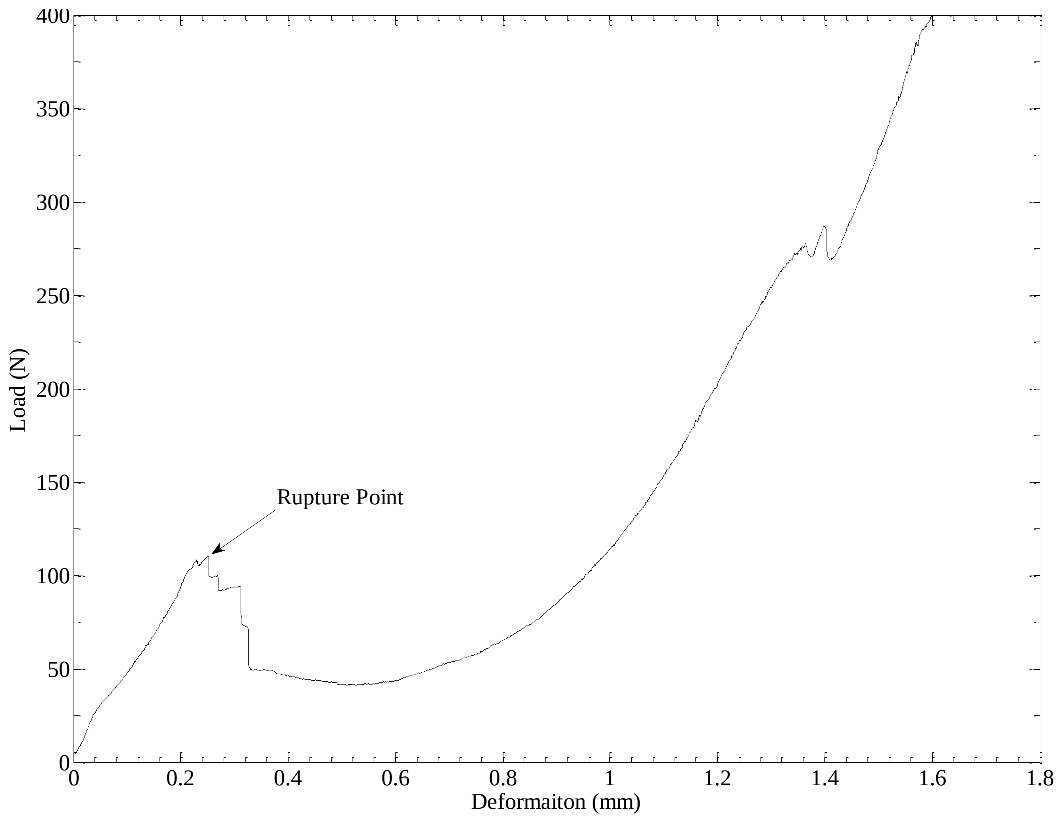


Figure 3-7 Example compression curve for miscanthus nodes

The bioyield point was found using logical indexing in MATLAB to find the location where the force between data points decreased by a threshold value. This was done to overcome noise in the data and provide consistent identification of the bioyield point. The point identified by the program was visually confirmed for each sample. A threshold value of 0.5 N was deemed to provide the most suitable results.

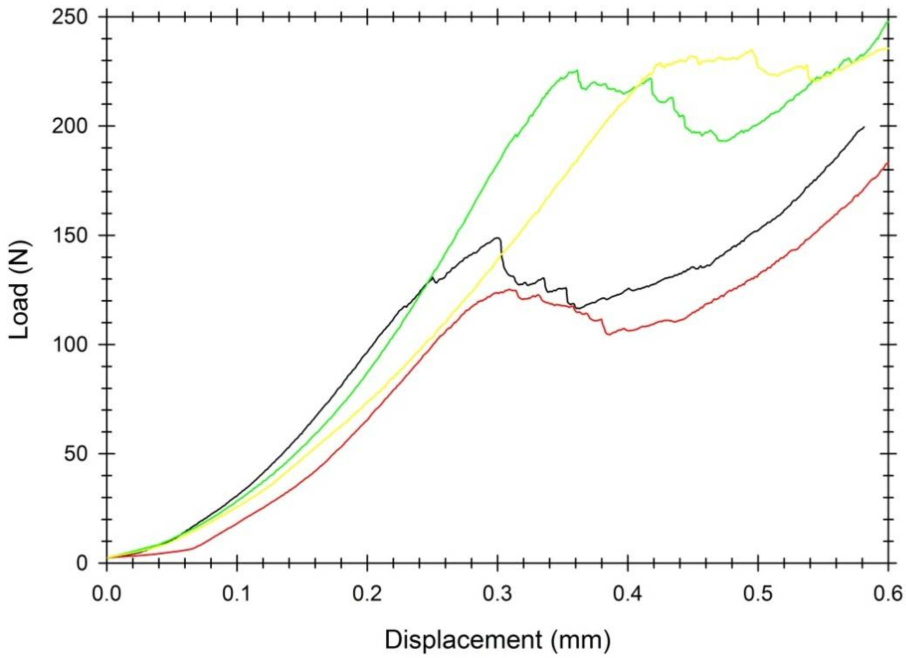


Figure 3-8 Example compression curves for switchgrass nodes, showing varied behavior at failure.

ASAE/ASABE (2000) states the apparent modulus of elasticity should only be calculated for deformations below the inflection point on the force deformation curve. This is because the changing slope represents the beginning of failure. Once the bioyield point was identified, the data was trimmed below this value and a third order polynomial was fit to the data to find the inflection point. Many of the samples appeared linear or had no distinct inflection point over the range in question, but the higher order fit was used for consistency. A third order fit was used because it gave a high correlation and was the lowest order polynomial that had an inflection point. At this point, the data was trimmed again and the Z value was found from Equation 2-13 using the fsolve function in MATLAB. The value used for μ was assumed to be 0.40 (Wang, Tabil et al. 2009). Figure 3-9 shows a graphical representation of this process. From this E was found using Equation 2-12. This was done for each point below the inflection point and the average was taken. The maximum contact stress was then found at the point of failure using Equation 2-17.

Multiple pairwise t-tests were performed to test the null hypothesis, that the means of E and Smax were the same between each node location and between each node position and the internode samples. This was accomplished using proc glm and lsmeans in SAS9.3 to compute the p value for each pair (α=0.05). The lsmeans procedure was used as opposed to the means procedure to account for the fact that not each plant had the same number of nodes, which caused the data set to not be balanced.

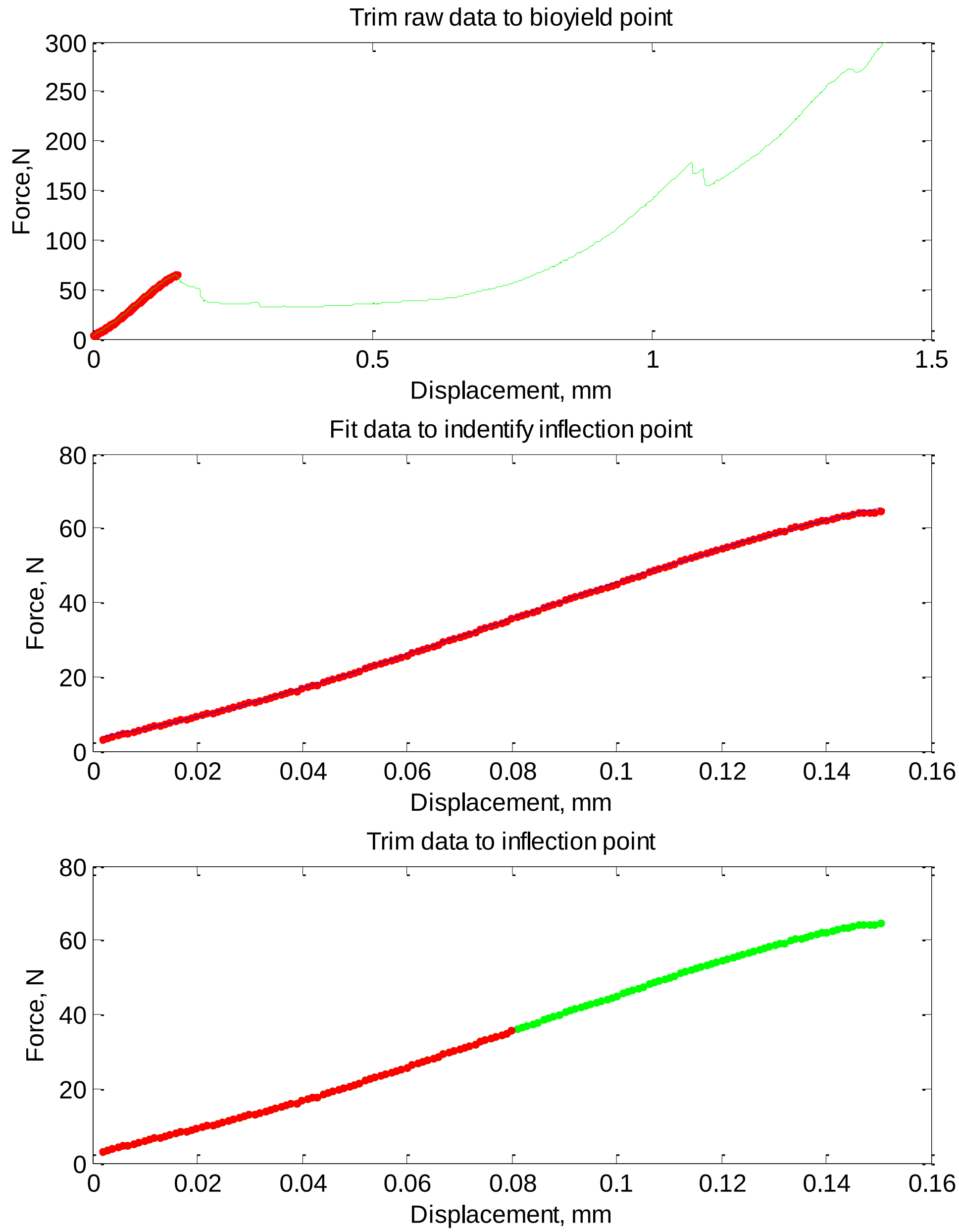


Figure 3-9: Graphical example of how the data was trimmed to determine the apparent modulus of elasticity

CHAPTER 4: RESULTS AND DISCUSSION

4.1 Objective 1: Bulk compression results

4.1.1 Overview

The results from the uniaxial bulk compression tests are presented in several sections, each addressing a separate aspect of the results. The mean pressure required to achieve a dry and wet density of 256 kg/m^3 at each moisture level for switchgrass and miscanthus were measured. The results are summarized in Figure 4-1 and Figure 4-2. The results for each individual test are found in Table A-3 and Table A-4. The results were analyzed based on both a wet and dry bulk density basis. Wet density was used to examine practical differences that would directly impact the mass of material loaded on a truck, and dry bulk density was used to examine changes in the material's behavior due to moisture.

4.1.2 Material processing efficiency

Nodes classified as cracked showed circumferential cracks and were more commonly found in switchgrass. Crushed nodes showed cracks running longitudinally through the nodes and internodes. The crushing efficiency was defined as the percentage of nodes damaged by the rollers, i.e. the combination of crushed and cracked nodes. The average crushing efficiency was 80% and 91% for switchgrass and Miscanthus, respectively.

4.1.3 Combined effect of moisture content and processing

The distribution of the pressure at the target density for each treatment and moisture level combination can be seen in Figure 4-1 for miscanthus and in Figure 4-2 for switchgrass. The figures include both the pressure requirement for both wet and dry bulk density, and the error bars represent the standard deviation. The interaction between moisture content and treatment was significant (α=0.05), for both crops using both wet and dry density. Due to this, subsequent discussion of the significance for moisture level and treatment were determined using the main effects examined via Tukey's HSD test for multiple pairwise comparisons.

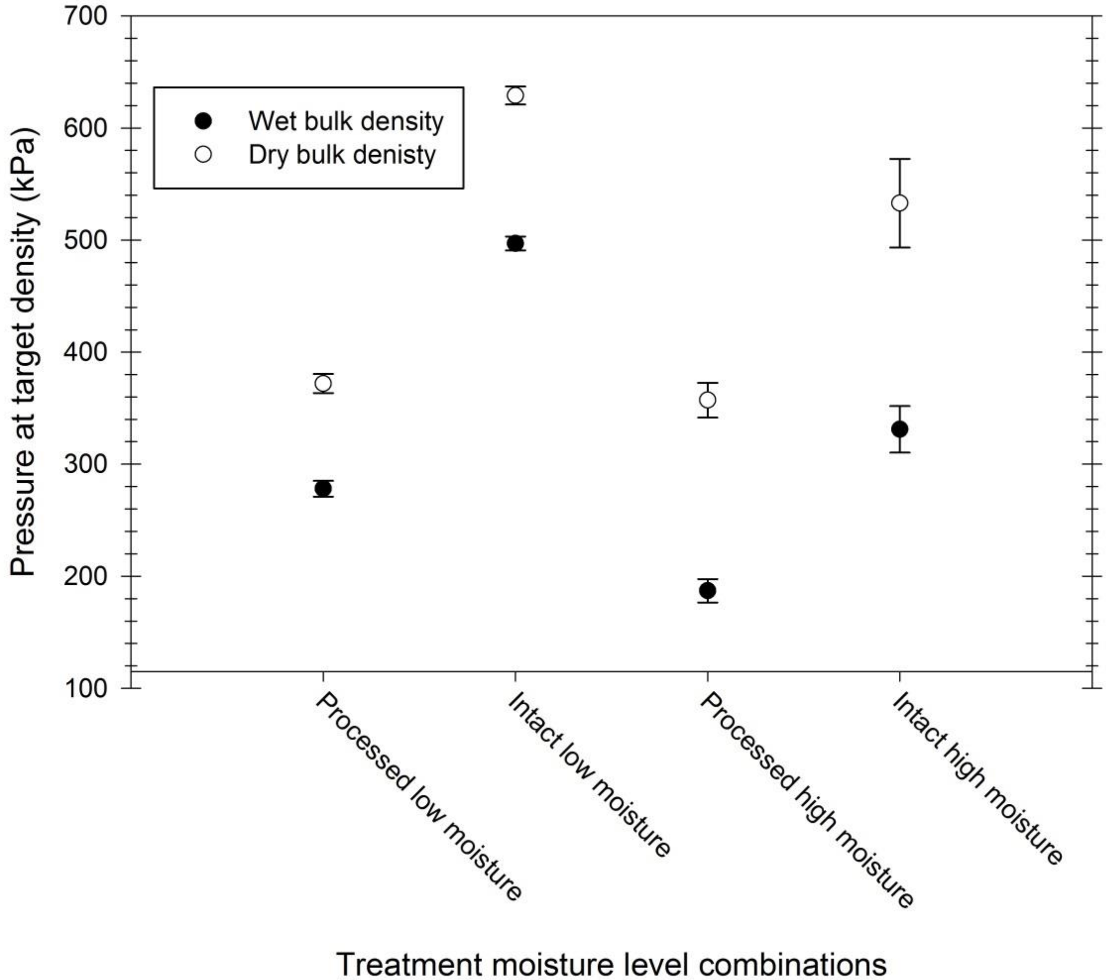


Figure 4-1 Distribution of required pressure to achieve 256 kg/m^3 for miscanthus, separated by treatment and moisture level combinations. Error bars are the standard deviation.

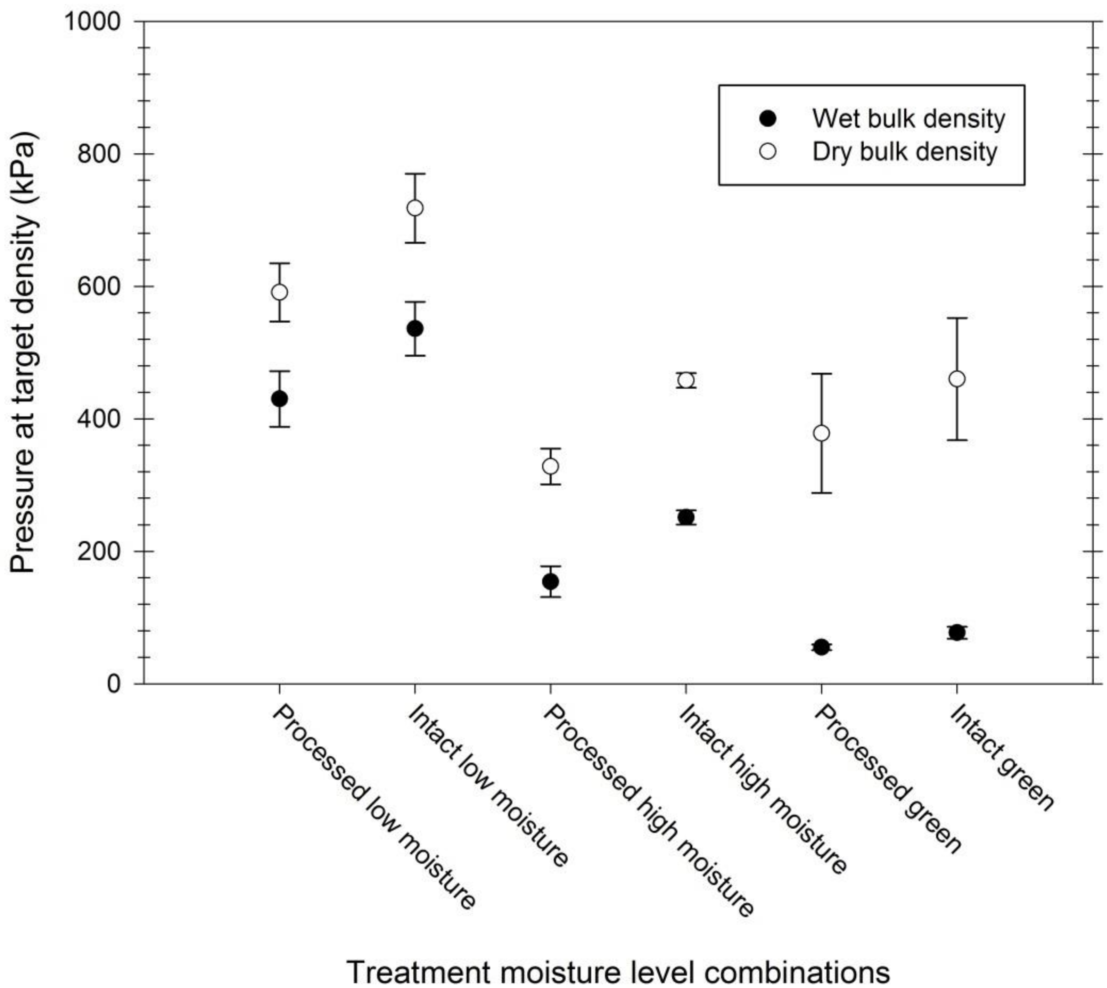


Figure 4-2 Distribution of required pressure to achieve 256 kg/m^3 for switchgrass, separated by treatment and moisture level combinations

4.1.4 Effects of processing the bulk material

The required pressure to achieve the target density across all moisture levels can be seen in Figure 4-3and Figure 4-4. For miscanthus, based on wet bulk density, the overall mean pressure to the target density was 414 kPa and 233 kPa for intact and processed material respectively for dry density these values change to 581kPa and 365 kPa. This represents a 44% and 37% reduction in pressure to reach the desired wet and dry bulk density respectively. Tukey's HSD test showed the effect of processing was significant for both the wet and dry bulk density.

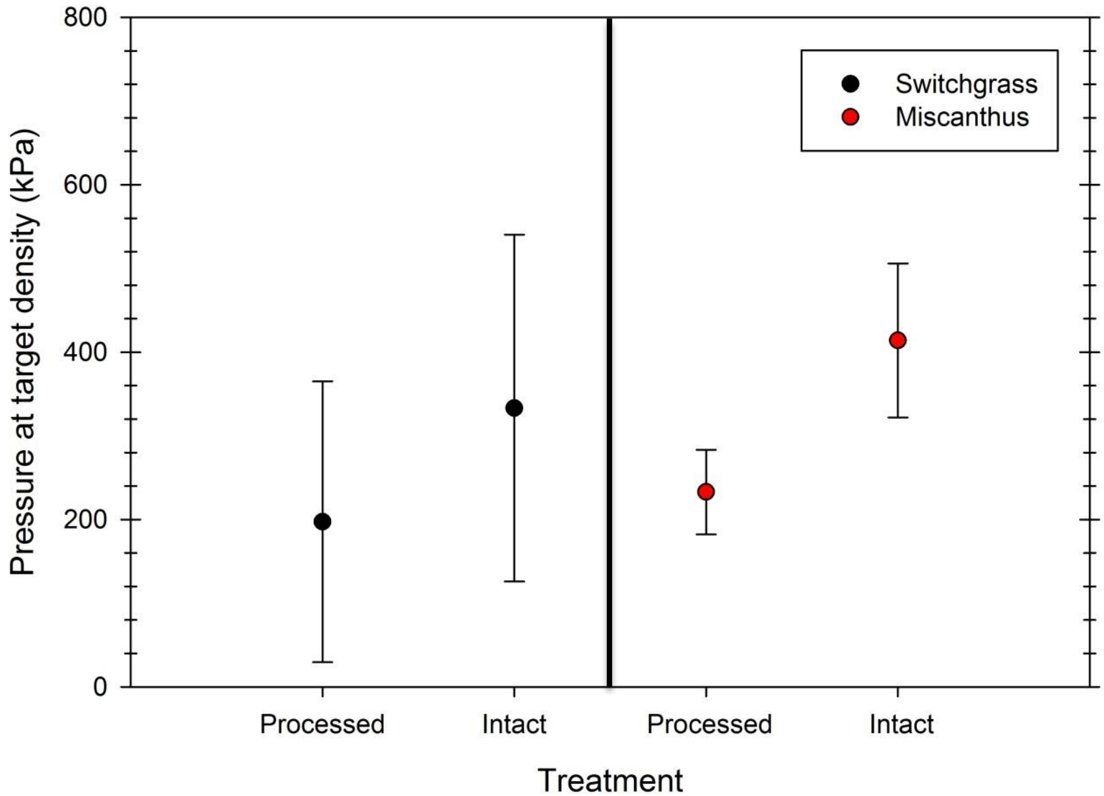


Figure 4-3 Effect of processing on the variation of required compression pressure to reach 256 kg/m^3 wet bulk density. Data points are the averages of all moisture contents for a given treatment, error bars are standard deviation

For switchgrass, the mean pressure required to reach the target wet density was 333 kPa and 197 kPa for intact and processed material, respectively. When evaluated on a dry bulk density basis, the mean pressure to reach the desired density was 577 kPa and 441 kPa for intact and processed material. Processing the material resulted in a 40.8% decrease in the required pressure to reach the target wet bulk density and a 23.6% decrease to achieve the target dry bulk density. The Tukey groupings showed significant difference between treatments for both wet and dry density.

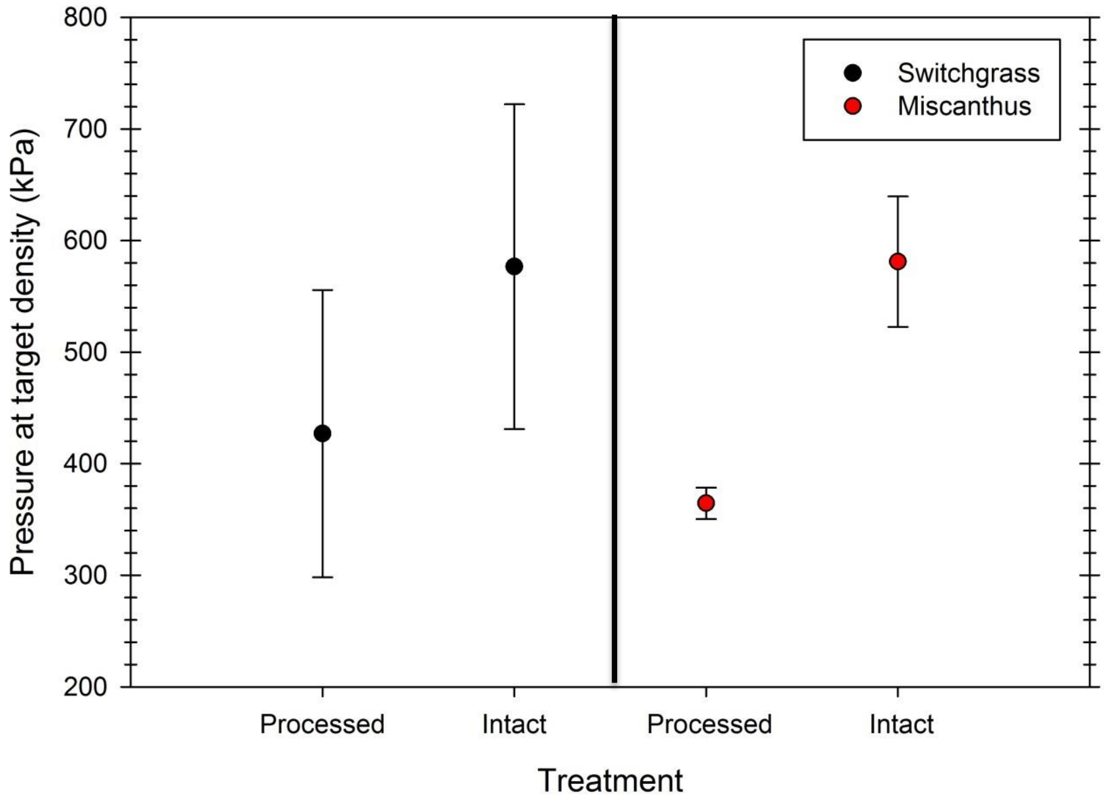


Figure 4-4 Effect of processing on the variation of required compression pressure to reach 256 kg/m^3 dry bulk density. Data points are the averages of all moisture contents for a given treatment, error bars are standard deviation

The reduction in pressure by processing the material was most likely achieved through a combination of reduced void space in the bulk material and changes in the processed materials ability to resist deformation; although there was no clear way to quantify how each factor contributed to the reduction in required pressure. Furthermore, there was no quantification of the effect of processing the plant node versus internode sections. The entire plant was processed using sheet metal rollers that compromised the node and internode sections.

From a practical perspective, this pressure decrease is indicative of the potential density gains that could result from processed material being baled at a higher density setting. This is possible because the viscous and elastic forces the plunger must overcome are reduced in the processed material, thereby allowing the lateral convergence to be increased.

Placed in the context of Equation 2-1, which represents the materials resistance to flow through the baler, and thus controls the bale density, the processed material may not achieve density gains from the reduction in pressure if baled at the same density setting as non-processed material. This is because a portion of the compressive force is exerted laterally against the converging section of the baler, contributing to the resistance to flow. It would be necessary to increase the convergence enough to overcome the reduction in convergence force that results from plausible reductions in the material's apparent modulus of elasticity, before appreciable density gains could be achieved. It is preferable to generate Fc by increased convergence because the elastic component acts against the strings once the bale is ejected, and it has been noted that this expansion force can cause strings to fail at high densities (200 kg/m^3 for switchgrass Kemmerer and Jude (2010)).

4.1.5 Effects of moisture content

Increasing moisture content had the effect of reducing pressure required to reach the target wet and dry density. The decrease in required pressure on a wet bulk density basis from the addition of water was expected due to the water's much higher density. As such, this phenomenon is of little significance, and further discussion was based on the reduction in pressure as it relates to dry bulk density.

The effect of moisture level on the required pressure can be seen in Figure 4-5, when the processed and unprocessed switchgrass and miscanthus were combined. The mean required pressure for switchgrass was 671kPa, 393kPa, and 413 kPa for low moisture, high moisture, and green high moisture, respectively. The Tukey's HSD groupings showed all comparisons were significant except for the high moisture samples compared to the green samples. The green cut high moisture samples were well above any practical moisture content encountered during actual harvest, but the not significant difference between the high moisture level and the green cut high moisture sample provided useful insights. The result provided an indication that rewetted samples behave similarly to naturally wet material, and the addition of moisture only influences the behavior up to a point.

The effect of moisture content was also significant for miscanthus, with a mean pressure required to reach the target dry bulk density of 501 kPa for low moisture samples and 445 kPa for high moisture samples. The low and high moisture miscanthus samples were not significantly different. The large standard deviations observed were due to grouping the processed and intact samples together by moisture level.

Conflicting data regarding the effect of moisture on the compaction of biological materials has been reported in literature. The decreased pressure requirement observed in this study was consistent with previous research that found the addition of moisture content reduced the tensile strength, bending stress, elastic modulus, and modulus of rigidity of individual plants (Nazari Galedar, Jafari et al. 2008; Tavakoli, Mohtasebi et al. 2009). This was also consistent with Talebi, Tabil et al. (2011) who found less pressure was required for high moisture timothy hay samples to reach the same density. However, this contradicts Srivastava, Goering et al. (1993) who developed Equation 2-1 as it relates to baler density control, indicated that additional moisture increases the apparent modulus of elasticity of the bulk material and that would require higher compression pressures and increase bale density.

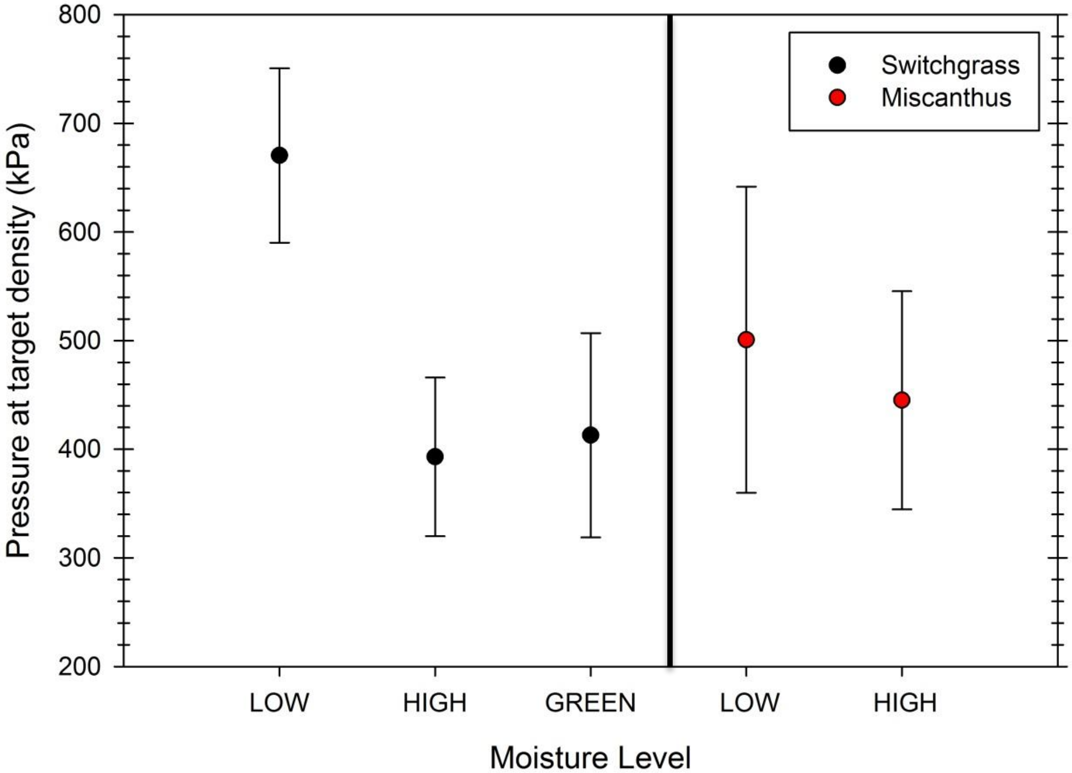


Figure 4-5 Effect of moisture content on the variation of required compression pressure to reach 256 kg/m^3 dry bulk density. Data points are the averages of processed and intact material.

4.1.6 Characteristic pressure density curves

The ideal response of the material to compression can be seen in Figure 4-6 for low moisture miscanthus in the processed and unprocessed state. There was a distinct difference between the treatments, with the pressure increasing at a faster rate for intact material. Figure 4-7 shows the response for low moisture switchgrass, which does not exhibit as clear of a distinction between the intact and processed samples, but all of the curves for intact material are above the processed material. These figures are based on wet density, which showed a larger distinction. Additional figures based on dry density and for the higher moisture content samples can be found in the appendix. The variation of these slopes is discussed in detail in section 4.2.

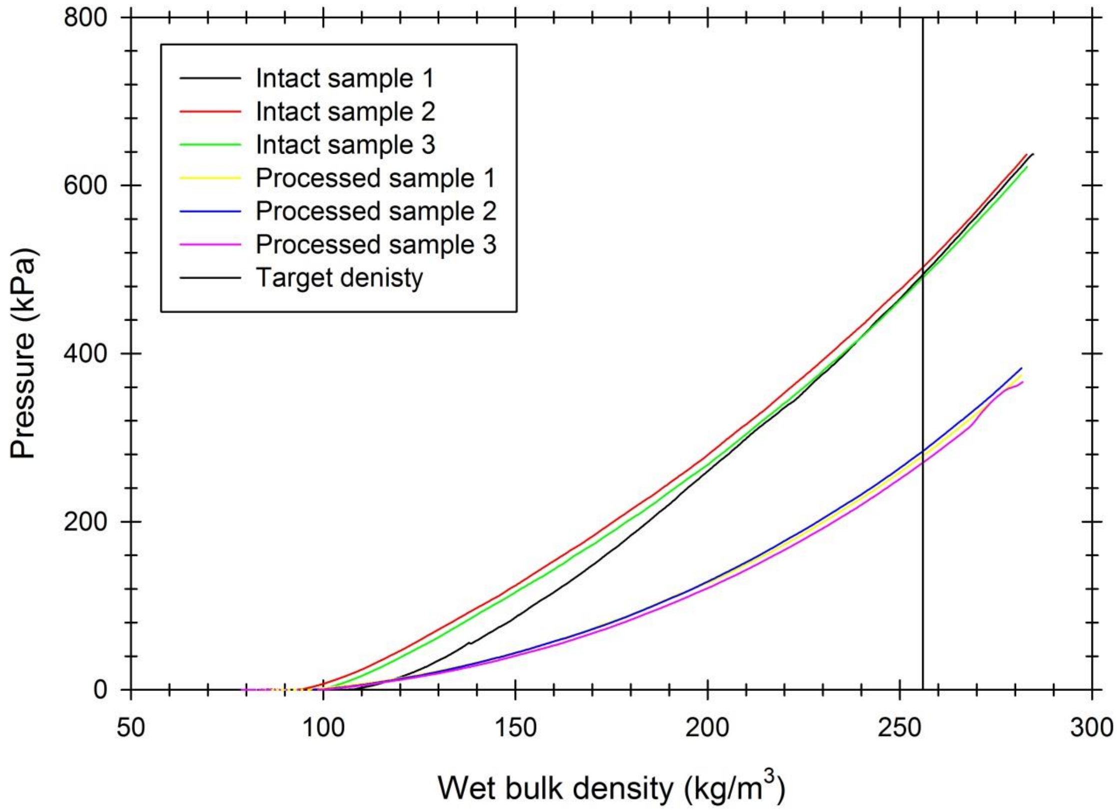


Figure 4-6 Pressure density relationship, based on wet sample weight, for low moisture miscanthus subject to uniaxial compression

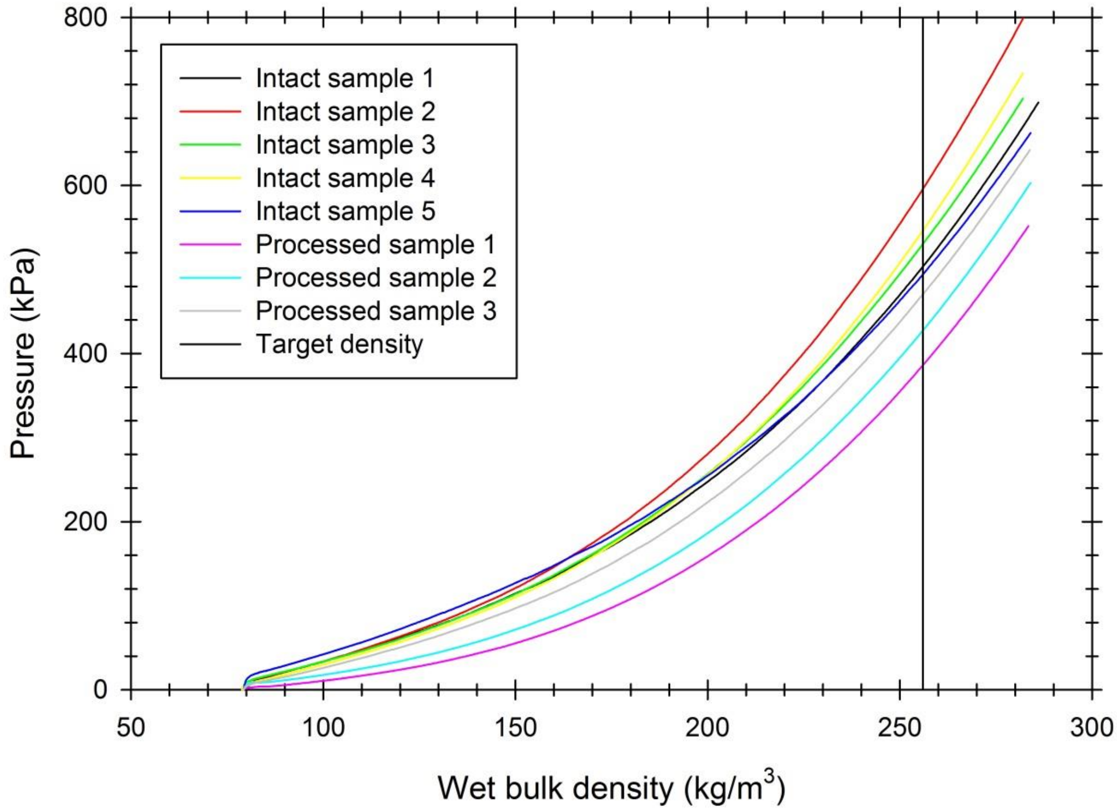


Figure 4-7 Pressure density relationship, based on wet sample weight, for low moisture switchgrass subject to uniaxial compression

4.1.7 Results from preliminary tests using long particles

The initial experiments that utilized particles cut to the length of the sample container (33 cm) served as the basis to develop the methodologies for the later experiments. These results were only discussed briefly as the data supported the conclusions from the experiments was already discussed. These experiments were conducted using a constant starting volume as opposed to the constant initial dry matter used in the later tests. This was done in attempt to model what would be seen in an actual baler; where the stuffer fills up and then feeds the charge into the bale chamber. The testing only considered compressing the material past the ideal wet bulk density. Additionally, the higher moisture level for these samples was 40% nominally.

Despite the difference in sample configuration, these experiments displayed a similar trend to the later experiments. The results are shown in Figure 4-8 for miscanthus and Figure 4-9 for switchgrass.

For the low moisture level switchgrass, the mean required pressure to achieve the target wet bulk density was reduced by 28.6% by processing the material. The mean pressure was 373 kPa with a standard deviation of 41 kPa for intact samples and 266 kPa with a standard deviation of 7.9 kPa for processed. At a moisture level of 40%, a more modest decrease of 15.8% with processing the material was observed. At a moisture level of 40%, intact samples required a mean pressure of 78.9 kPa with a standard deviation of 8.4 kPa; while processed material had a mean of 66.4 kPa with a standard deviation of 5.1 kPa.

Large reductions in pressure were achieved for miscanthus by processing the material. The low moisture level had a 65.5% reduction in the mean pressure required to reach the target density with processing. The intact material required 245 kPa with a standard deviation of 28.2 kPa, while the processed material required a mean pressure of 86.6 kPa with a standard deviation of 16.3 kPa. At a moisture content of 40%, a 79% reduction in the required pressure to reach the target density was achieved by processing. Intact samples required a mean pressure of 73.9 kPa with a standard deviation of 16 kPa and the processed material required 15.5 kPa with a standard deviation of 5.1 kPa. These extremely large reductions in the required pressure are a reflection of the higher initial bulk density with the processed material. This, combined with the fact that the experiments were run with a consistent starting volume, lead to very little compression being necessary to reach the target density, especially for the samples at a moisture content of 40% w.b. that would be at a level higher than experienced during real baling operation.

With both particle sizes, processing the material resulted in a lower pressure required to reach the desired density. However, with long particles (33 cm) packed in an orderly manner, processing the material did not have as great of an effect on lowering the required pressure compared to the smaller particles randomly oriented. This could have been due to a number of reasons. The initial density with the larger particles varied between treatments. In addition, ordering the particles when filling the container likely would have resulted in different material properties within the test box.

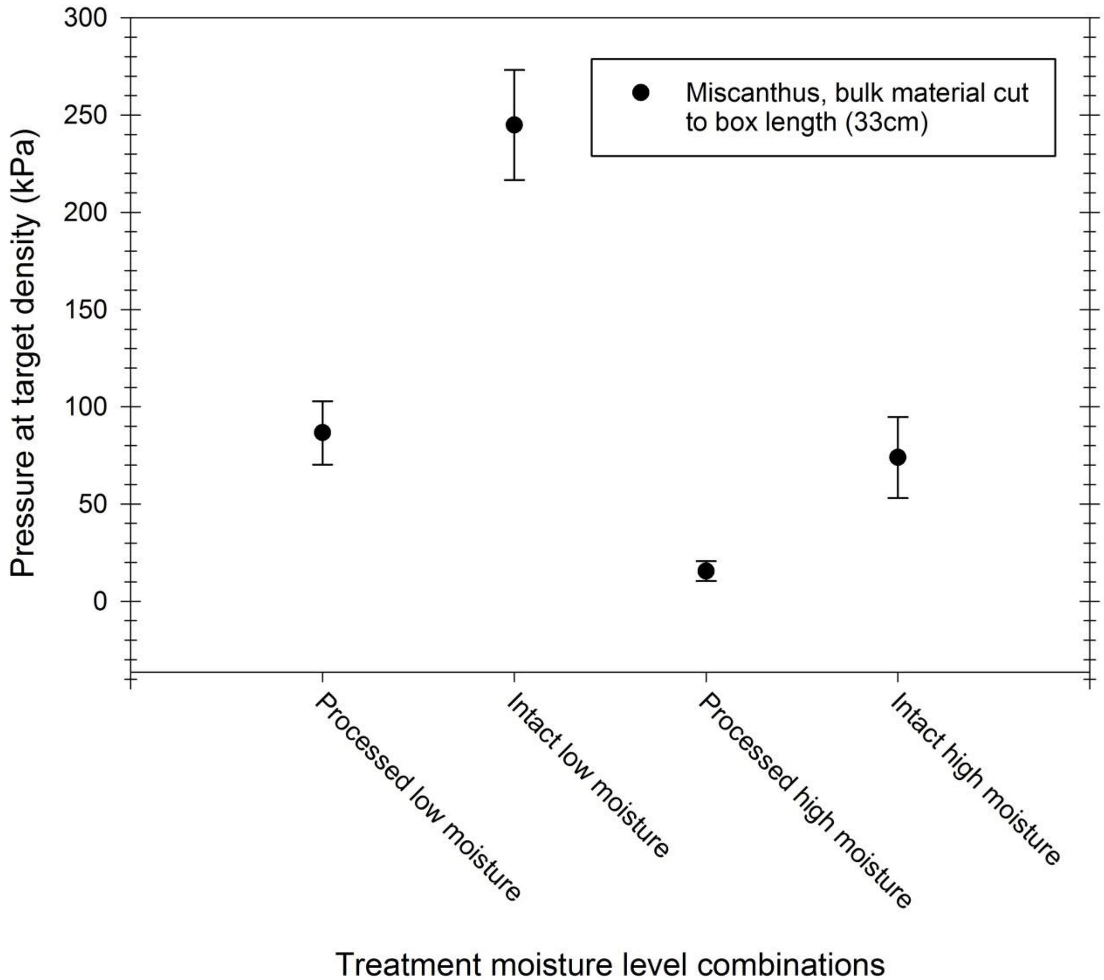


Figure 4-8: Distribution of required pressure to achieve 256 kg/m^3 found from initial tests using particles the full length of the sample container, and a constant initial volume for miscanthus.

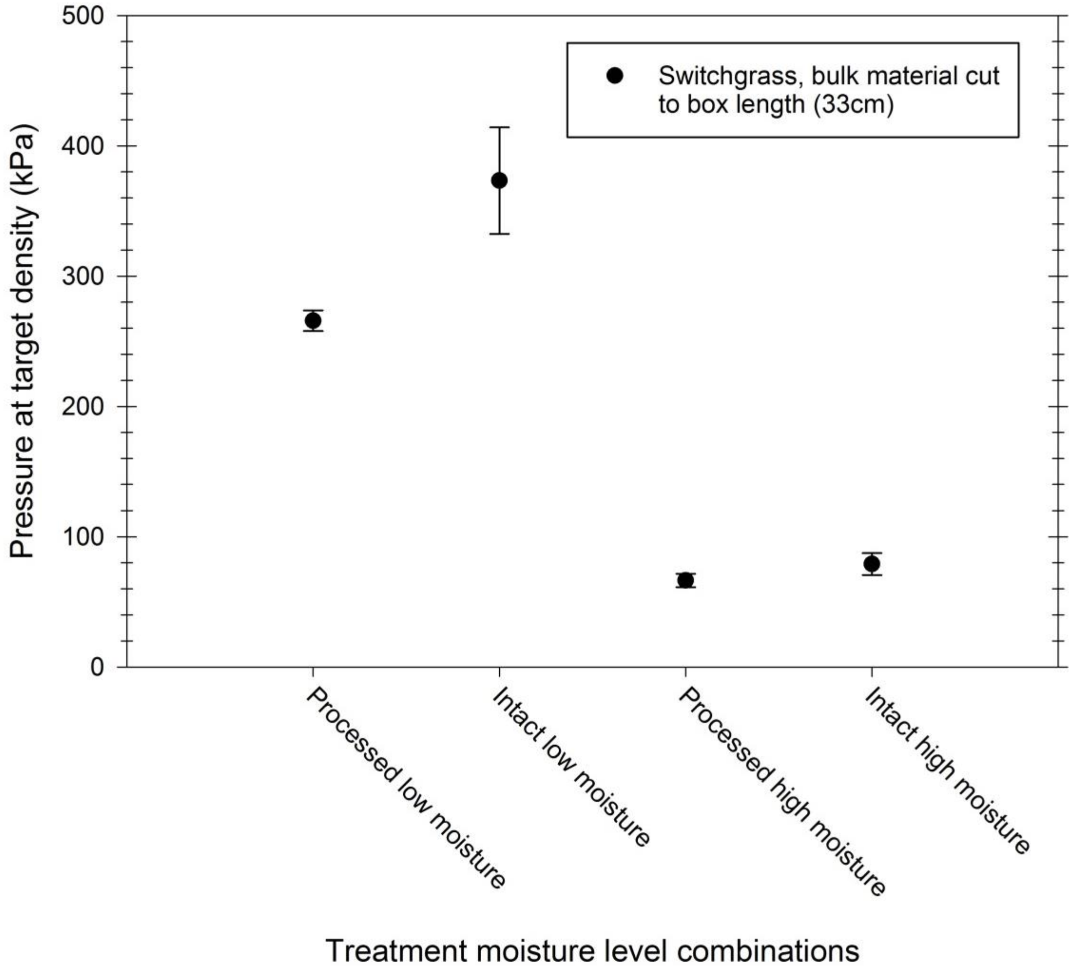


Figure 4-9: Distribution of required pressure to achieve 256 kg/m^3 found from initial tests using particles the full length of the sample container, and a constant initial volume for switchgrass.

*High moisture content for initial testing was 40%.

4.1.8 Pressure relaxation under constant displacement

The pressure relaxation of the material was measured against time in the final stage of the experiments. As expected in viscoelastic materials, the pressure leveled off asymptotically as time increased. Figure 4-10 exemplifies the difference in the pressure relaxation between intact and processed materials. The pressure relaxation data for all crop and moisture content combinations can be found in Figure A-11 to Figure A-15.

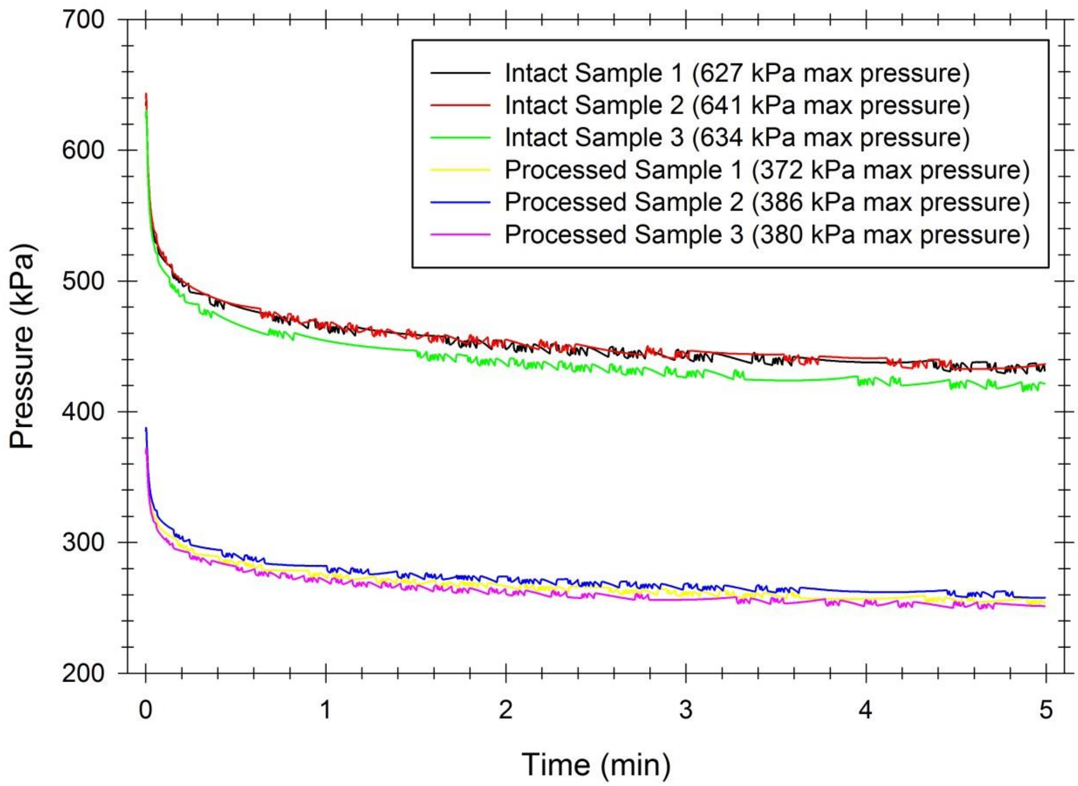


Figure 4-10 Pressure Relaxation for intact and processed low moisture miscanthus with a constant displacement of 0.025 mm/h.

The percent relaxation after a period of 5 minutes was determined for all crop moisture content combinations. Low moisture intact miscanthus had a mean relaxation percentage of 33.1%, and the processed material had a comparable relaxation of 33.3%. The high moisture level samples displayed a similar trend between treatments and relaxed 43.7% and 45.3% for intact and processed samples, respectively. The same can be said for low moisture switchgrass, with means of 40.0% and 38.1% for intact and processed material. High moisture switchgrass displayed the greatest difference with 45.4% and 50.0% relaxation.

The trend appears to be that the percent relaxation was more influenced by moisture content and the treatment had little effect on the percentage relaxation, however, in every case the final pressure was lower for the processed samples. This can be seen in Figure 4-11 and Figure 4-12.

The increase in percent relaxation with higher moisture values was consistent with O'Dogherty and Wheeler (1984) and even though the hay samples in that study were compressed using pressures an order of magnitude higher than this study, the percentages found for switchgrass and miscanthus are within the range observed. Due to the fact that relaxation is partially dependent on the final compression pressure, the normalized relaxation behavior was examined in section 4.2.6

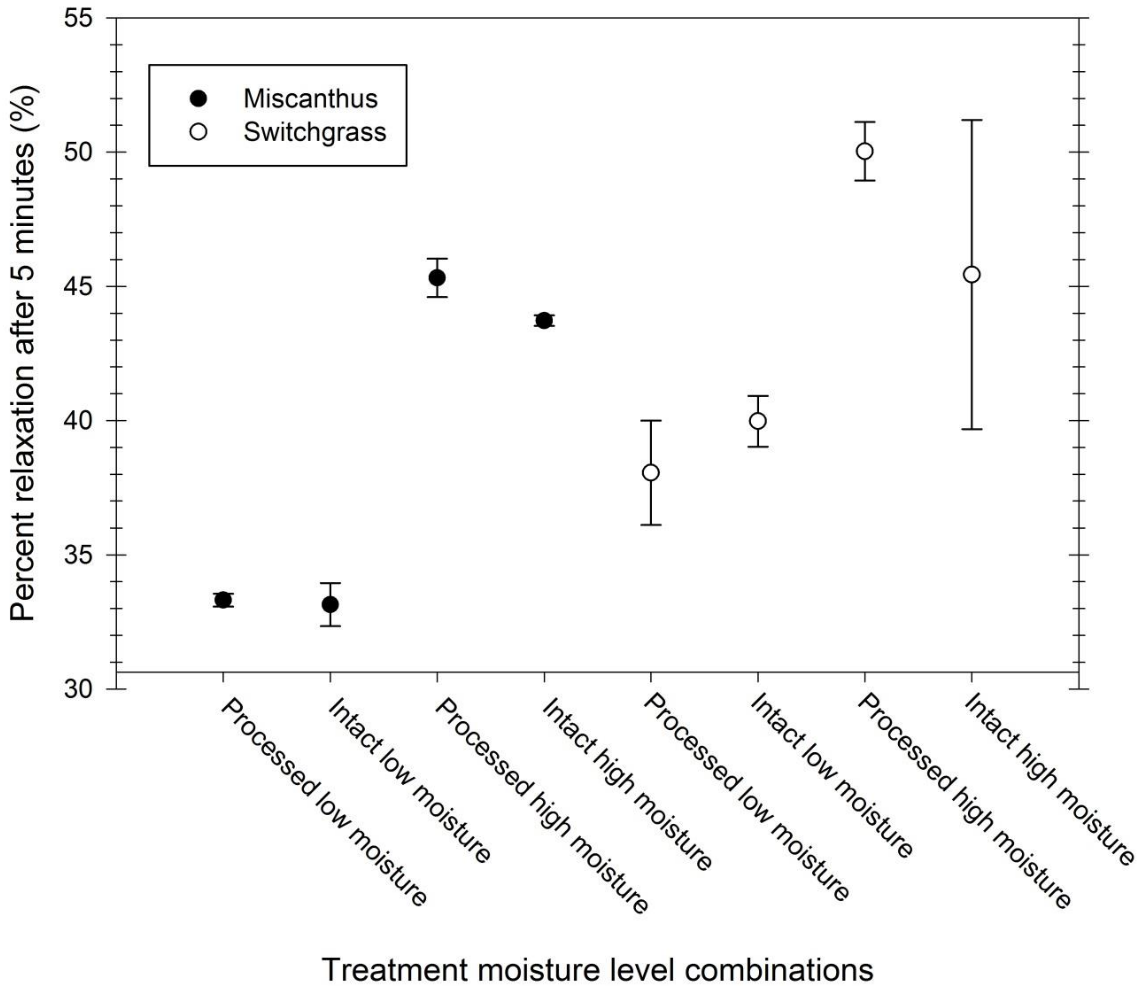


Figure 4-11 Percent relaxation over a period of 5 minutes for intact and processed switchgrass and Miscanthus at two moisture levels

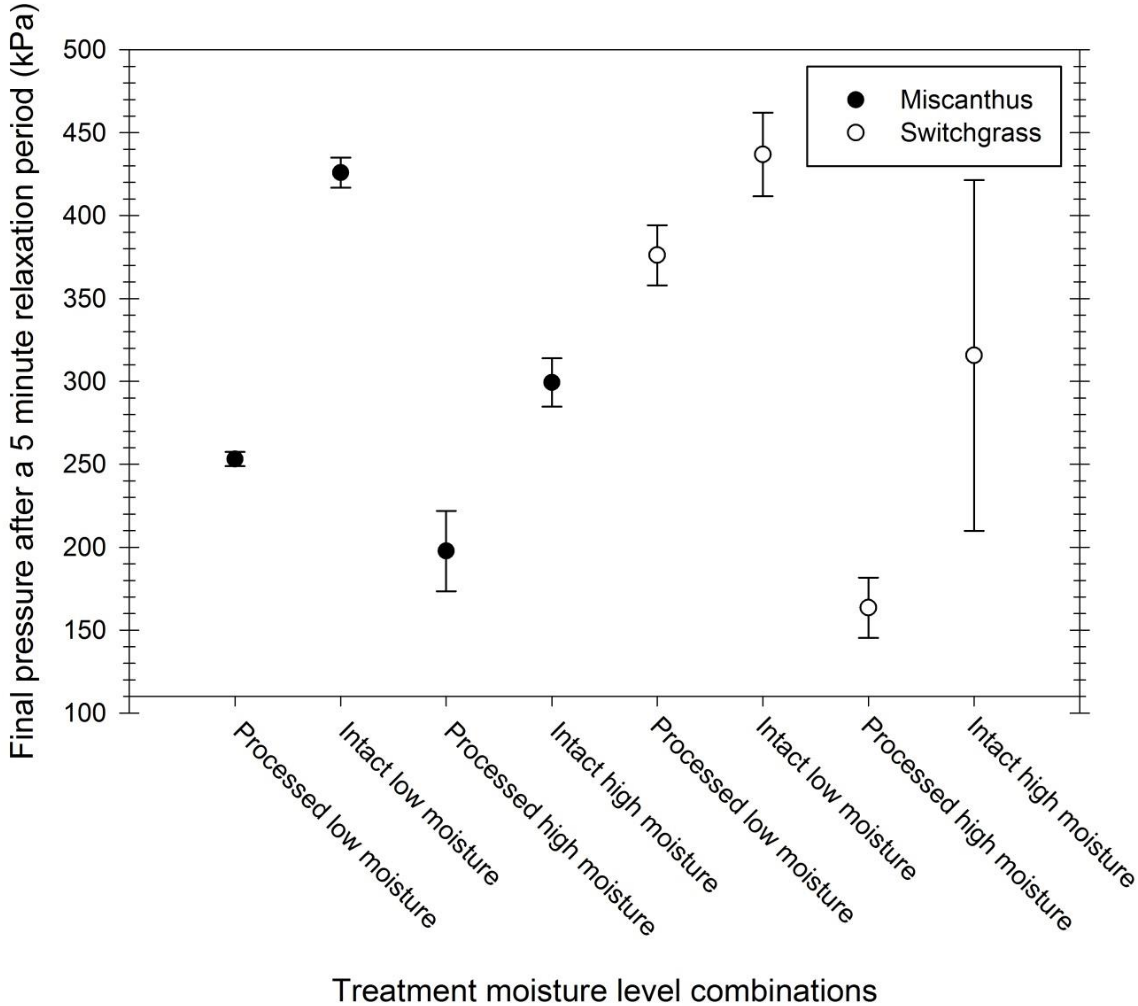


Figure 4-12 Final pressure after a relaxation period of 5 minutes for intact and processed

4.1.9 Variation in sample preparation

The high moisture content that was targeted for testing was nominally 20%. This was intended to represent the upper end of the moisture content range encountered during baling. For switchgrass, the average moisture content achieved was 19.75% with a standard deviation of 0.80%. The average sample dry matter was 2.27 kg (5.00 lbs.) with a standard deviation of 0.03 kg (0.07 lbs). For miscanthus, the average moisture content that was achieved for the high moisture samples was 20.18%, with a standard deviation of 0.76%. The average sample dry matter was 2.26 kg (4.98 lbs.) with a standard deviation of 0.04 kg (0.09 lbs).

The lower moisture level used was the storage equilibrium moisture content (10% nominally). For the low moisture samples the average dry matter was 2.27 kg with a standard deviation of 0.003 kg and the average moisture was 9.14% with a standard deviation of 0.26%. For switchgrass, the average dry matter was 2.27 kg with a standard deviation of 0.01 kg and the average moisture was 9.38% with a standard deviation of 0.41%.

For the green high moisture switchgrass, the average moisture was 45.9% with a standard deviation of 1.17%. The average sample dry matter was 2.33 kg (5.14 lbs) with a standard deviation of 0.11 kg (0.24 lbs). This treatment had inherently higher variability because the material was used as “cut from the field” and not conditioned in the lab.

4.1.10 Sources of error

The two major potential sources of error associated with these experiments were the moisture content determination prior to testing and the initial density determination. The test method required the initial height of the platen be recorded using a tape measure. This value was used to determine the initial bulk density, and all subsequent compressed densities were calculated relative to the initial height.

The moisture content used to calculate the required wet weight for each sample was approximated using the Ohaus moisture analyzer at the time of testing, and the amount of dry matter in the sample was adjusted for analysis using the oven drying method after testing. This estimation led to complications for evaluation based on dry density. For six of the experiments, the initial moisture analysis under predicted the moisture of the sample, and the sample was not compressed fully to the target density (by an average of 1.5% for miscanthus and 1.3% for switchgrass), and the pressure at the required dry bulk density was linearly extrapolated. These instances were noted in the individual test results shown in the appendix Table A-3 and Table A-4. The change in density, that resulted from the error in moisture content, measurement for replication four of the processed, green high moisture content resulted in this replication falling 4.5% short of the target density. This was deemed too great a distance to interpolate, so the result was excluded from the dry density analysis. Including this result did not influence the statistical significance, only the treatment means.

4.2 Objective 2: Modeling compression and relaxation behavior

4.2.1 Overview

This section contains the results from fitting three existing models for the pressure density relationship of compressed forage materials to data collected for the uniaxial bulk compression tests. The fit parameters for these models allow insight into how processing the bulk material affects its response in compression. The models were fit to each treatment (processed and intact) and the two crops separated by low, high, and all moisture levels combined. The coefficients of the model deemed to have the best fit were used to assess changes in the materials' behavior due to processing. The relaxation data was fit based on Equation 2-9. The data displayed a notable trend of samples grouping by moisture content rather than by the treatment.

4.2.2 Assessing the model fit

The fit parameters, coefficient of determination, RMSE, and AIC values can be seen in Table 4-1 for miscanthus and Table 4-2 for switchgrass. Graphical representations of the model fit with the predicted versus observed values can be found in appendix B.1. Since the models are not nested, lower values for RMSE and AIC can be used as an indicator of which model better explained the variation in the data. The same number of regression parameters were fit for all the models, therefore, looking at either indicator would result in the same conclusion.

The average RMSE for the power model (Equation 2-2) across all cases considered was 21.7 kPa for miscanthus and 28.5 kPa for switchgrass. For Equation 2-10, these values changed to 19.7 kPa for miscanthus and 23.0 kPa for switchgrass. Equation 2-11 was best suited to describe the behavior of switchgrass and miscanthus, as it provided the lowest or near the lowest RMSE for all cases. The average RMSE found were 14.9 kPa and 19.1 kPa for miscanthus and switchgrass, respectively.

From the graphical representation of predicted pressure versus observed pressure, (shown in Figure B-1to Figure B-12), it was seen that the moisture level influenced the behavior. The poor fit, especially at higher pressures, was also apparent from the higher RMSE values for the cases with moisture levels combined.

Equation 2-11 was the only model that used dry bulk density, which allowed it to better account for the addition of moisture. Based on previous work (section 2.6) and the experimental results from this study (section 4.1.5), compression models should be modified to include a moisture term since moisture influences mechanical properties of the crop. Other general observations from the results are that processed miscanthus and intact switchgrass conformed to the model better than their counter parts. Switchgrass is a finer stemmed crop that more closely resembles the original forage crops models.

Table 4-1: Model fit statistics for miscanthus

Treatment	**Moisture level**	**Model**[a]	**b_0**	**b_1**	**R^2**	**RMSE (kPa)**	**AIC**
Intact	All	(1)	2.42	0.001	0.896	47.40	45,835
Intact		(2)	1.75	0.401	0.948	33.43	41,687
Intact		(3)	357	0.006	0.969	25.99	38,698
Intact	Low	(1)	2.90	0.000	0.980	22.93	17,037
Intact		(2)	1.77	0.507	0.954	34.69	19,288
Intact		(3)	229	0.008	0.968	28.73	18,262
Intact	High	(1)	2.44	0.000	0.972	22.17	19,958
Intact		(2)	1.82	0.239	0.990	13.35	16,690
Intact		(3)	785	0.003	0.987	14.94	17,414
Processed	All	(1)	3.03	0.000	0.928	23.20	36,047
Processed		(2)	0.75	0.666	0.941	21.08	34,945
Processed		(3)	66	0.011	0.988	9.30	25,570
Processed	Low	(1)	3.47	0.000	0.994	7.01	10,420
Processed		(2)	0.65	1.062	0.998	3.98	7,395
Processed		(3)	59	0.012	0.998	3.76	7,081
Processed	High	(1)	3.25	0.000	0.993	7.26	12,122
Processed		(2)	0.63	0.725	0.980	11.76	15,073
Processed		(3)	64	0.011	0.994	6.62	11,561

[a](1) Equation 2-2 (2) Equation 2-3 (3) Equation 2-6

Table 4-2: Model fit statistics for switchgrass

Treatment	Moisture level	Model[a]	b_0	b_1	R^2	RMSE (kPa)	AIC
Intact	All	(1)	2.40	0.001	0.806	60.99	79,816
Intact		(2)	1.03	0.694	0.899	44.09	73,515
Intact		(3)	127	0.010	0.937	34.72	68,877
Intact	Low	(1)	2.88	0.000	0.993	13.35	31,450
Intact		(2)	1.18	0.736	0.993	13.05	31,172
Intact		(3)	127	0.010	0.993	12.73	30,878
Intact	High	(1)	2.66	0.000	0.996	6.45	13,568
Intact		(2)	0.83	0.603	0.996	6.58	13,718
Intact		(3)	123	0.008	0.996	6.10	13,166
Processed	All	(1)	2.67	0.000	0.674	61.52	55,318
Processed		(2)	0.53	1.000	0.877	37.84	48,790
Processed		(3)	44	0.014	0.913	31.70	46,414
Processed	Low	(1)	3.30	0.000	0.981	17.48	20,820
Processed		(2)	0.70	0.947	0.981	17.59	20,866
Processed		(3)	59	0.013	0.981	17.61	20,873
Processed	High	(1)	3.43	0.000	0.975	11.41	14,979
Processed		(2)	0.54	0.701	0.932	18.84	18,066
Processed		(3)	44	0.012	0.972	12.01	15,295

[a](1) Equation 2-2 (2) Equation 2-3 (3) Equation 2-6

4.2.3 Model adjustments to utilize dry bulk density

The use of only two moisture levels in the bulk compression tests limited the ability to develop a new equation that included the moisture term. Equation 2-6 was derived based on the dry bulk density. Since the equation provided the best overall fit, it was decided to fit the other two equations using dry density. This was done in an attempt to account for the variation in the pressure density response based on moisture. The RSME values used to compare these fits are shown in Table B-3 and Table B-4. The resulting values from Equation 2-11 remained unchanged, as this model already used dry density. The results for both crops show very little change in the RMSE value when the crops were separated by moisture values, but the fit for the power model improved by an average of 21 kPa when the moisture levels were grouped together. The converse was true for Equation 2-3 which resulted in an 14 kPa averge increase in RMSE, when moisture levels were grouped together.

The average RMSE for the power model based on the dry bulk density improved from 21.7 kPa to 16.1 kPa for switchgrass, and from 28.5 kPa to 19.6 kPa for miscanthus. Equation 2-11 still had the lowest average RMSE for both crops.

4.2.4 Model coefficient comparison and treatment effects

Due to its consistently lower RMSE values, Equation 2-6 was selected for further examination of how the model coefficients changed with processing. The 95 % confidence interval for both crops can be seen in Table 4-3. These values for all models can be found in Table B-5 and Table B-6.

Table 4-3: Model coefficients and confidence intervals for Equation 2-6

	Treatment	Moisture level	b_0	95% CI		b_1	95% CI	
Miscanthus	Intact	All	357	344	370	0.0056	0.0054	0.0057
	Intact	Low	229	219	239	0.0077	0.0075	0.0079
	Intact	High	785	744	827	0.0029	0.0028	0.003
	Processed	All	66	65	67	0.011	0.0109	0.0111
	Processed	Low	59	59	60	0.012	0.012	0.0121
	Processed	High	64	63	65	0.0108	0.0107	0.0109
Switchgrass	Intact	All	127	123	130.3	0.0096	0.0094	0.0097
	Intact	Low	127	126	128.5	0.0103	0.0102	0.0103
	Intact	High	123	122	124.83	0.0084	0.0083	0.0084
	Processed	All	44	42	45.49	0.0139	0.0137	0.0141
	Processed	Low	59	57	60.13	0.0132	0.013	0.0133
	Processed	High	44	42	45.01	0.0122	0.012	0.0124

4.2.5 Treatment response curve comparison

The impact of processing the material on the pressure density response, as modeled by Equation 2-6, was evaluated in the manner described in Motulsky (2004). The F statistic and p value were calculated based on Equation 4-1; where SSc was the sum of squares for a global fit using both treatments, SSs was the combined sum of squares for the treatments fitted individually, DFc was the degrees of freedom for the combined model, given by the sum of the replications for each treatment minus 2 parameters fit, and DFs was the degrees of the separate curves, given by the sum of the replications minus 4 (2 parameters fit to each treatment) .

$$F = \frac{(SS_c - SS_s) / (DF_c - DF_s)}{SS_s / DF_s} \qquad \text{Equation 4-1}$$

The results from this analysis can be seen in Table 4-4. Based on this table, there is not enough evidence to conclude that the treatment produced a significantly different curve (α=0.05). This could in part be explained by the small number of degrees of freedom remaining once the treatments are separated by moisture level. Though the comparison did not prove to be significant, observation of the predicted versus actual plots (Figure 4-13-Figure 4-16) showed the treatments began to separate once the pressure increased into the area of interest. The agreement in the lower pressure range could be due to the increase in the initial bulk density term used in the model that resulted from processing the material. The general trend of the model was under predicting for intact material and over predicting for processed material.

Table 4-4 Evaluation of treatment effect on model fit

	Moisture level	**SS_c**	**SS_s**	**F value**	**P-value**
Miscanthus	Low	14,053,127	2,279,895	5.16	0.162
	High	14,271,000	851,850	15.75	0.061
Switchgrass	Low	7,423,000	2,111,020	5.03	0.070
	High	3,196,800	578,820	4.52	0.189

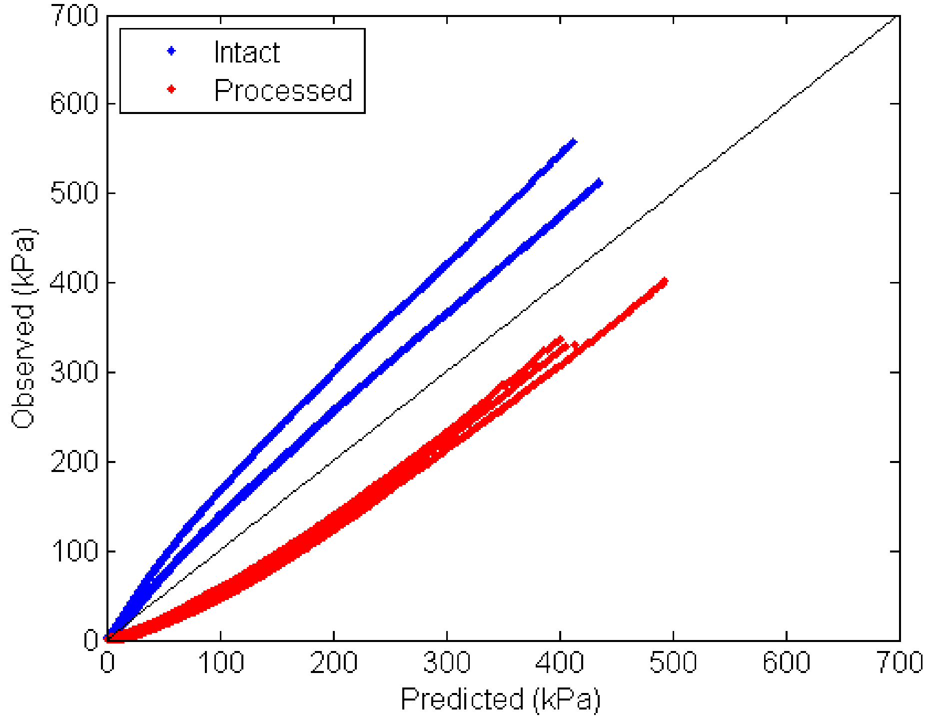


Figure 4-13: Actual versus predicted plot of pressure for high moisture miscanthus with a 1:1 line

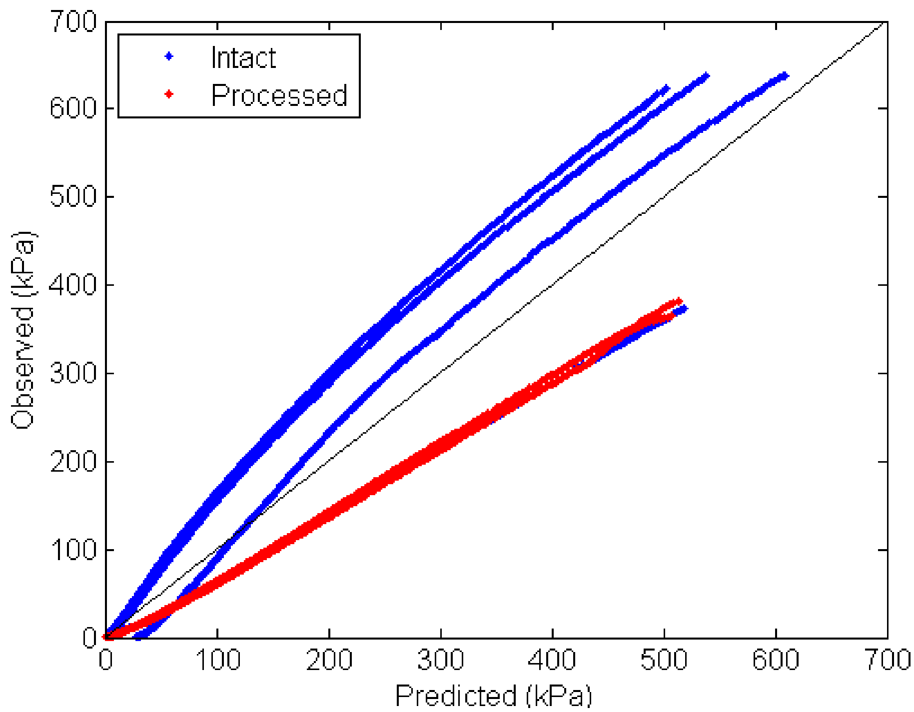


Figure 4-14: Actual versus predicted plot of pressure for low moisture miscanthus with a 1:1 line

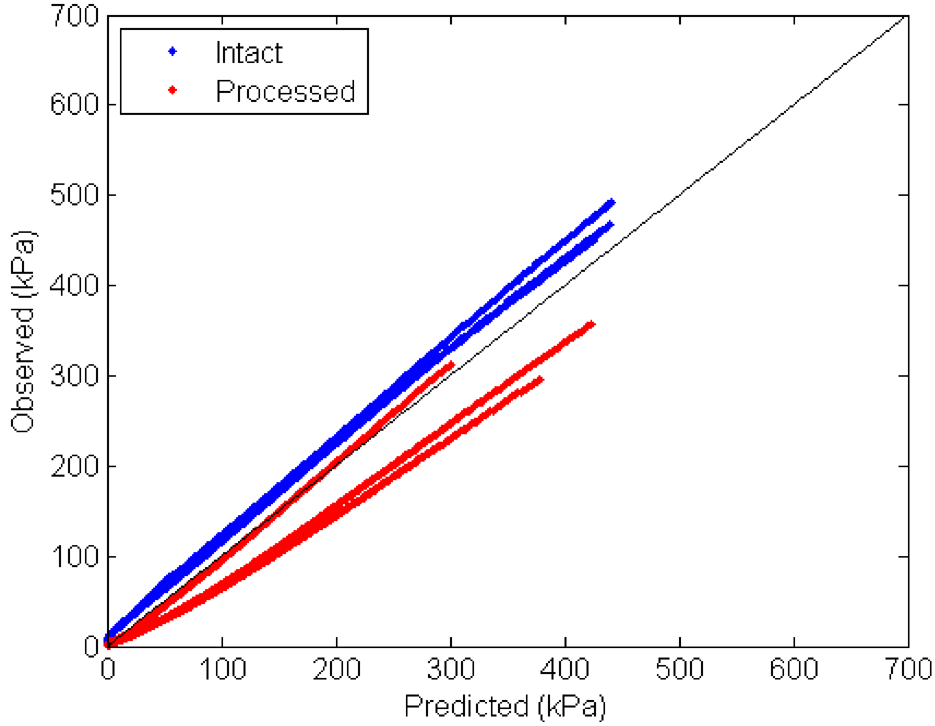


Figure 4-15: Actual versus predicted plot of pressure for high moisture switchgrass with a 1:1 line

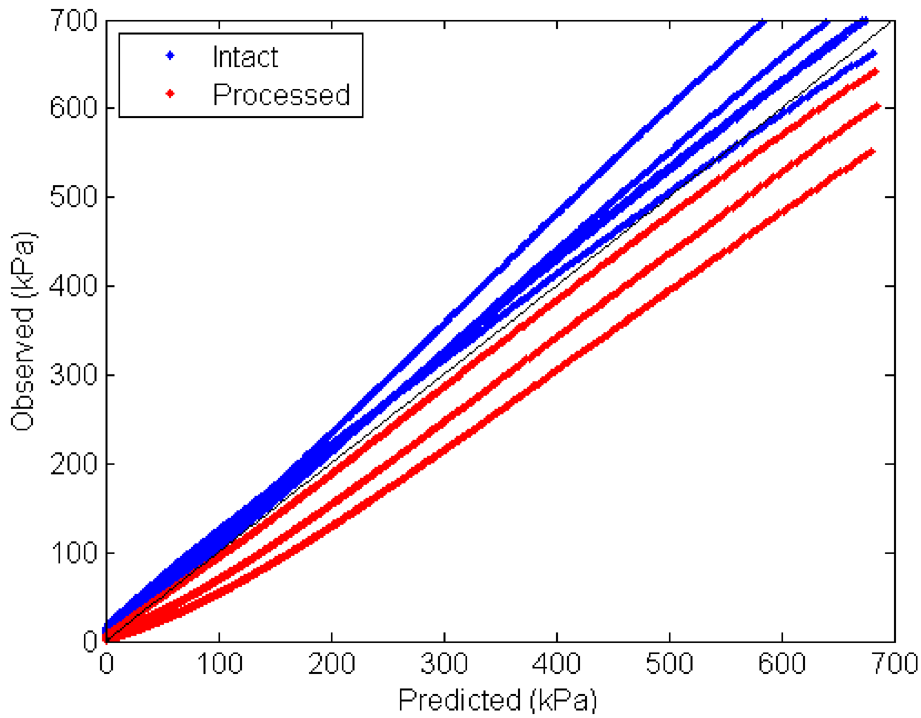


Figure 4-16: Actual versus predicted plot of pressure for low moisture switchgrass with a 1:1 line

4.2.6 Normalized relaxation

The results of fitting the normalized force relaxation data can be seen in Figure 4-17 and Figure 4-18 for miscanthus and switchgrass, respectively. The data showed a separation of the normalized values based on moisture content, rather than treatment. The data fit separated by treatment and moisture content can be seen in Appendix B.4. Normalized relaxation.

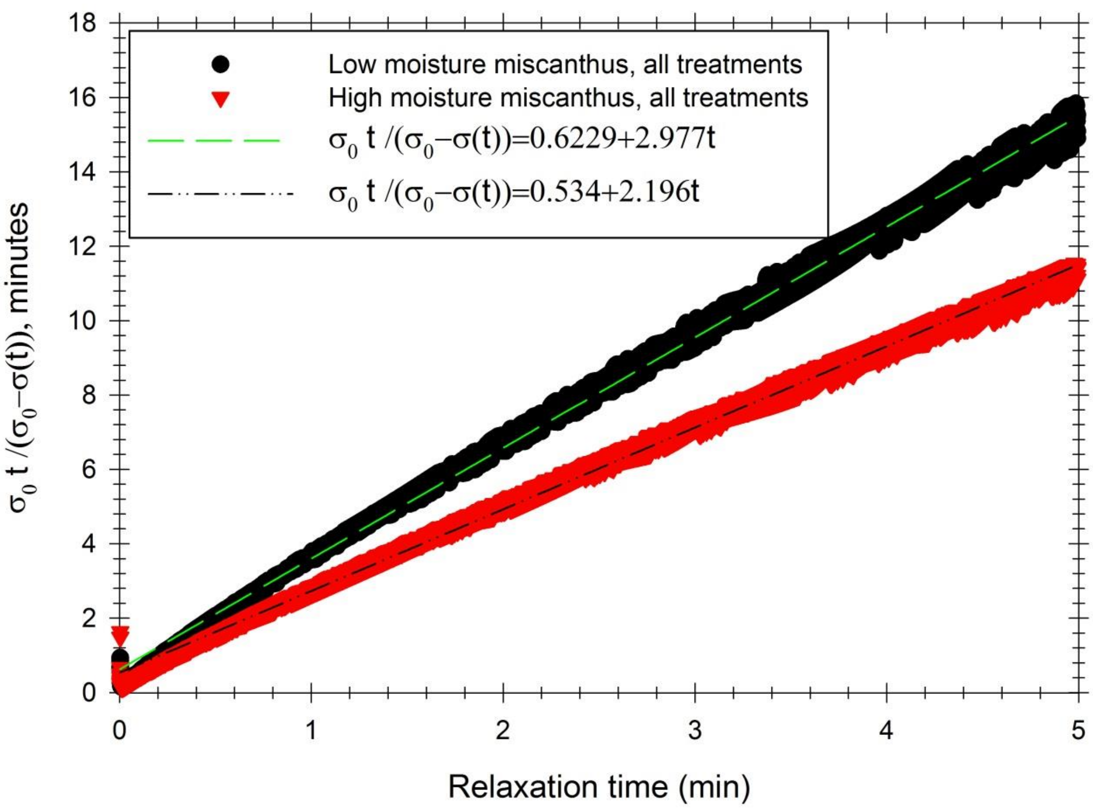


Figure 4-17 Normalized stress relaxation fit to Equation 2-9 for miscanthus, including all treatments separated by moisture content

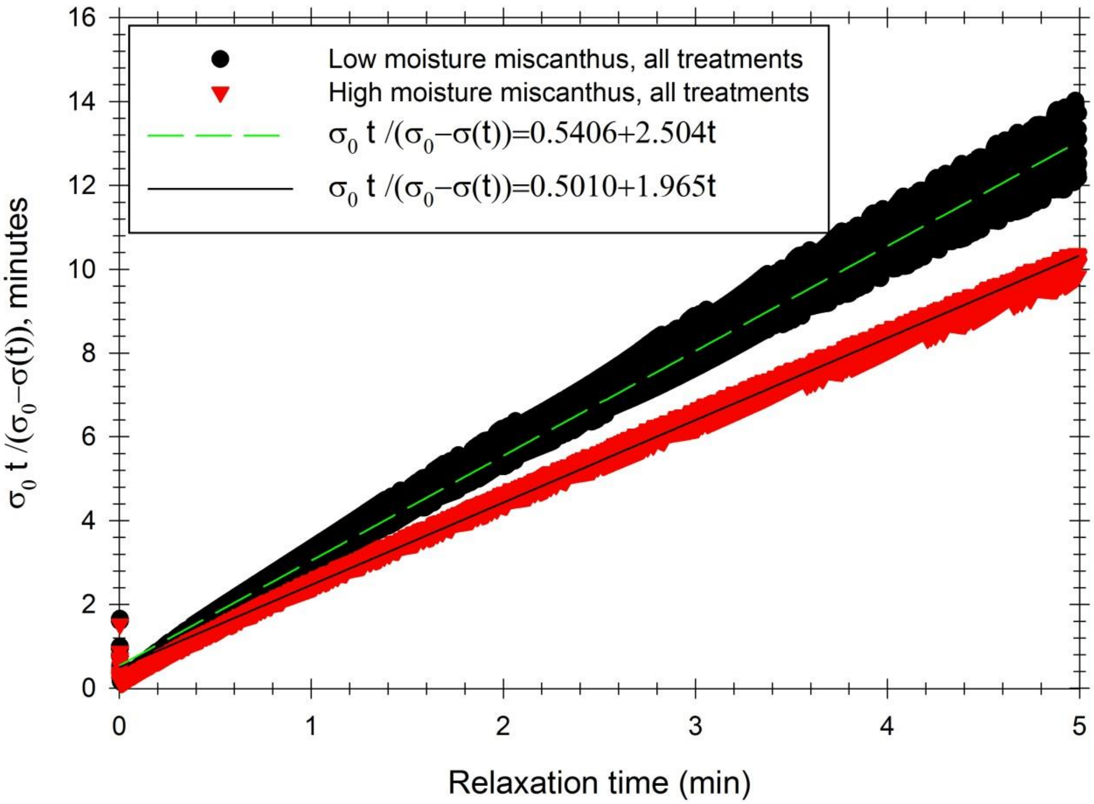


Figure 4-18 Normalized stress relaxation fit to Equation 2-9 for switchgrass, including all treatments separated by moisture content

4.3 Objective 3: Individual node compression results

4.3.1 Overall results

The results of the radial compression tests for the individual nodes and internodes were presented by crop. The samples were tested at lab equilibrium moisture (average of 8.1% for switchgrass and 8.5% MC for miscanthus). The average temperature and relative humidity during testing was 23.9°C and 49%, respectively during testing. The data was separated by node position and as a mean of all node locations combined. Figure 4-19 shows the mean bioyield point and standard deviation for switchgrass and miscanthus, separated by node position. The mean failure point for all miscanthus nodes was 90.8 N with a standard deviation of 47.8 N and for switchgrass these values were 164.9 N and 71.6 N, respectively. The large standard deviations were not ideal, but was expected due to the nature of the material tested. The data showed a general decrease in the bioyield point as the node position increased, which intuitively made sense because the closer to the top of the stem the node was located; the less strength was required to support the rest of the plant. The mean bioyield point for internode samples was larger than for node samples (269 N and 165 N for switchgrass and miscanthus respectively) due to the larger physical size of the internode samples. The mean diameter, length, and mass for of the samples can be seen in Table 4-5. Miscanthus consistently had more nodes than switchgrass due to the height difference between the two crops.

Figure 4-20 and Figure 4-21 show the apparent modulus of elasticity and maximum contact stress (Smax) for each crop separated by node position. Both the apparent modulus of elasticity and maximum contact stress have units of pressure, which accounts for the different lengths and contact area of the samples and allows for comparison of the sample's relative strength. The mean apparent modulus of elasticity found for all nodes was 152.3 MPa with a standard deviation of 70.1 for miscanthus and a slightly lower value of 129.3 MPa with a standard deviation of 59.7 for switchgrass. The internode sections had lower mean values at 57.8 MPa and 13.9 MPa for miscanthus and switchgrass respectively. The mean value for maximum contact stress in miscanthus was 10.5 MPa with a standard deviation of 4.1. Switchgrass had a higher mean value at 16.46 MPa with a larger standard deviation of 5.83. Again, internode sections had lower mean values at 4.2 MPa and 1.2 MPa for miscanthus and switchgrass respectively.

Table 4-5: Physical measurements of individual node samples

crop	Node	Mean Length (mm)	Standard Deviation (mm)	Mean Diameter (mm)	Standard Deviation (mm)	Mean Mass (g)	Standard Deviation (g)

miscanthus	1	14.06	5.46	9.65	3.09	0.389	0.254
	2	13.17	2.87	9.11	1.82	0.382	0.257
	3	12.99	3.16	8.35	1.65	0.356	0.248
	4	12.60	2.81	7.67	1.55	0.275	0.188
	5	11.40	2.93	7.43	1.51	0.218	0.153
	6	10.98	2.64	7.00	1.33	0.180	0.116
	7	11.01	2.99	6.68	1.44	0.167	0.114
	8	11.85	1.72	6.79	1.19	0.326	0.261
	9	10.71	2.42	6.48	1.35	0.387	0.295
	10	11.72	2.60	6.81	1.15	0.160	0.097
	11	9.84	0.95	7.05	1.13	0.180	0.090
	12	10.40	1.41	6.27	1.50	0.160	0.080
	Mean	11.90	2.94	7.59	1.75	0.279	2.886
switchgrass	1	10.77	2.67	6.35	1.84	0.190	0.115
	2	10.02	2.72	6.00	1.57	0.163	0.102
	3	10.90	3.18	5.66	1.49	0.156	0.099
	4	10.57	2.37	5.54	1.36	0.132	0.077
	5	9.50	1.57	5.59	1.64	0.120	0.074
	6	9.60	1.72	6.15	1.28	0.136	0.072
	7	10.69	1.66	6.93	0.66	0.12	0.06
	Mean	10.28	2.44	5.91	1.51	0.15	0.09

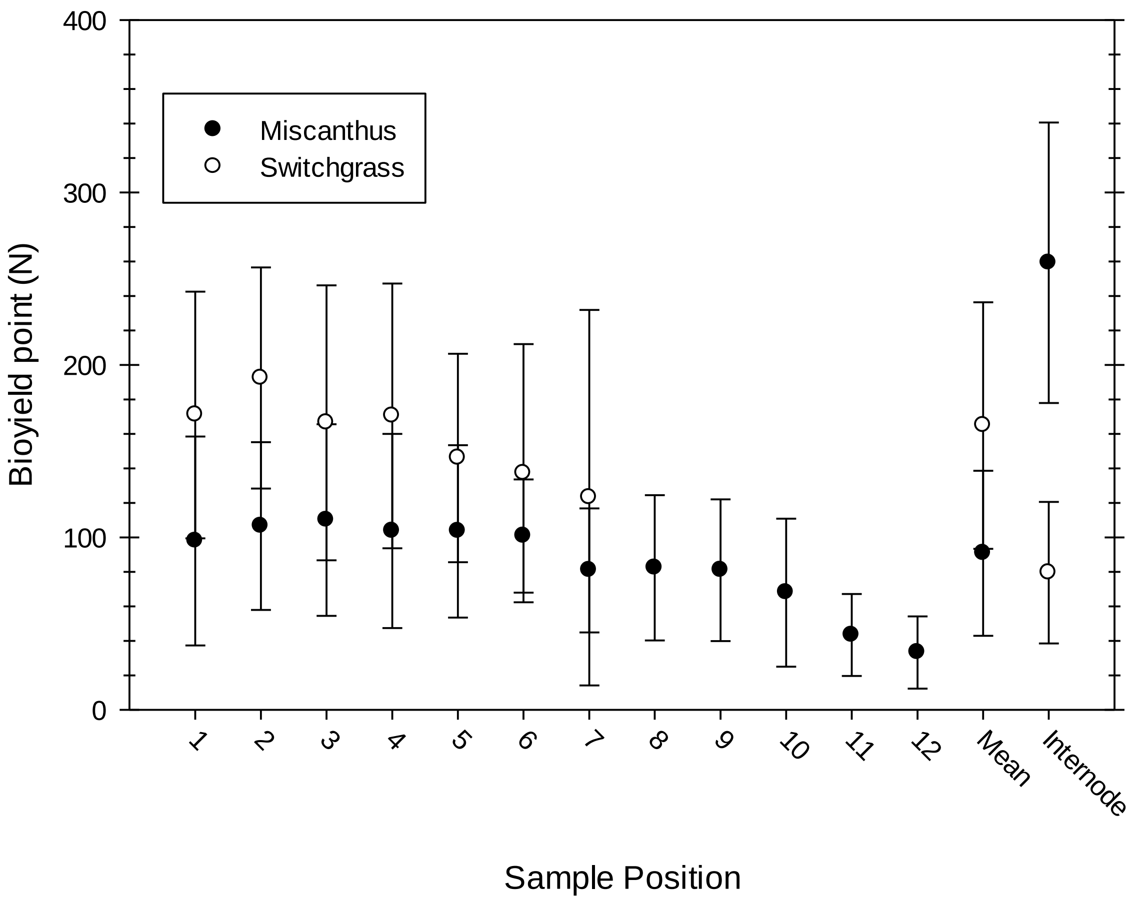


Figure 4-19: Force (N) at the bioyield point separated by node location, mean of all nodes, and the average of the internodes for switchgrass and miscanthus

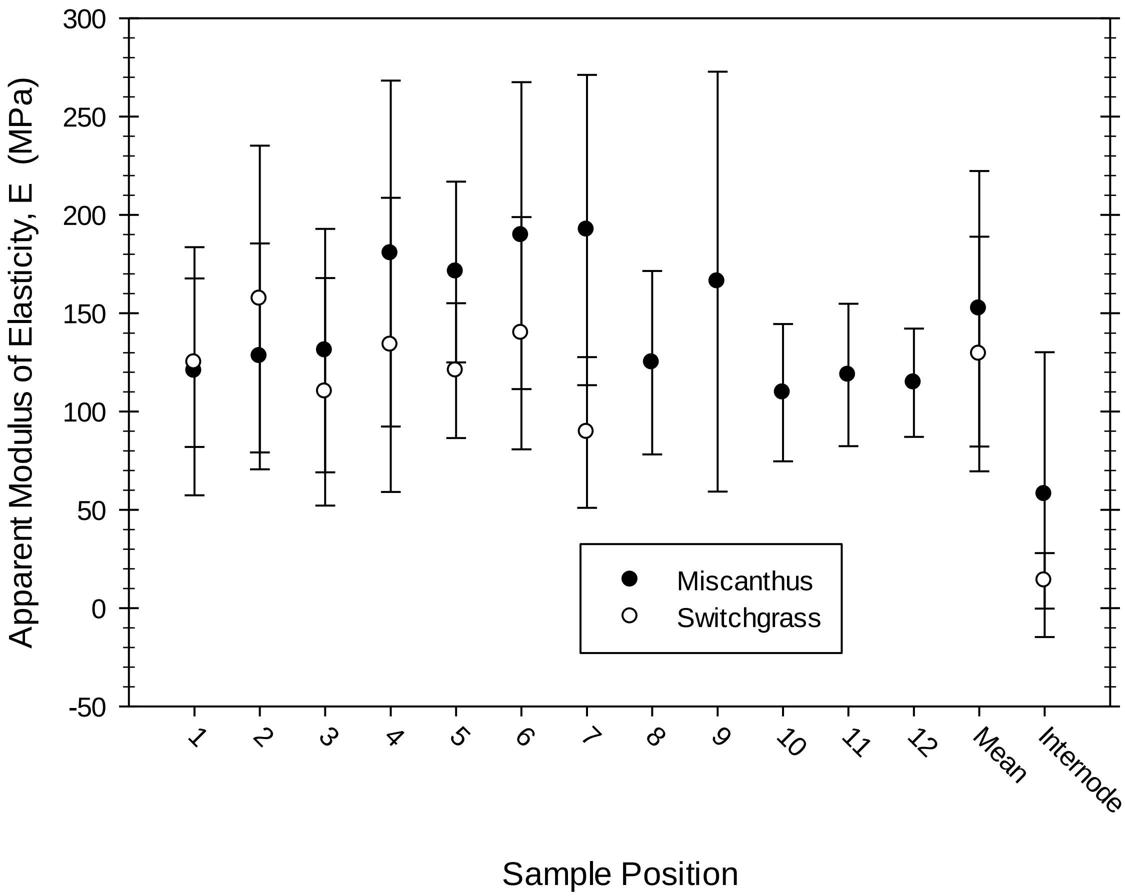


Figure 4-20: Apparent modulus of elasticity for miscanthus and switchgrass by node location, mean of all nodes, and the average of the internodes for switchgrass and miscanthus

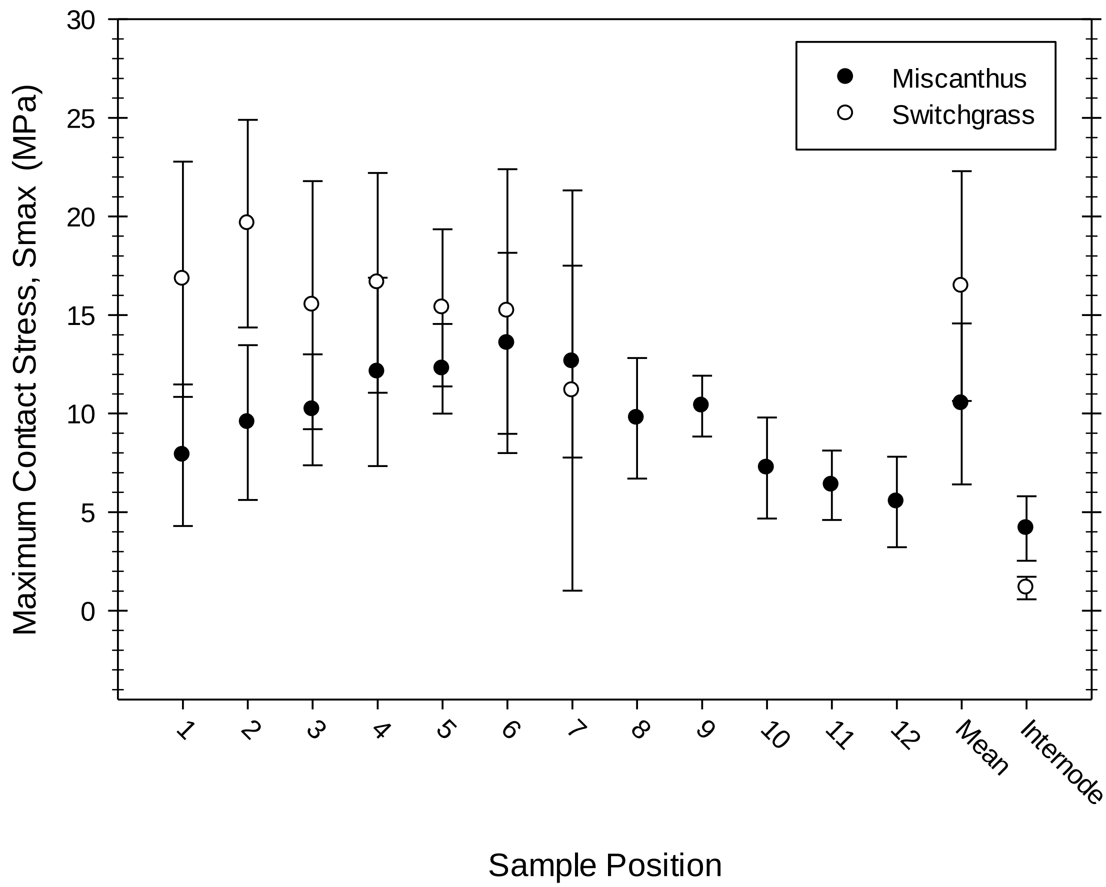


Figure 4-21: Maximum contact stress (Smax) for switchgrass and miscanthus separated by node position, by node location, mean of all nodes, and the average of the internodes

4.3.2 Comparison of node position and internode strength: switchgrass

P values for the comparison of the apparent modulus of elasticity and maximum contact stress by sample position on the stalk can be seen in

Table C-3 and Table C-4 for switchgrass. Based on these tables it can be seen that the internode samples had significantly lower values (α=0.05) for E and Smax in all but one case (Smax comparing node 7 to the internode). This could partly be explained by the small sample size that resulted from a low number of plants that had a 7^{th} node (n=4). All comparisons between node positions were not significant with the exception of the modulus of elasticity for node 7 compared to node 2. This appears consistent with Figure 4-20 and Figure 4-21, which shows no obvious pattern in the data.

4.3.3 Comparison of node position and internode strength: miscanthus

P values for the comparison of the apparent modulus of elasticity and maximum contact stress by sample position on the stalk can be seen in Table C-1 and Table C-2 for miscanthus. Based on these tables, the internode samples had significantly lower values (α=0.05) for E and Smax for node position 1-9. This is consistent with Figure 4-20 and Figure 4-21, which shows a bell shaped trend with the strongest nodes located in the middle of the plant and the Smax and E values decreasing toward the base and tip. This is counterintuitive to what was expected, as the lower nodes need to be stronger when the plant is standing to support the rest of the plant above. A possible explanation for this could be damage that occurred to the lower portion of the stem during harvest, due to miscanthus' brittle nature.

CHAPTER 5: SUMMARY AND CONCLUSIONS

The primary goal of this thesis was to explore the feasibility of using processing rolls to increase the dry matter bulk density of baled switchgrass and miscanthus. The motivation to increase the material's bulk density stems from the desire to increase transportation and handling efficiency from the producer to the processing facility through the reduction of unused capacity that results from the currently attainable bulk density. The main questions addressed by this study were:

1. Can the compression pressure required to achieve a target density be reduced by processing the material?
2. What influence does material moisture content have on the required pressure?
3. How does the pressure relaxation characteristics of processed and intact material compare?
4. Can existing models for forage compression be applied to switchgrass and miscanthus? How does processing affect the model coefficients?
5. What are the values of the engineering properties of individual node and internode sections that need to be overcome to compromise the plant's structure?

Uniaxial compression experiments were conducted on bulks samples of switchgrass and miscanthus to evaluate the potential of intensively processing forage material prior to baling to increase bale density. Experiments were conducted using samples of intact and processed material for each crop at two moisture levels typically found during baling (10 and 20% nominally). Additionally, green high moisture switchgrass was evaluated.

These experiments showed that compared to intact material, processed material required 40.8% (333 kPa to197 kPa) and 44% (414 kPa to 233 kPa) less pressure to reach the target wet density for switchgrass and miscanthus, respectively. When evaluated, based on dry bulk density, these values changed to 23.6% (577 kPa to 441 kPa) and 37% (581 kPa to 365 kPa). These results would support a system to increase bale density without significant redesign of the plunger gear box and knotter system on existing balers.

There was a general trend of reduced pressure requirement with the increased moisture content for the wet bulk density and the dry bulk density. This was consistent with previous works which showed increased moisture content reduced the strength of the individual plants and reduced coefficients of friction. The green high moisture switchgrass was not significantly different from the high moisture rewetted switchgrass. This indicated rewetted samples respond to compression similarly to green material.

The percent relaxation, after being held at a constant displacement for five minutes was similar for processed and intact material, but graphical examination of the pressure relaxation curves show a trend of the processed material relaxing to a lower final pressure. This relaxation characteristic is important because it can be used to draw insight into the potential for processed material to reduce rebounding forces that can ultimately cause twine failure once the bale is ejected from the bale chamber.

In order to evaluate how processing the material changes its response to compression, three previously proposed models for forage compression were evaluated for suitability to model switchgrass and miscanthus. All the proposed models had high values for coefficient of determination (greater than 0.8), but it was apparent that the models diverged quickly when both moisture levels were fitted together. Equation 2-6 had the lowest or near the lowest RMSE for every case, thus it was deemed best suited to describe the behavior of both switchgrass and miscanthus under compression.

Once Equation 2-6 was selected as the best fit, it was possible to examine the effect of the treatment on the model coefficients. Toward that end, a global fit to the data was compared to fits separated by treatment. There was not enough evidence to conclude that individual fits to the data by treatment were significantly different from a global fit. In spite of this, when the predicted pressure was plotted against the observed, there was a separation between the treatments.

It was not clear that the pressure reduction achieved was solely due to compromising the nodes because the processing method cracked nodes and often cracked the entire stem. As a direct result of the methodology employed several key assumptions were made. Some of these including a constant ram speed, and uniform lateral pressure variation were consistent with Faborode and O'Callaghan (1986). Additionally, the loading rate in these experiments was much slower than the plunger loading rate in an actual baler. This was done so the experiments could be assumed quasi static and reduce additional variables that dynamic system behaviors introduce. This resulted in an increase in the viscous resistance to deformation and thus the pressures generated during actual baling would be higher. Characterizing how processed material would respond to the increased loading was outside the scope of this thesis and was left for future work.

The experiments were also conducted using uniaxial compression and Poisson's ratio and laterally exerted pressure was not explicitly examined. In reality, bale chambers have a convergence to control bale density, but as previously discussed, this convergence is variable to account for changing conditions.

Experiments were also conducted to evaluate the plant's node and internode sections strength. Understanding the engineering properties such as apparent modulus of elasticity and maximum contact stress is essential to gain insight for the development of harvesting and processing systems. Toward that end, node and internode sections of miscanthus and switchgrass were subjected to radial compression between parallel plates to examine the material's resistance to crushing. The bioyield point, apparent modulus of elasticity, and maximum contact stress were determined. The apparent modulus of elasticity ranged from 110 MPa to 192 MPa for miscanthus and 89 MPa to 157 MPa for switchgrass. The maximum contact stress ranged from 5.5 MPa to 13.6 MPa for miscanthus and from 11.2 MPa to 19.6 MPa for switchgrass. Internode sections of switchgrass had a mean modulus of elasticity of 13.8 MPa and the mean maximum contact stress was 1.2MPa. For miscanthus the mean modulus of elasticity was 58 MPa and the mean maximum contact stress was 4.2 MPa. For switchgrass, the results indicated that node sections are significantly stronger than internode sections, but the values are not significantly influenced by node position. The strength of miscanthus nodes were influenced by node position, with the strongest nodes trending toward the middle of the plant. Node sections were stronger than the internode section for all but the upper nodes.

This research provided evidence that supports the feasibility of processing biomass material prior to baling to increase bale density, and thus improving transportation efficiency. It was found that moisture level had a significant influence on the required compression pressure for both wet and dry density. It was found that Equation 2-6 was suitable to describe the behavior of switchgrass and miscanthus under compression. The apparent modulus of elasticity and maximum contact stress was evaluated for node and internode sections using radial compression to provide insight for further processing roller development.

CHAPTER 6: FUTURE WORK

Now that the feasibility of processing the material to reduce the pressure required to increase bale density has been demonstrated, the next logical step is to field test the concept and evaluate any practical and appreciable density gains. Additionally, the effect of processing the material on the whole system (handling, storage, downstream processing, etc.) warrants examination, should the field test provide promising results. Simulating the fast loading rate of modern balers is not feasible in the laboratory. As a result, this would need to be validated with field experiments. Further examination of individual node and internode sections at additional moisture levels are needed to strengthen the results presented in this thesis. Additionally, the assumption of Possion's ratio used to calculate the maximum contact stress should be validated as Anazodo and Chikwendu (1983) showed this varies widely for biological material. The significant effect of moisture content on the material's response shows a need to examine additional moisture levels to include a moisture term in the pressure density models. This would allow for a more general model.

APPENDICES

Appendix A. Bulk Compression Test results

A.1. Tabular Results

Table A-1: Summary of Pressure Required to Reach a Wet Bulk Density of 256 kg/m^3

	Treatment	Moisture Level	N	Mean Pressure, kPa (psi)		Std. Dev.	
Switchgrass	Processed	Low	3	430	(62.4)	42.2	(6.1)
	Processed	Green	4	55	(8.0)	4.4	(0.6)
	Processed	High	3	154	(22.4)	23.2	(3.4)
	Intact	Low	5	536	(77.8)	40.6	(5.9)
	Intact	Green	3	77	(11.2)	9.0	(1.3)
	Intact	High	3	251	(36.5)	10.5	(1.5)
Miscanthus	Processed	Low	3	278	(40.3)	7.0	(1.0)
	Processed	High	3	187	(27.1)	10.4	(1.5)
	Intact	Low	3	497	(72.1)	6.1	(0.9)
	Intact	High	3	331	(48.0)	20.8	(3.0)

Table A-2: Summary of Pressure Required to Reach a Dry Bulk Density of 256 kg/m^3

	Treatment	Moisture Level	N	Mean Pressure, kPa (psi)		Std. Dev.	
Switchgrass	Processed	Low	3	591	(85.7)	44.1	(6.4)
	Processed	Green	3	404	(58.6)	90.3	(13.1)
	Processed	High	3	328	(47.6)	27.0	(3.9)
	Intact	Low	5	718	(104.2)	52.1	(7.6)
	Intact	Green	3	460	(66.7)	92.4	(13.4)
	Intact	High	3	458	(66.4)	11.1	(1.6)
Miscanthus	Processed	Low	3	372	(54.0)	8.5	(1.2)
	Processed	High	3	357	(51.8)	15.6	(2.3)
	Intact	Low	3	629	(91.2)	8.0	(1.2)
	Intact	High	3	533	(77.3)	39.6	(5.7)

Table A-3 Miscanthus Bulk Compression Results

	Length(1)	Treatment	Rep	Moisture Level(2)	Pressure, kPa @ 256 kg/m^3 Wet density	Dry density
	short	Intact	1	low	496	630
	short	Intact	2	low	504	637
	short	Intact	3	low	492	621
	short	Processed	1	low	279	372
	short	Processed	2	low	285	381
	short	Processed	3	low	271	364
*	**short**	Intact	1	high	355	579
	short	Intact	2	high	318	510
	short	Intact	3	high	320	511

Table A-3 Miscanthus Bulk Compression Results (cont'd)

	Length(1)	Treatment	Rep	Moisture Level(2)	Pressure, kPa @ 256 kg/m^3 Wet density	Dry density
*	**short**	Processed	1	high	179	340
*	**short**	Processed	2	high	184	359
	short	Processed	3	high	199	371
	long	Intact	1	low	274	-
	long	Intact	2	low	217	-
	long	Intact	3	low	243	-
	long	Processed	1	low	86	-
	long	Processed	2	low	71	-
	long	Processed	3	low	103	-
	long	intact	1	high	90.0	-
	long	intact	2	high	73.8	-
	long	intact	3	high	58.1	-
	long	processed	1	high	15.7	-
	long	processed	2	high	10.3	-
	long	processed	3	high	20.5	-

*Represents samples that never fully reached 256 kg/m^3based on dry density.

(1) short particles were cut to 10cm and tested with a starting mass of 2.56kg dry matter. long particles were cut to the length of the sample container, 33cm, and tested using a constant initial volume

(2) the high moisture content for short particles was 20% w.b. and 40% for long particles.

Table A-4 Switchgrass Bulk Compression Results

	Length(1)	Treatment	Rep	Moisture Level(2)	Pressure, kPa @ 256 kg/m^3 Wet density	Dry density
	Short	Intact	1	low	505	699
	Short	Intact	2	low	598	798
	Short	Intact	3	low	532	703
	Short	Intact	4	low	549	733
	Short	Intact	5	low	496	658
	Short	Processed	1	low	388	546
	Short	Processed	2	low	429	593
	Short	Processed	3	low	472	634
	Short	Intact	1	high	239	451
*	**Short**	Intact	2	high	257	452
	Short	Intact	3	high	257	470
	Short	Processed	1	high	181	357
	Short	Processed	2	high	137	304
*	**Short**	Processed	3	high	145	324
	Short	Intact	1	green	80	542
	Short	Intact	2	green	84	478
	Short	Intact	3	green	67	360
	short	Processed	1	green	61	409
	short	Processed	2	green	55	491
	short	Processed	3	green	51	305
*	**short**	Processed	4	green	53	305
	long	Intact	1	low	372	-
	long	Intact	2	low	415	-
	long	Intact	3	low	333	-
	long	Processed	1	low	265	-
	long	Processed	2	low	258	-

Table A-4 Switchgrass Bulk Compression Results (cont'd)

Length(1)	Treatment	Rep	Moisture Level(2)	Pressure, kPa @ 256 kg/m^3	
				Wet density	Dry density
long	Processed	3	low	274	-
long	intact	1	high	85	-
long	intact	2	high	69	-
long	intact	3	high	82	-
long	processed	1	high	64	-
long	processed	2	high	72	-
long	processed	3	high	63	-

*Represents samples that never fully reached 256 kg/m^3based on dry density.

(1) short particles were cut to 10cm and tested with a starting mass of 2.56kg dry matter. long particles were cut to the length of the sample container, 33cm, and tested using a constant initial volume

(2) the high moisture content for short particles was 20% w.b. and 40% for long particles.

A.2. Miscanthus Results

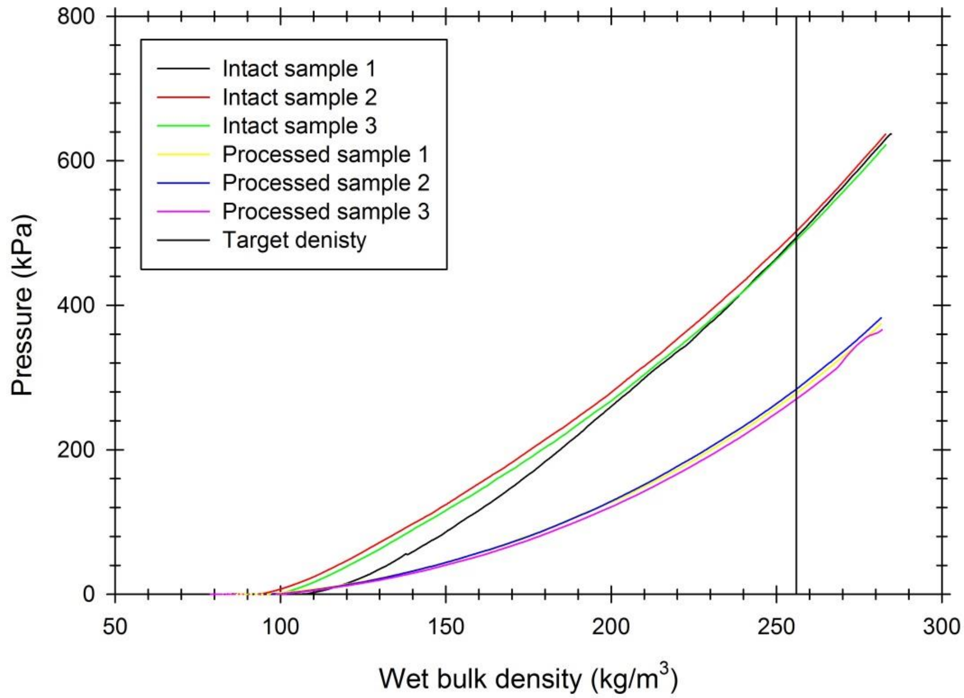


Figure A-1 Pressure density relationship, based on wet sample weight, for low moisture miscanthus subject to uniaxial compression

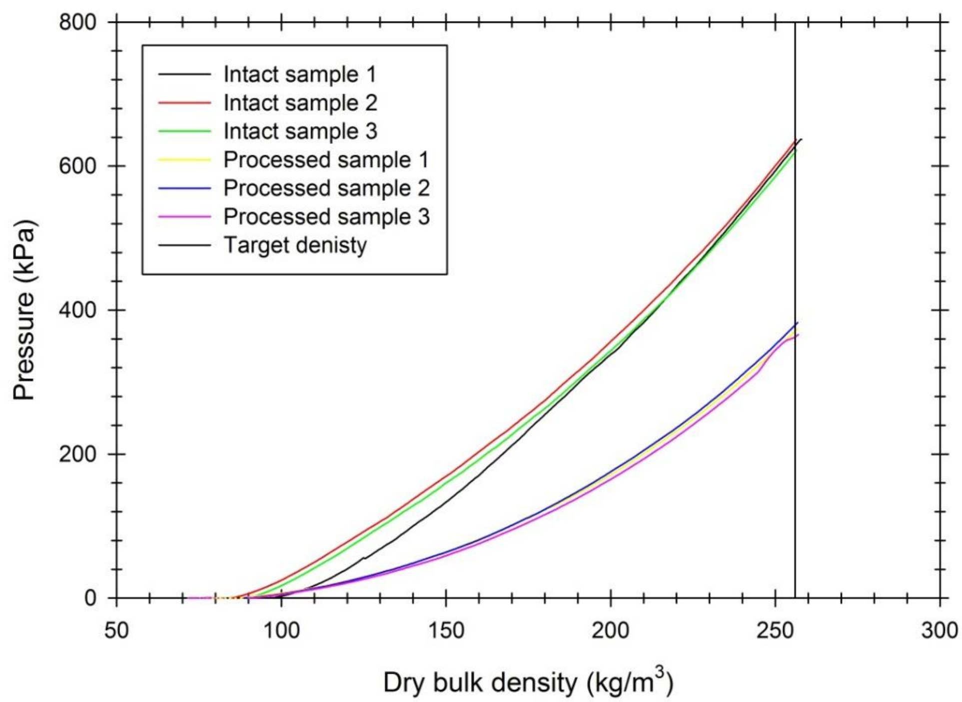


Figure A-2 Pressure density relationship, based on sample dry weight, for low moisture miscanthus subject to uniaxial compression

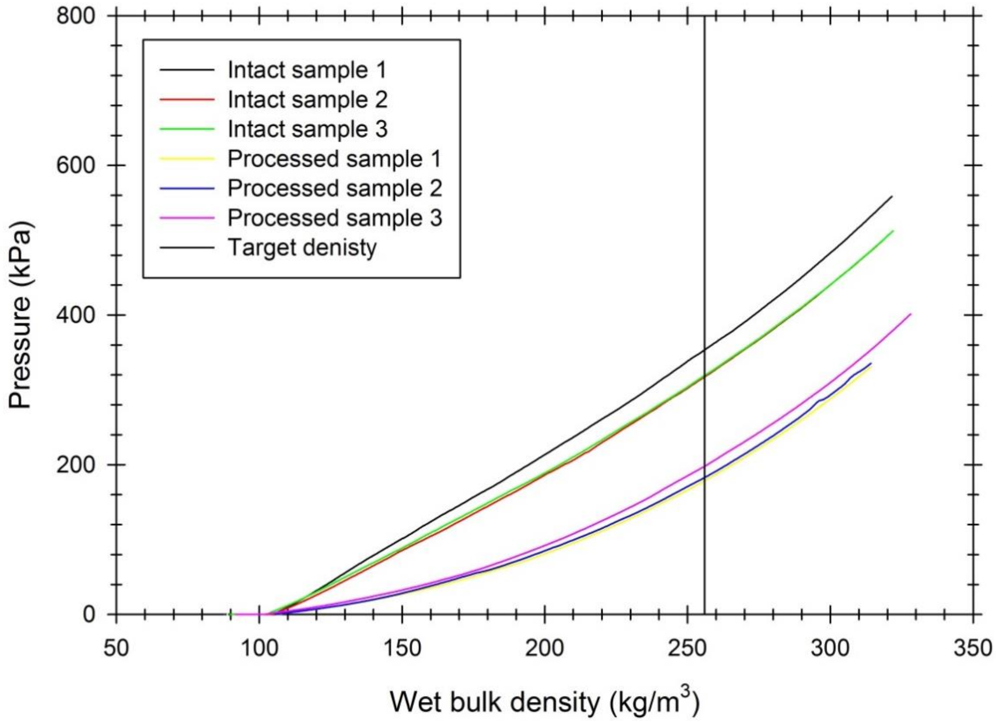


Figure A-3 Pressure density relationship, based on wet sample weight, for high moisture (20%) miscanthus subject to uniaxial compression

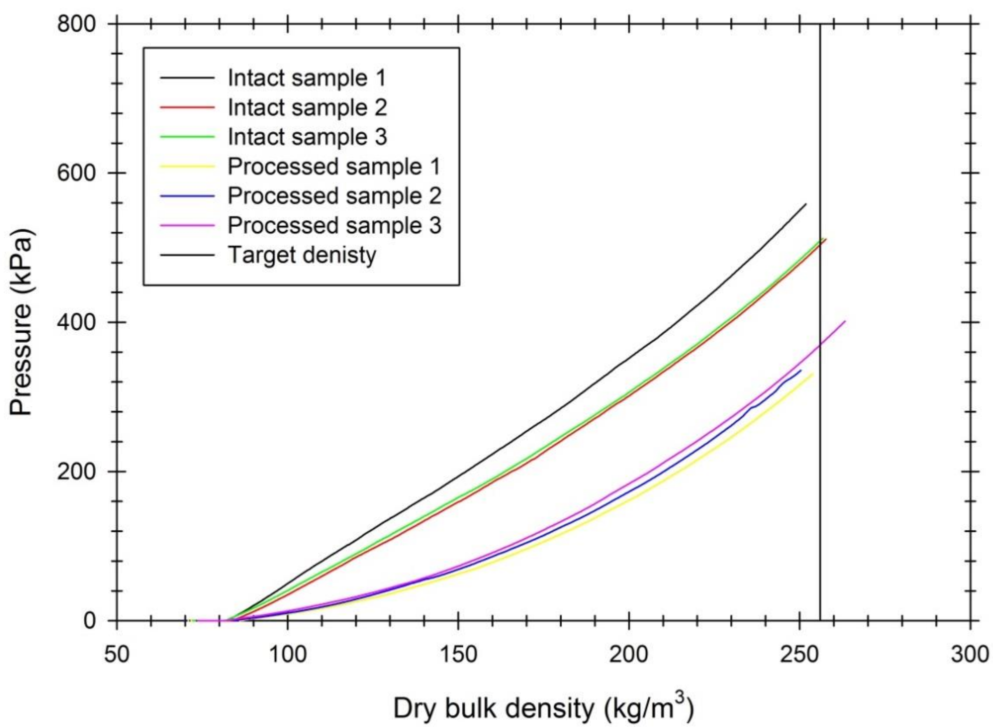


Figure A-4 Pressure density relationship, based on sample dry weight, for high moisture (20%) miscanthus subject to uniaxial compression

A.3. Switchgrass Results

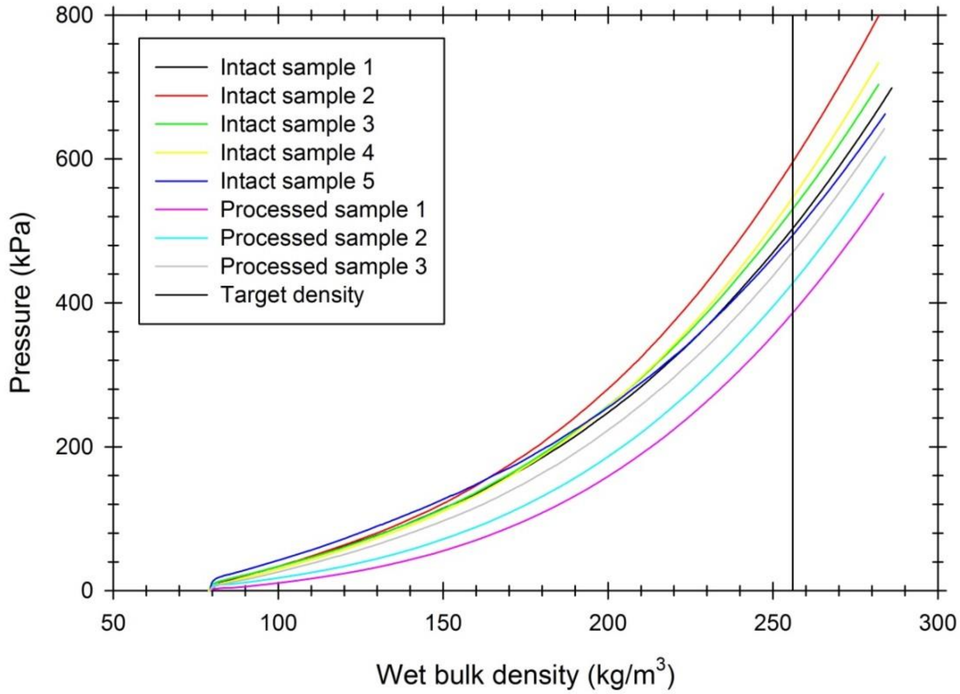


Figure A-5 Pressure density relationship, based on wet sample weight, for low moisture switchgrass subject to uniaxial compression

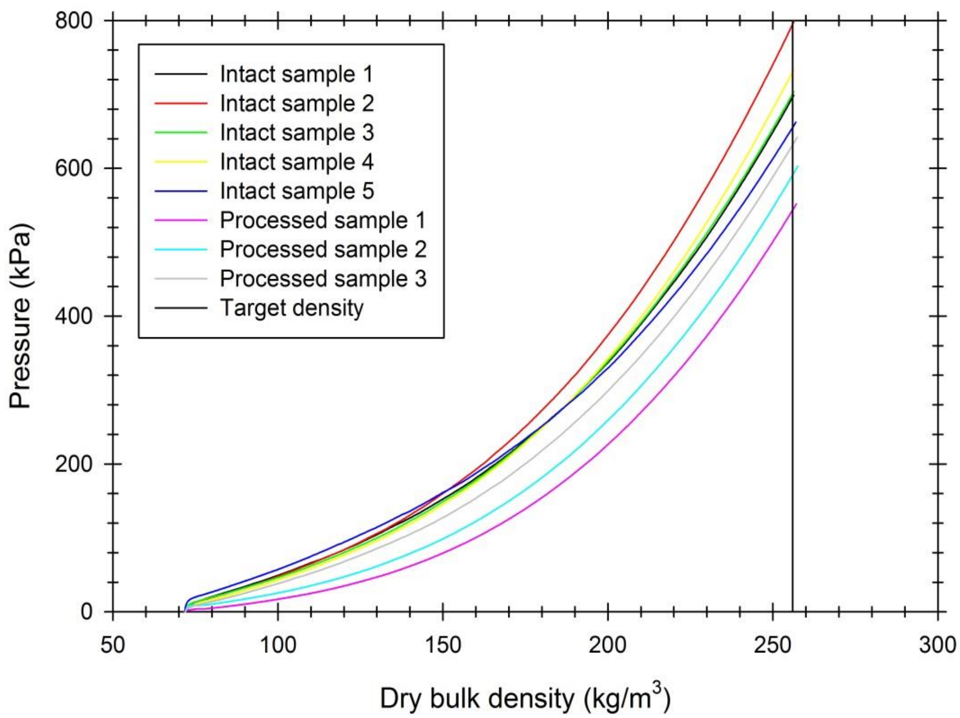


Figure A-6 Pressure density relationship for low moisture switchgrass subject to uniaxial compression

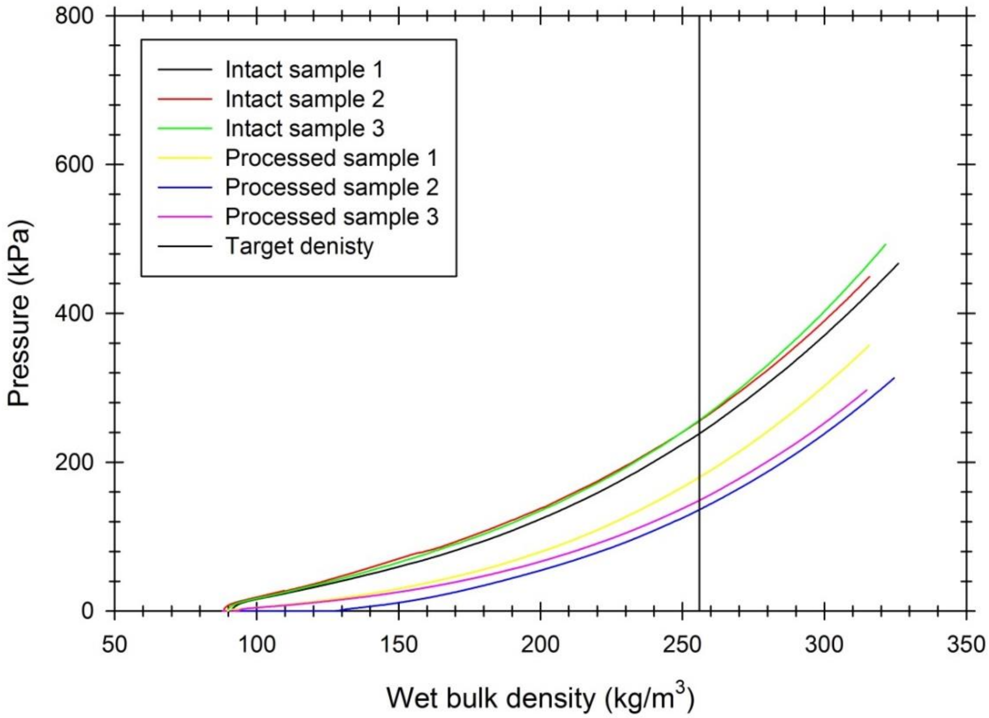


Figure A-7 Pressure density relationship, based on wet density for high moisture (20%) switchgrass subject to uniaxial compression

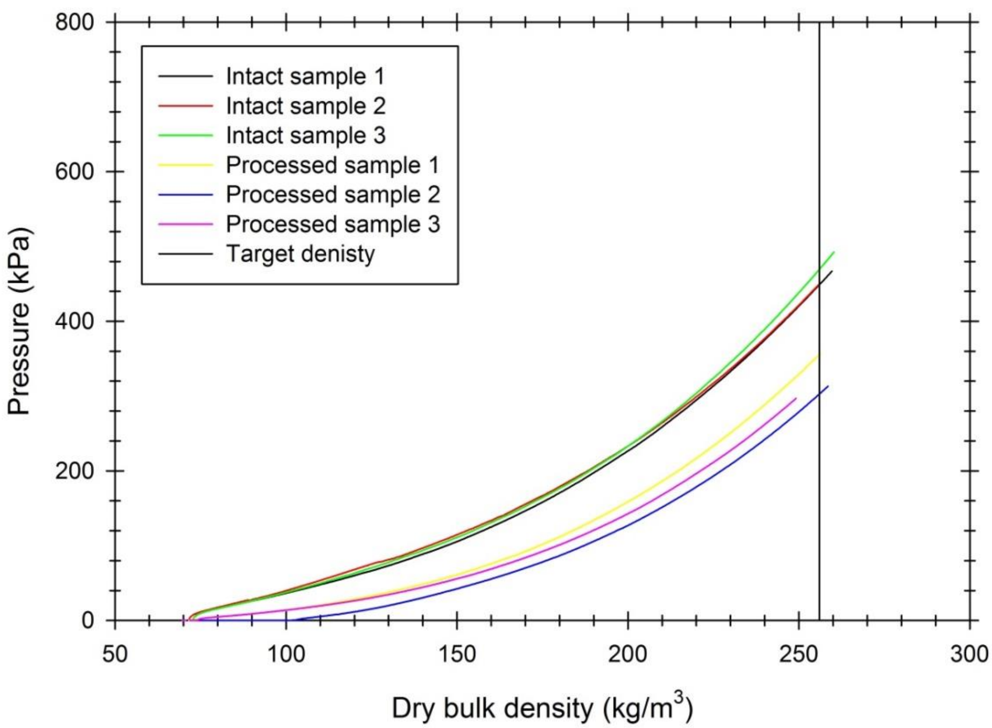


Figure A-8 Pressure density relationship, based on dry density for high moisture (20%) switchgrass subject to uniaxial compression

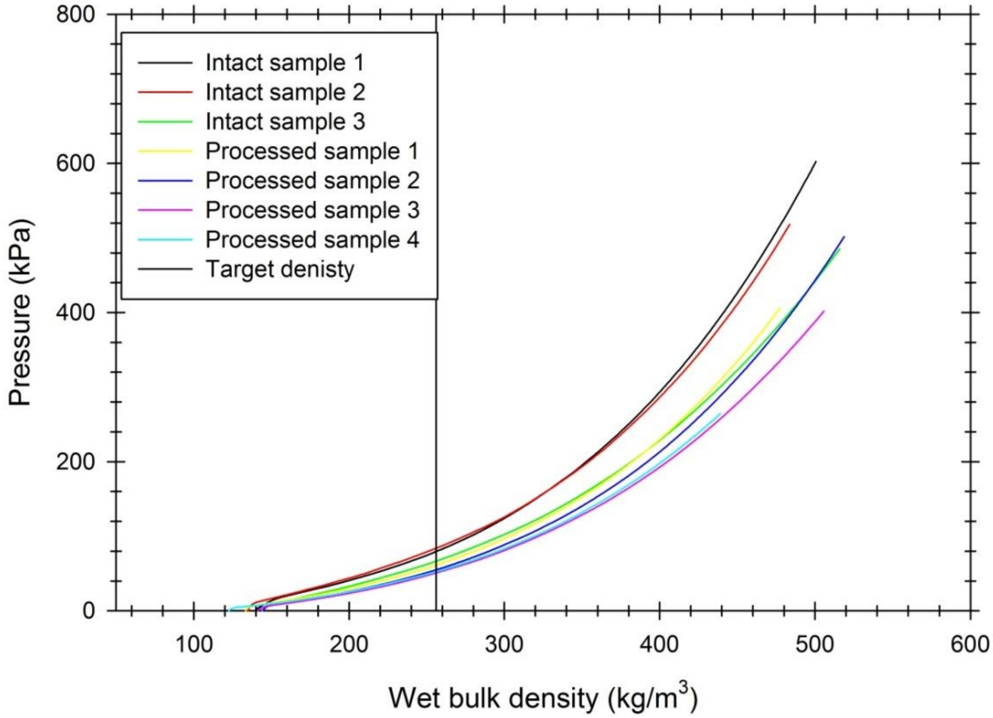


Figure A-9 Pressure density relationship, based on wet density for high moisture (45-50%) green cut switchgrass subject to uniaxial compression

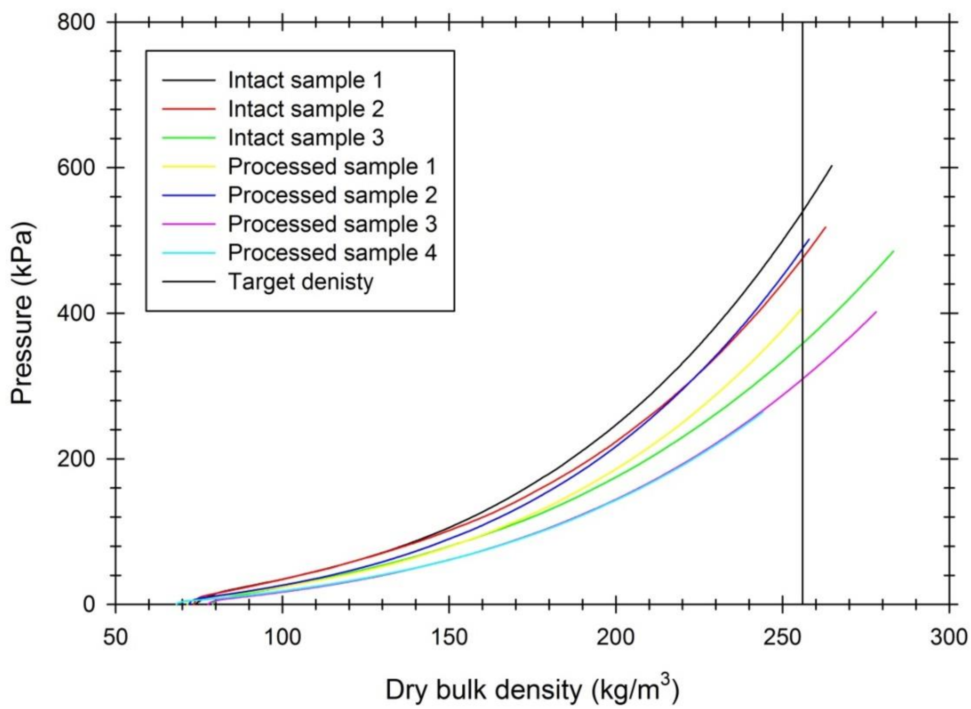


Figure A-10 Pressure density relationship, based on dry density for high moisture (45-50%) green cut switchgrass subject to uniaxial compression

A.4. Pressure Relaxation Under Constant Displacement

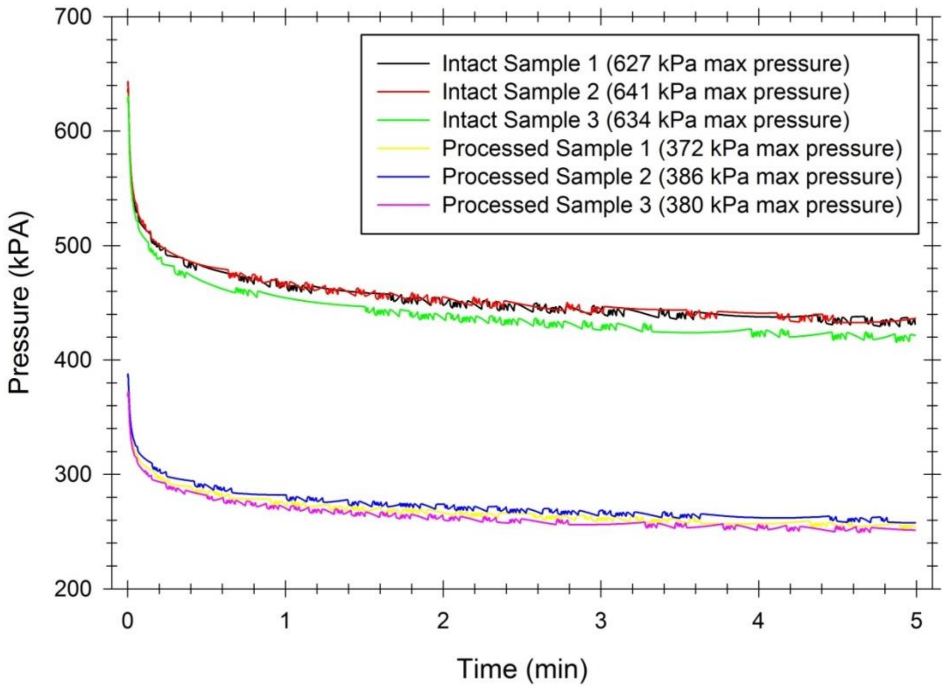


Figure A-11 Pressure relaxation for low moisture miscanthus under constant displacement

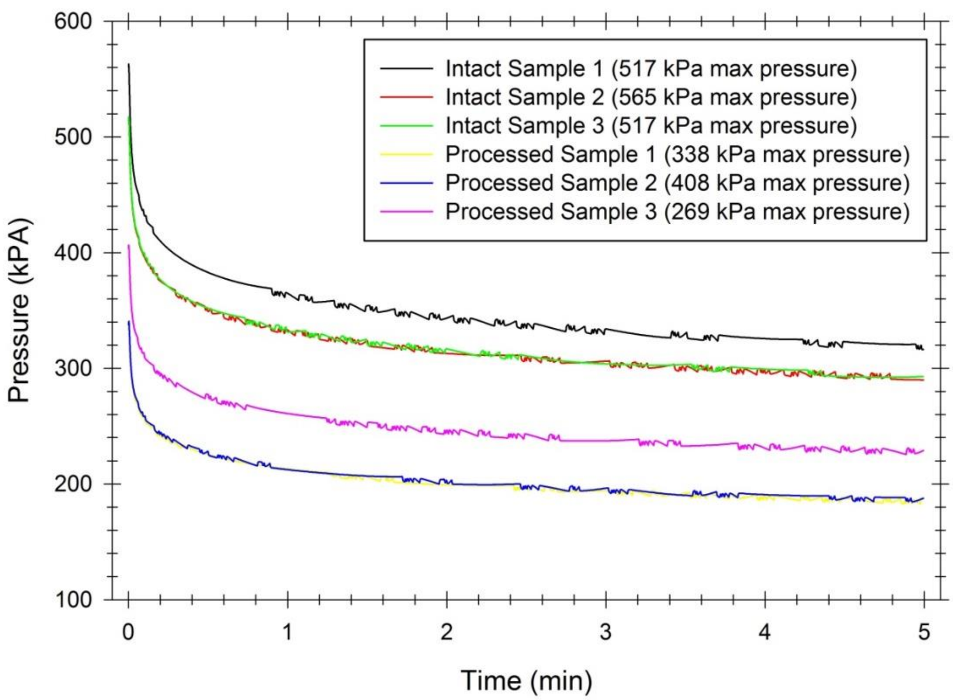


Figure A-12 Pressure relaxation for high moisture (20%), rewetted miscanthus under constant displacement

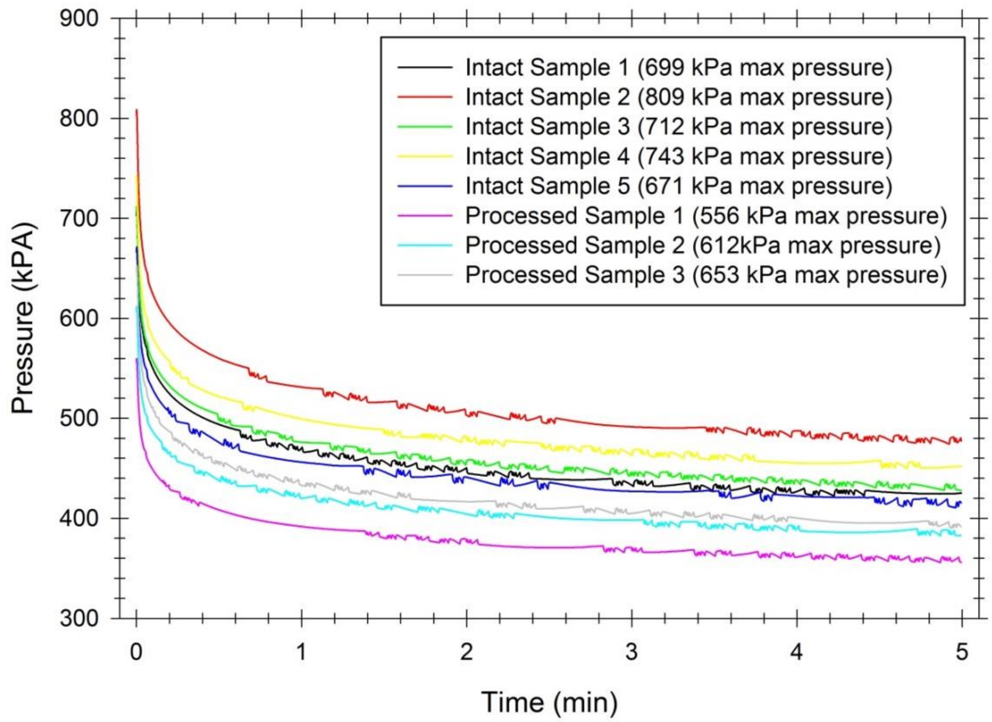


Figure A-13 Pressure relaxation for low moisture switchgrass under constant displacement

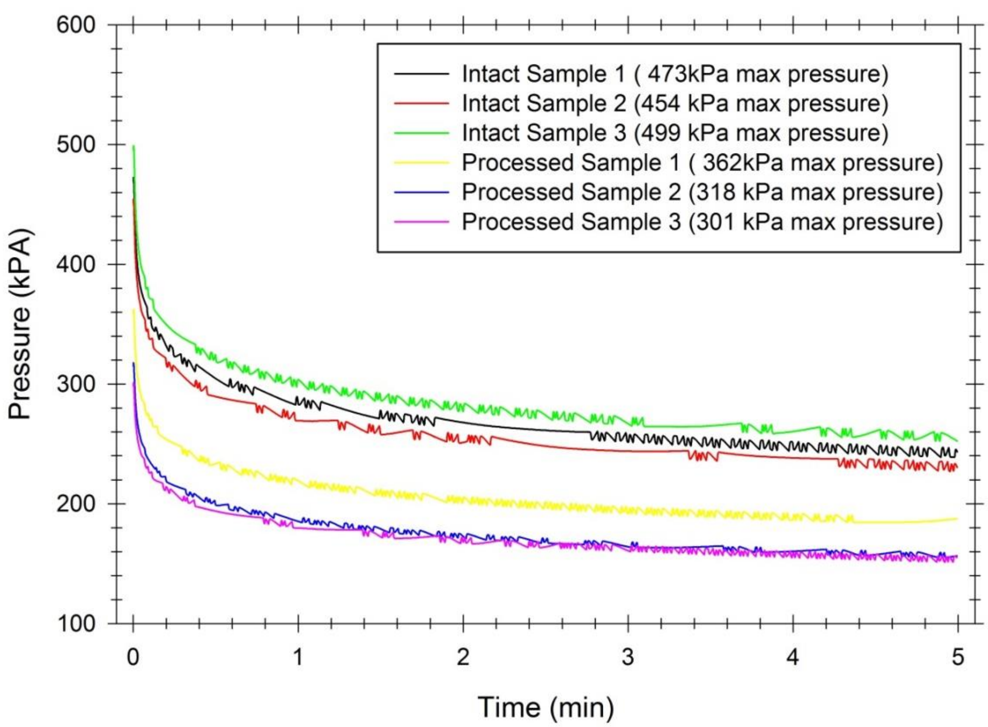


Figure A-14 Pressure Relaxation for high moisture (20%) switchgrass under constant displacement

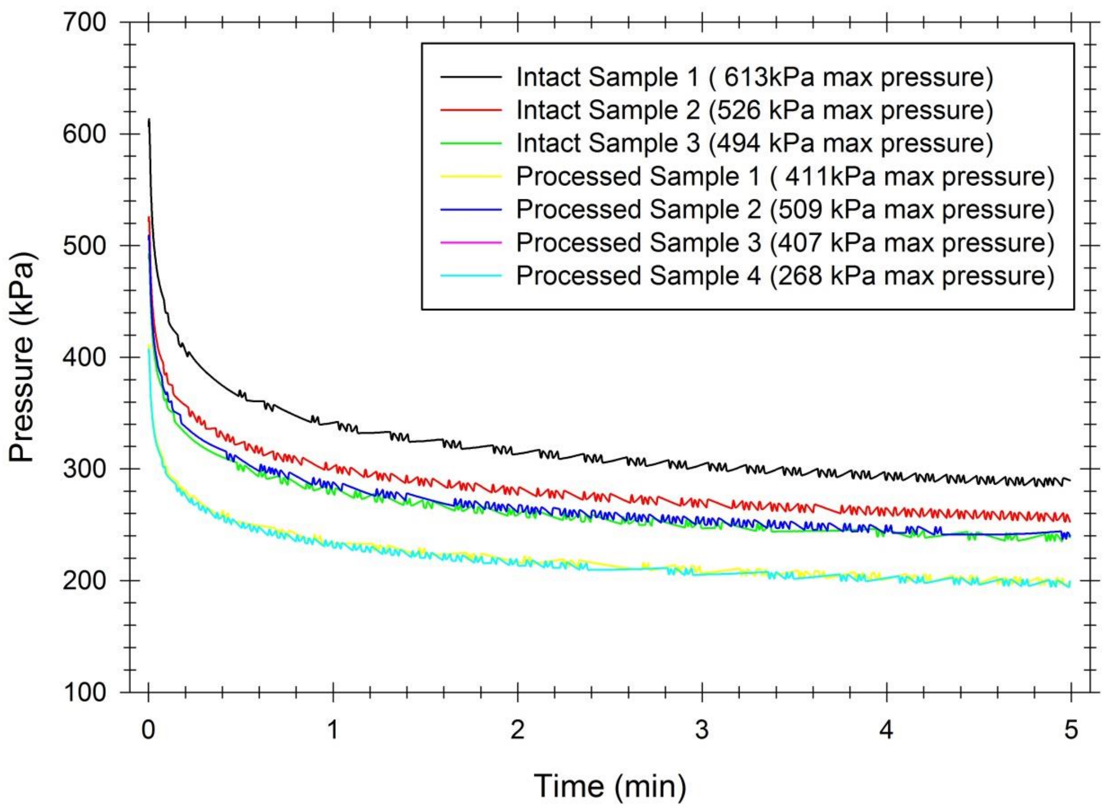


Figure A-15 Pressure relaxation for high moisture (45-50%), green switchgrass under constant displacement

Appendix B. Model Simulation Results

B.1. Pressure density model fit parameters

Table B-1: Model fit coefficient and confidence interval, miscanthus

Treatment	**Moisture level**	**Model**	**bo**	**95% CI**		**b1**	**95% CI**	
Intact	All	(1)	2.42	2.40	2.45	0.0005	0.0005	0.0006
		(2)	1.75	1.72	1.77	0.4009	0.3859	0.4159
		(3)	357	344	370	0.0056	0.0054	0.0057
Intact	Low	(1)	2.90	2.88	2.92	0.0001	0.0000	0.0001
		(2)	1.77	1.74	1.81	0.5070	0.4875	0.5265
		(3)	229	219	239	0.0077	0.0075	0.0079
Intact	High	(1)	2.44	2.42	2.45	0.0004	0.0004	0.0005
		(2)	1.82	1.80	1.83	0.2391	0.2296	0.2486
		(3)	785	744	827	0.0029	0.0028	0.0030
Processed	All	(1)	3.03	3.00	3.05	0.0000	0.0000	0.0000
		(2)	0.75	0.74	0.77	0.6657	0.6507	0.6806
		(3)	66	65	67	0.0110	0.0109	0.0111
Processed	Low	(1)	3.47	3.45	3.48	0.0000	0.0000	0.0000
		(2)	0.65	0.65	0.65	1.0623	1.0572	1.0674
		(3)	59	59	60	0.0120	0.0120	0.0121
Processed	High	(1)	3.25	3.24	3.26	0.0000	0.0000	0.0000
		(2)	0.63	0.62	0.64	0.7255	0.7145	0.7364
		(3)	64	63	65	0.0108	0.0107	0.0109

Table B-2: Model fit coefficient and confidence interval, switchgrass

Treatment	**Moisture level**	**Model**	**bo**	**95% CI**		**b1**	**95% CI**	
Intact	All	(1)	2.40	2.37	2.43	0.0006	0.0005	0.0007
		(2)	1.03	1.01	1.04	0.6937	0.6796	0.7079
		(3)	127	123	130.30	0.0096	0.0094	0.0097
Intact	Low	(1)	2.88	2.87	2.89	0.0001	0.0001	0.0001
		(2)	1.18	1.17	1.19	0.7364	0.7318	0.7410
		(3)	127	126	128.50	0.0103	0.0102	0.0103
Intact	High	(1)	2.66	2.65	2.67	0.0001	0.0001	0.0001
		(2)	0.83	0.83	0.84	0.6033	0.5989	0.6077
		(3)	123	122	124.83	0.0084	0.0083	0.0084
Processed	All	(1)	2.67	2.61	2.73	0.0001	0.0001	0.0001
		(2)	0.53	0.52	0.55	0.9999	0.9807	1.0192
		(3)	44	42	45.49	0.0139	0.0137	0.0141
Processed	Low	(1)	3.30	3.28	3.32	0.0000	0.0000	0.0000
		(2)	0.70	0.69	0.71	0.9471	0.9368	0.9574
		(3)	59	57	60.13	0.0132	0.0130	0.0133
Processed	High	(1)	3.43	3.40	3.45	0.0000	0.0000	0.0000
		(2)	0.54	0.52	0.55	0.7013	0.6810	0.7217
		(3)	44	42	45.01	0.0122	0.0120	0.0124

B.2. Fit parameters for models 1 and 2 evaluated based on dry density

Table B-3 Model fit parameters using dry density, miscanthus

Treatment	Moisture level	Model	bo	b1	r^2	RMSE (kPa)	AIC
Intact	All	(1)	2.66	0.000	0.966	27.04	39,166
		(2)	1.43	0.362	0.899	46.80	45,683
		(3)	357	0.006	0.969	25.99	38,698
Intact	Low	(1)	2.90	0.000	0.980	22.93	17,037
		(2)	1.46	0.552	0.948	36.79	19,607
		(3)	229	0.008	0.968	28.73	18,262
Intact	High	(1)	2.42	0.001	0.967	24.34	20,560
		(2)	1.14	0.430	0.983	17.19	18,321
		(3)	785	0.003	0.987	14.94	17,414
Processed	All	(1)	3.35	0.000	0.992	7.73	23,444
		(2)	0.65	0.508	0.869	31.39	39,514
		(3)	66	0.011	0.988	9.30	25,570
Processed	Low	(1)	3.47	0.000	0.994	7.01	10,420
		(2)	0.52	1.055	0.995	6.05	9,635
		(3)	59	0.012	0.998	3.76	7,081
Processed	High	(1)	3.25	0.000	0.991	7.76	12,526
		(2)	0.42	0.699	0.969	14.79	16,474
		(3)	64	0.011	0.994	6.62	11,561

Table B-4 Model fit parameters using dry density, switchgrass

Treatment	Moisture level	Model	bo	b1	r^2	RMSE (kPa)	AIC
Intact	All	(1)	2.80	0.000	0.936	35.08	69,077
		(2)	1.09	0.430	0.813	59.94	79,478
		(3)	127	0.010	0.937	34.72	68,877
Intact	Low	(1)	2.89	0.000	0.994	11.97	30,124
		(2)	1.00	0.714	0.993	12.90	31,034
		(3)	127	0.010	0.993	12.73	30,878
Intact	High	(1)	2.66	0.000	0.998	4.58	11,073
		(2)	0.59	0.583	0.997	5.43	12,317
		(3)	123	0.008	0.996	6.10	13,166
Processed	All	(1)	3.39	0.000	0.865	39.54	49,382
		(2)	0.57	0.664	0.752	53.59	53,463
		(3)	44	0.014	0.913	31.70	46,414
Processed	Low	(1)	3.30	0.000	0.981	17.48	20,820
		(2)	0.59	0.900	0.981	17.67	20,897
		(3)	59	0.013	0.981	17.61	20,873
Processed	High	(1)	3.45	0.000	0.984	9.01	13,525
		(2)	0.36	0.688	0.924	19.90	18,400
		(3)	44	0.012	0.972	12.01	15,295

Table B-5: Dry density model fit coefficient and confidence interval, miscanthus

Treatment	Moisture level	Model	bo	95% CI		b1	95% CI	
Intact	All	(1)	2.66	2.64	2.67	0.0002	0.0002	0.0003
		(2)	1.43	1.40	1.46	0.3615	0.3459	0.3772
		(3)	357	344	370	0.0056	0.0054	0.0057
Intact	Low	(1)	2.90	2.88	2.92	0.0001	0.0001	0.0001
		(2)	1.46	1.43	1.49	0.5525	0.5350	0.5699
		(3)	229	219	239	0.0077	0.0075	0.0079
Intact	High	(1)	2.42	2.40	2.44	0.0008	0.0007	0.0009
		(2)	1.14	1.13	1.15	0.4296	0.4215	0.4377
		(3)	785	744	827	0.0029	0.0028	0.0030
Processed	All	(1)	3.35	3.34	3.36	0.0000	0.0000	0.0000
		(2)	0.65	0.64	0.67	0.5076	0.4916	0.5235
		(3)	66	65	67	0.0110	0.0109	0.0111
Processed	Low	(1)	3.47	3.45	3.48	0.0000	0.0000	0.0000
		(2)	0.52	0.52	0.53	1.0547	1.0480	1.0614
		(3)	59	59	60	0.0120	0.0120	0.0121
Processed	High	(1)	3.25	3.23	3.26	0.0000	0.0000	0.0000
		(2)	0.42	0.42	0.43	0.6988	0.6890	0.7087
		(3)	64	63	65	0.0108	0.0107	0.0109

Table B-6: Dry density model fit coefficient and confidence interval, switchgrass

Treatment	Moisture level	Model	bo	95% CI		b1	95% CI	
Intact	All	(1)	2.80	2.78	2.82	0.0001	0.0001	0.0001
		(2)	1.09	1.07	1.12	0.4304	0.4152	0.4455
		(3)	127	123	130.30	0.0096	0.0094	0.0097
Intact	Low	(1)	2.89	2.88	2.90	0.0001	0.0001	0.0001
		(2)	1.00	1.00	1.01	0.7136	0.7097	0.7175
		(3)	127	126	128.50	0.0103	0.0102	0.0103
Intact	High	(1)	2.66	2.66	2.67	0.0002	0.0002	0.0002
		(2)	0.59	0.59	0.59	0.5825	0.5799	0.5851
		(3)	123	122	124.83	0.0084	0.0083	0.0084
Processed	All	(1)	3.39	3.34	3.43	0.0000	0.0000	0.0000
		(2)	0.57	0.55	0.59	0.6636	0.6411	0.6861
		(3)	44	42	45.49	0.0139	0.0137	0.0141
Processed	Low	(1)	3.30	3.28	3.32	0.0000	0.0000	0.0000
		(2)	0.59	0.58	0.60	0.8997	0.8907	0.9087
		(3)	59	57	60.13	0.0132	0.0130	0.0133
Processed	High	(1)	3.45	3.43	3.48	0.0000	0.0000	0.0000
		(2)	0.36	0.35	0.37	0.6883	0.6727	0.7040
		(3)	44	42	45.01	0.0122	0.0120	0.0124

B.3. Graphical representation of pressure density model fits

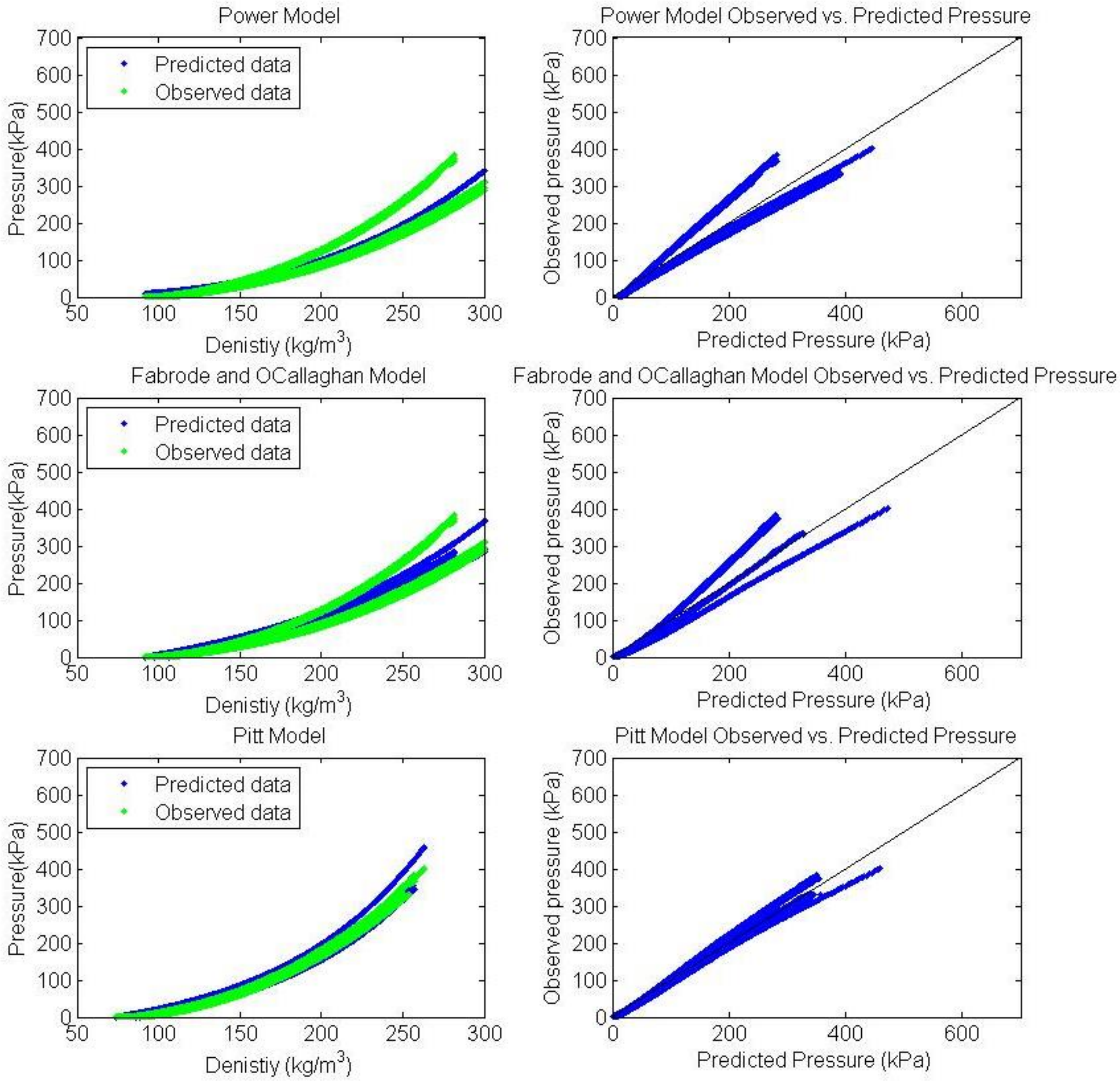


Figure B-1 Fit assessment for processed miscanthus, all moisture levels

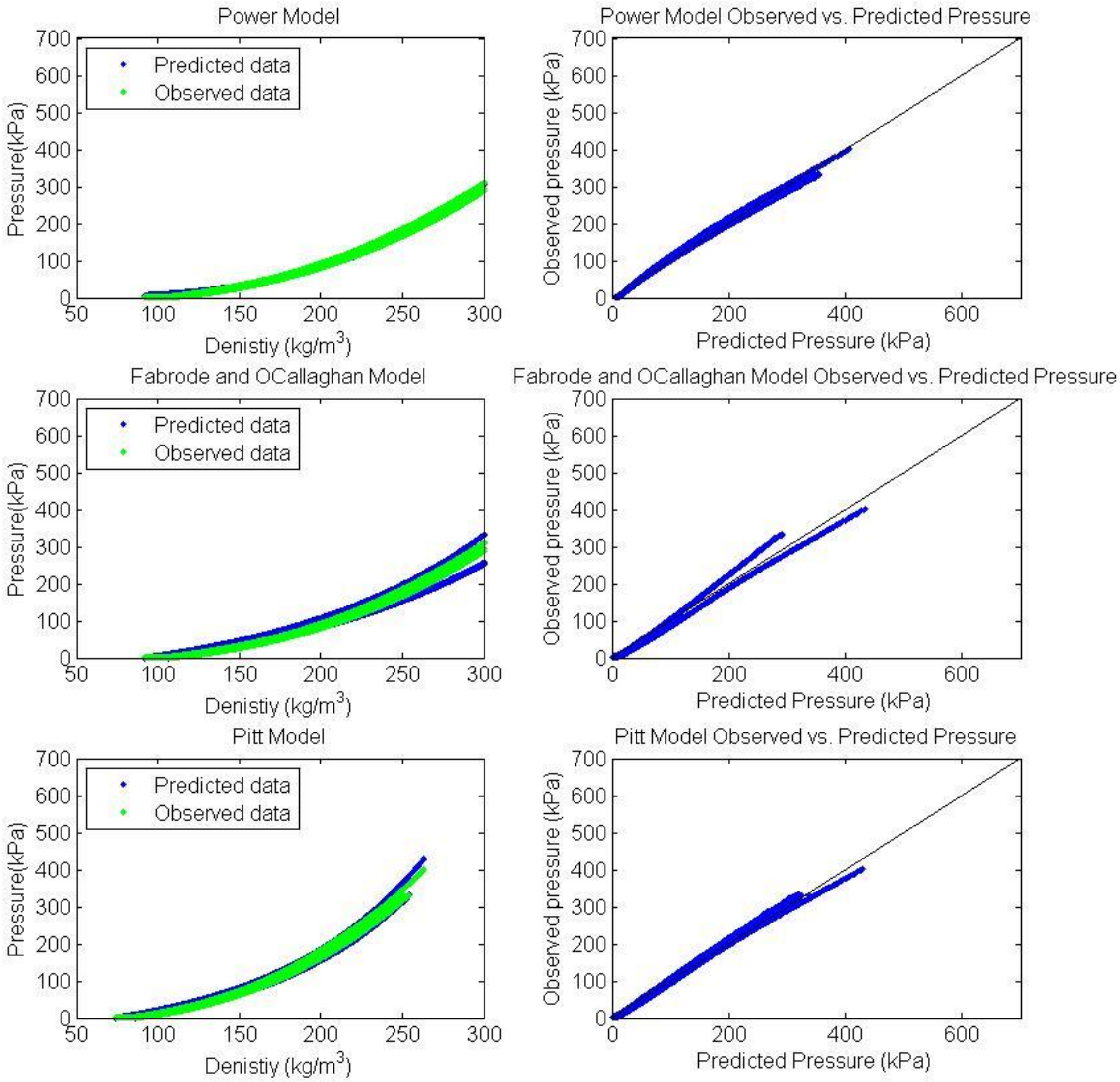


Figure B-2 Fit assessment for processed, high moisture miscanthus

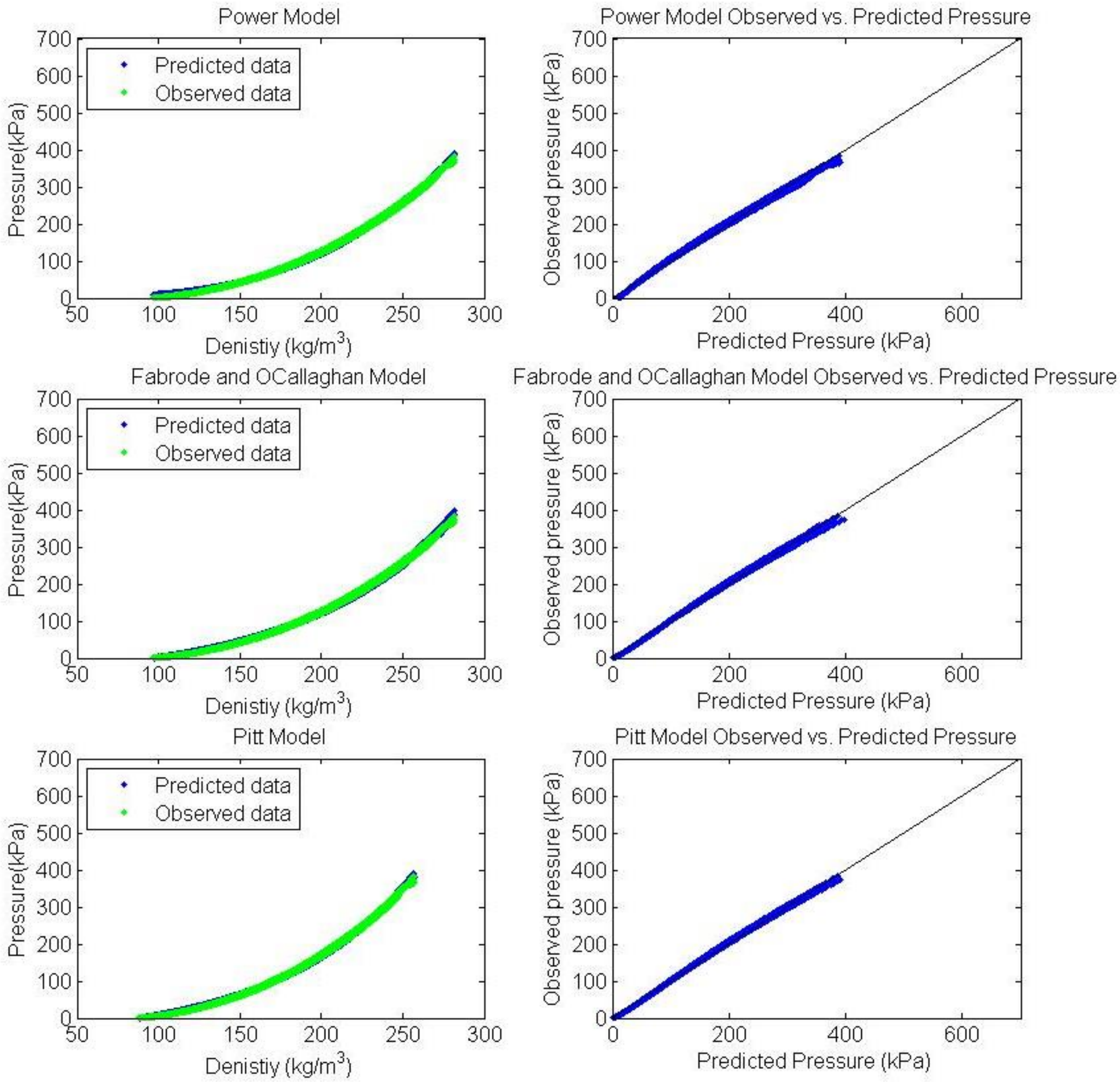


Figure B-3 Fit assessment for processed, low moisture, miscanthus

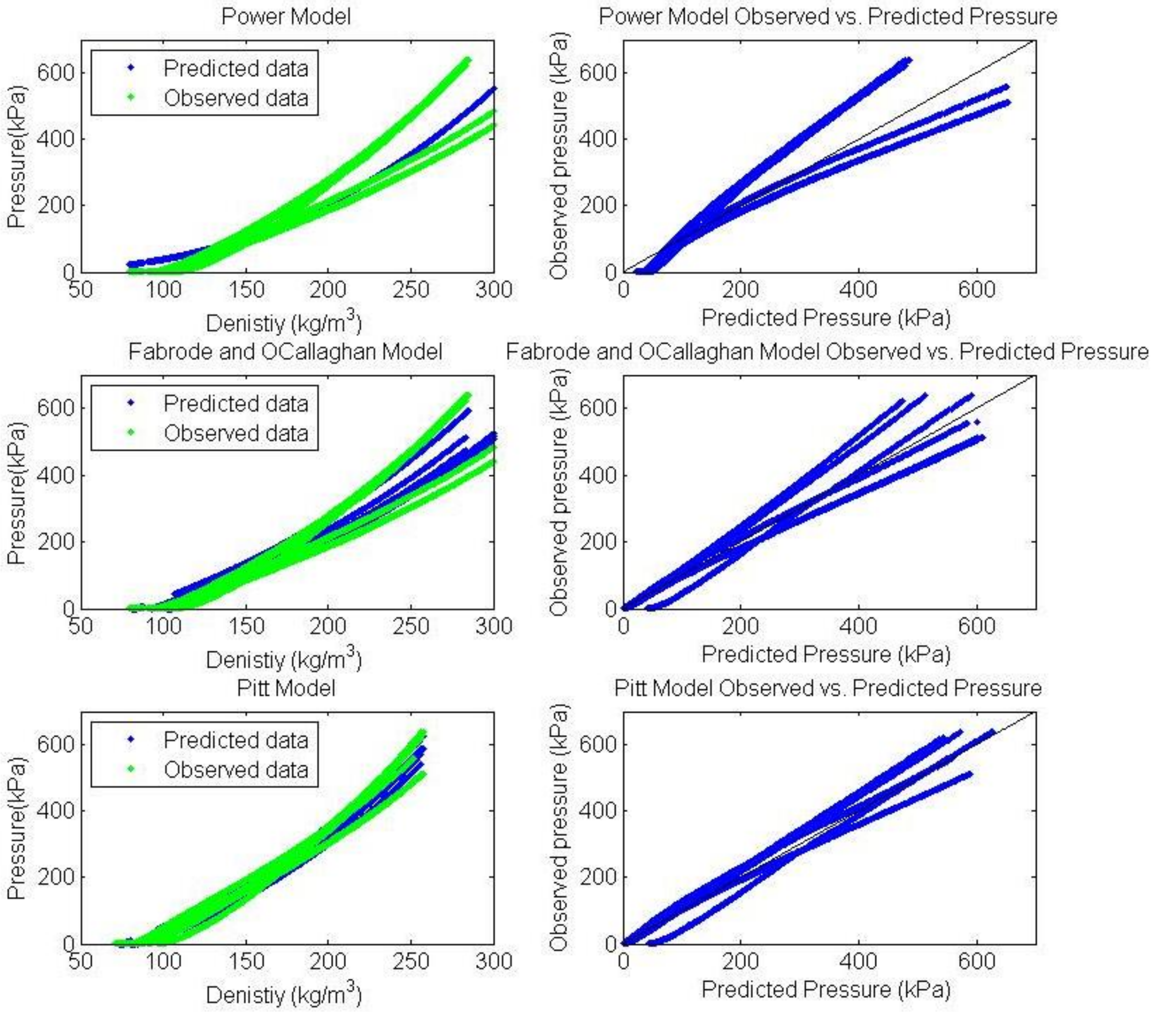


Figure B-4 Fit assessment for intact miscanthus, all moisture levels

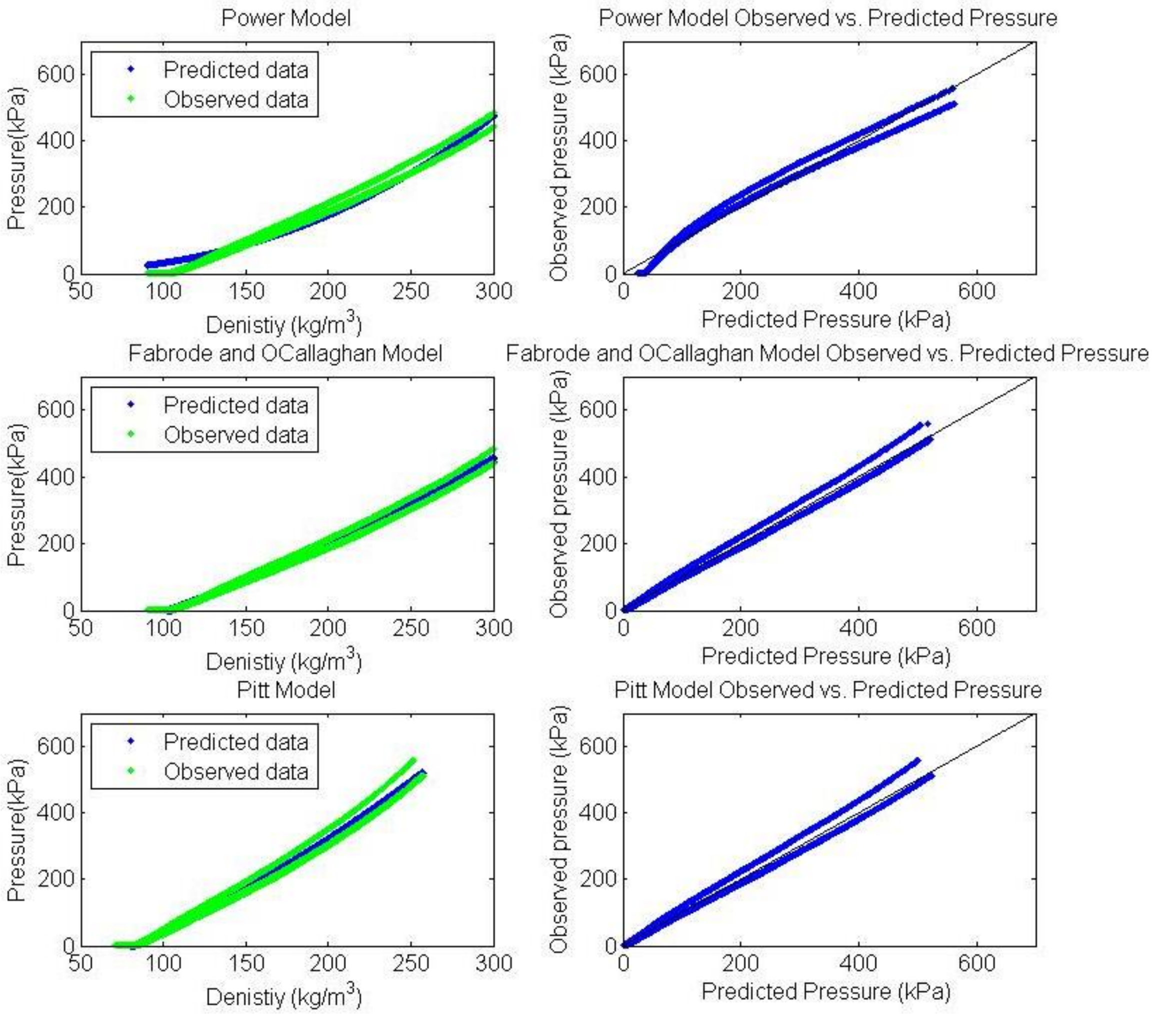


Figure B-5 Fit assessment for intact, high moisture miscanthus

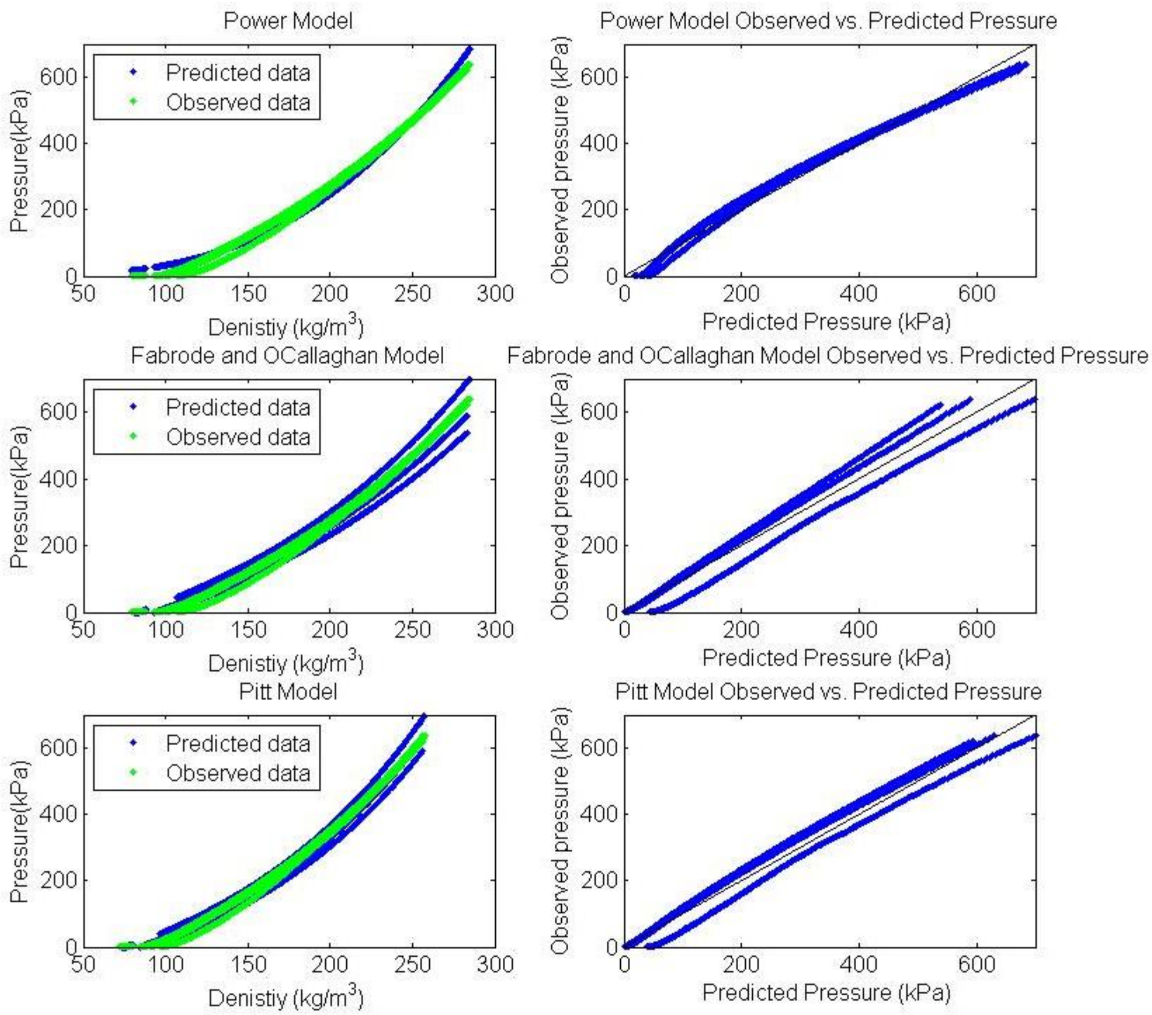


Figure B-6 Fit assessment for intact, low moisture miscanthus

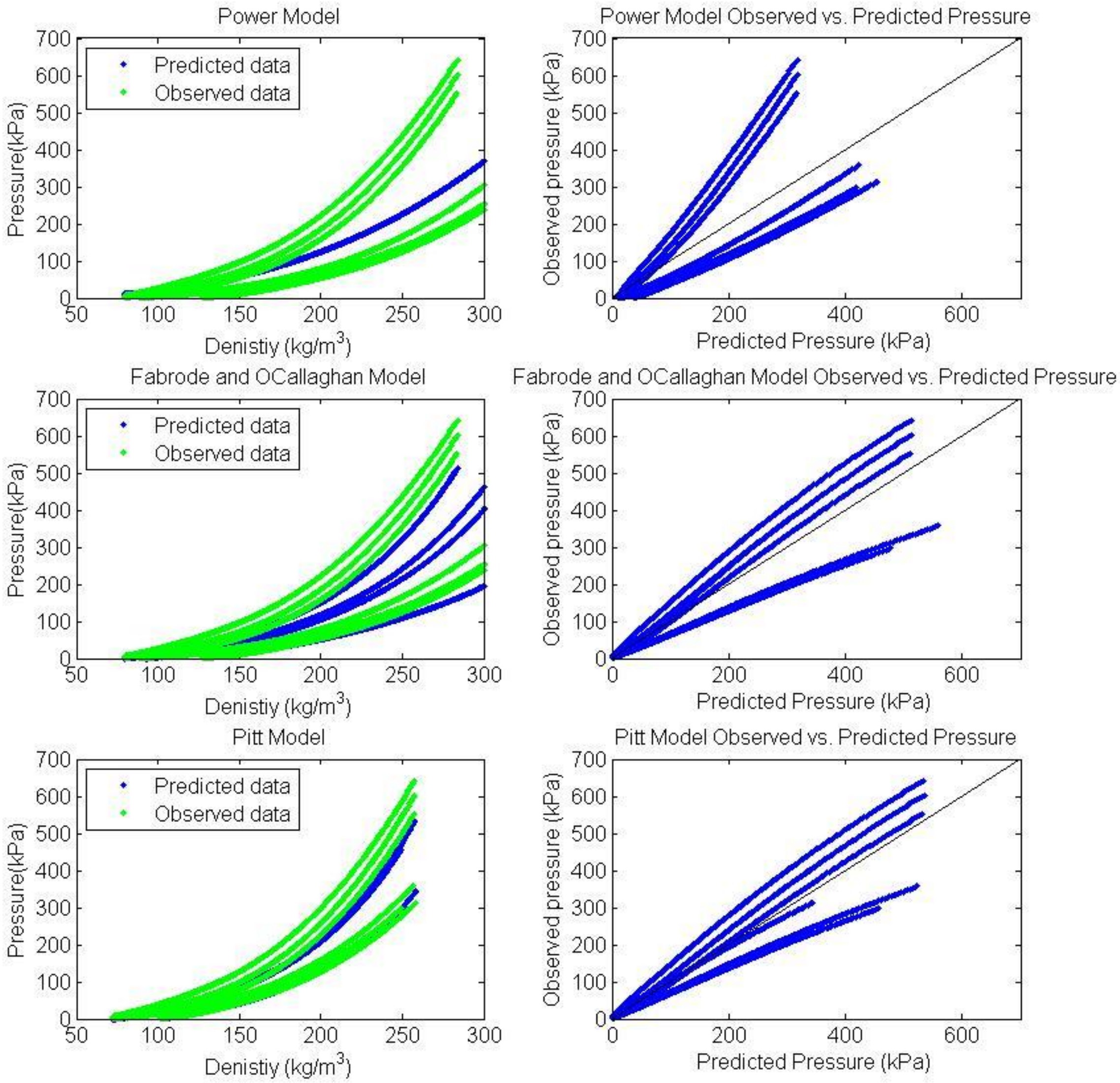


Figure B-7 Fit assessment for processed switchgrass, all moisture levels

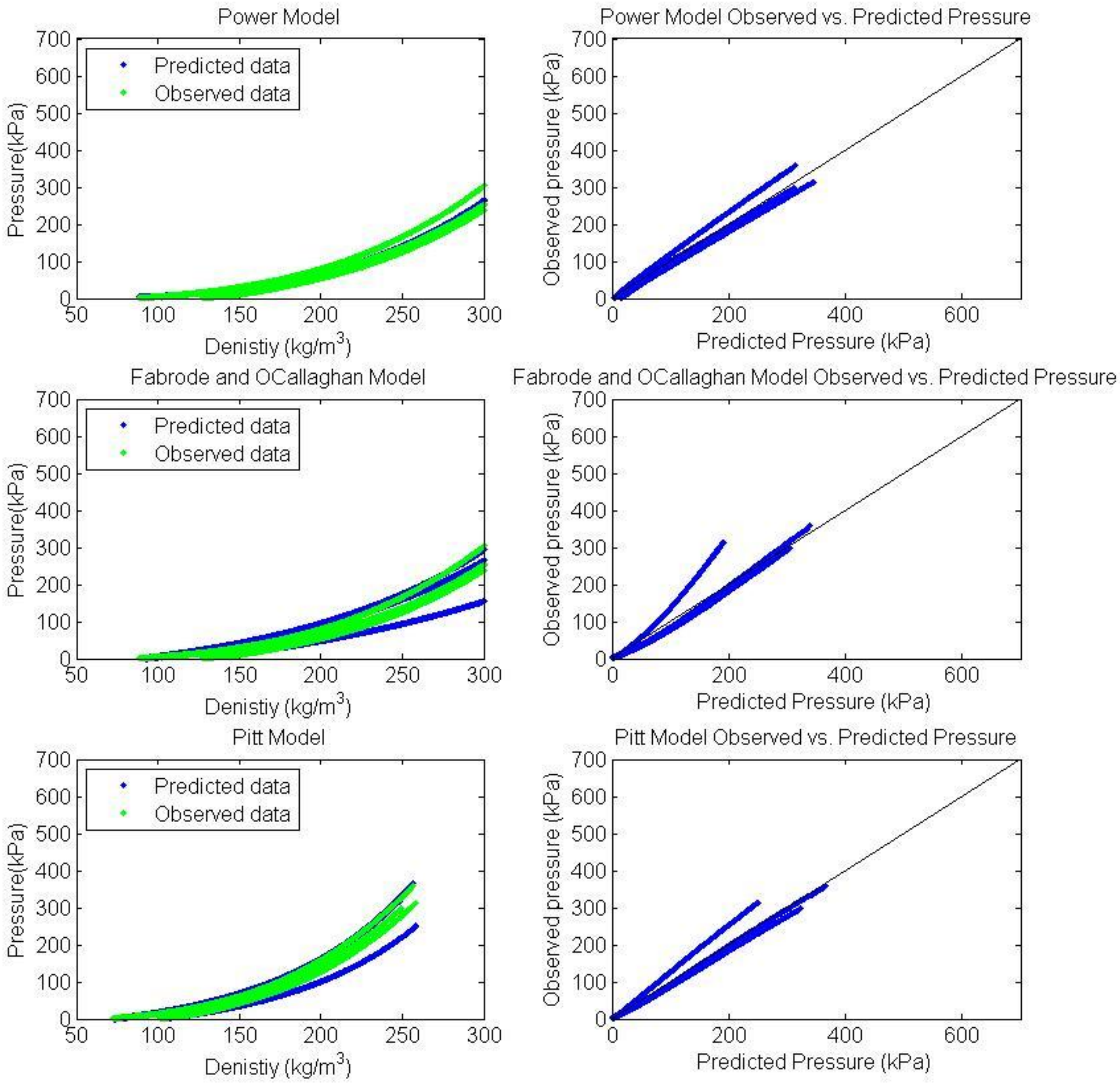


Figure B-8 Fit assessment for processed, high moisture switchgrass

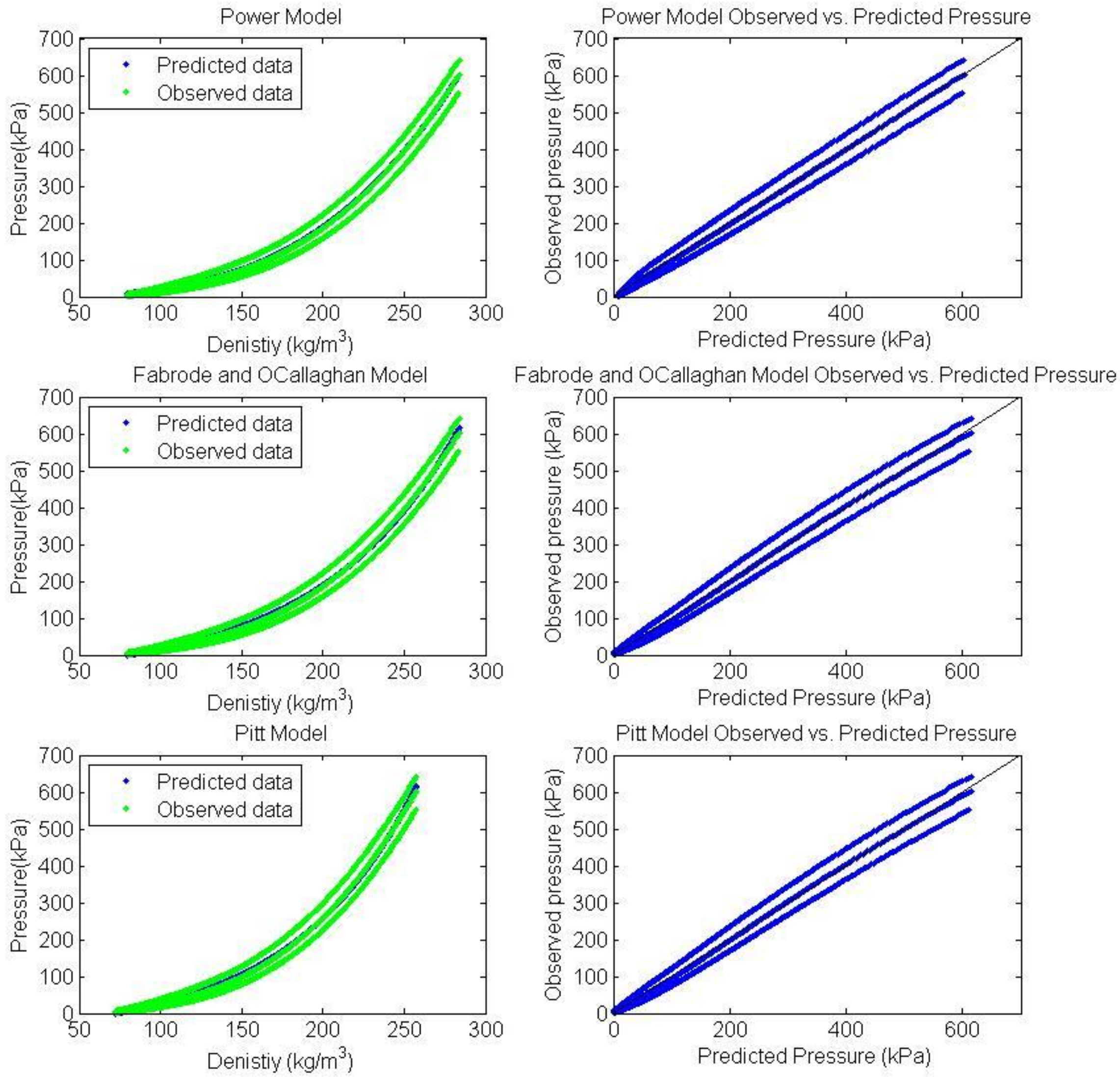


Figure B-9 Fit assessment for processed, low moisture, switchgrass

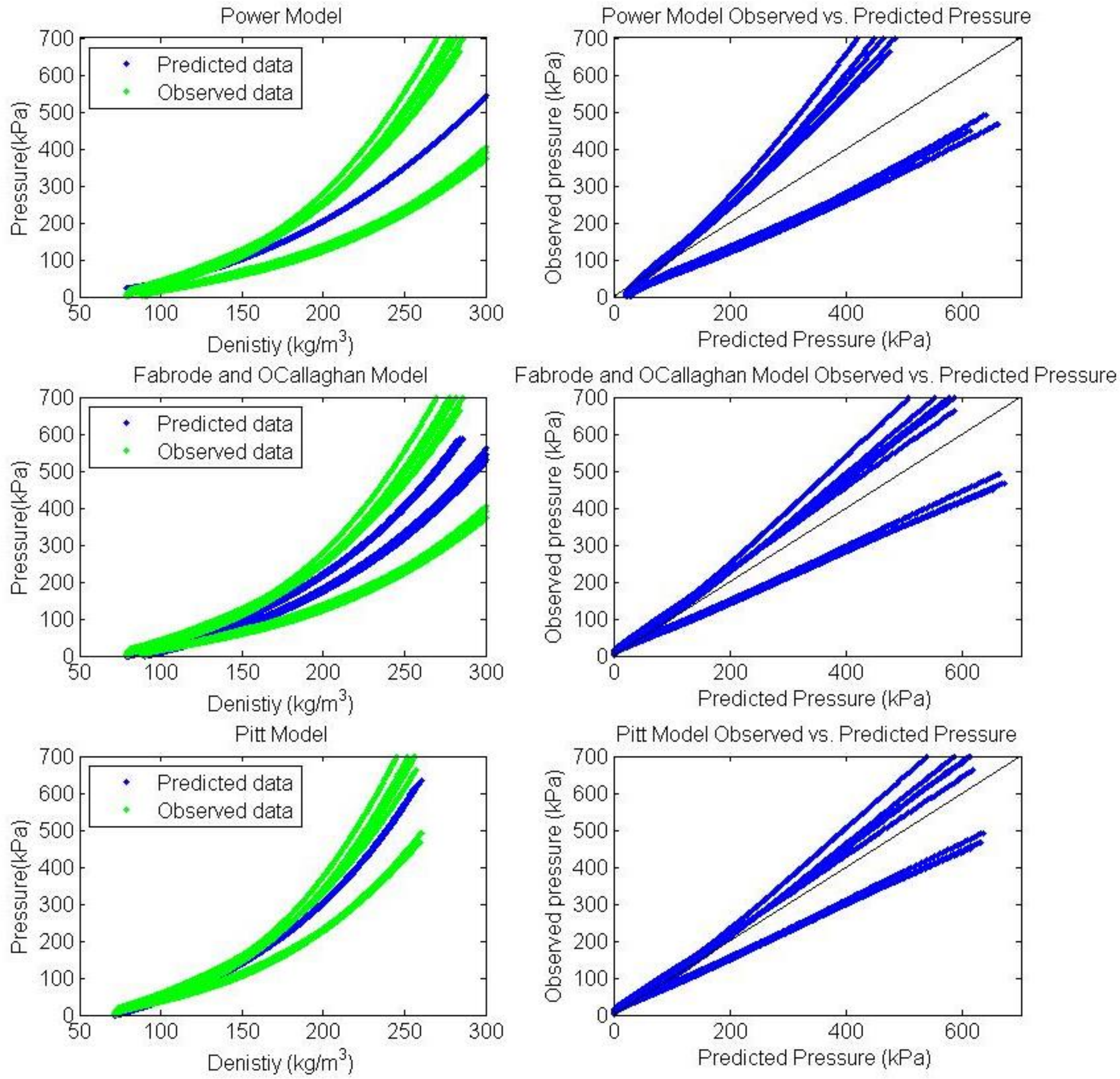


Figure B-10 Fit assessment for intact switchgrass, all moisture levels

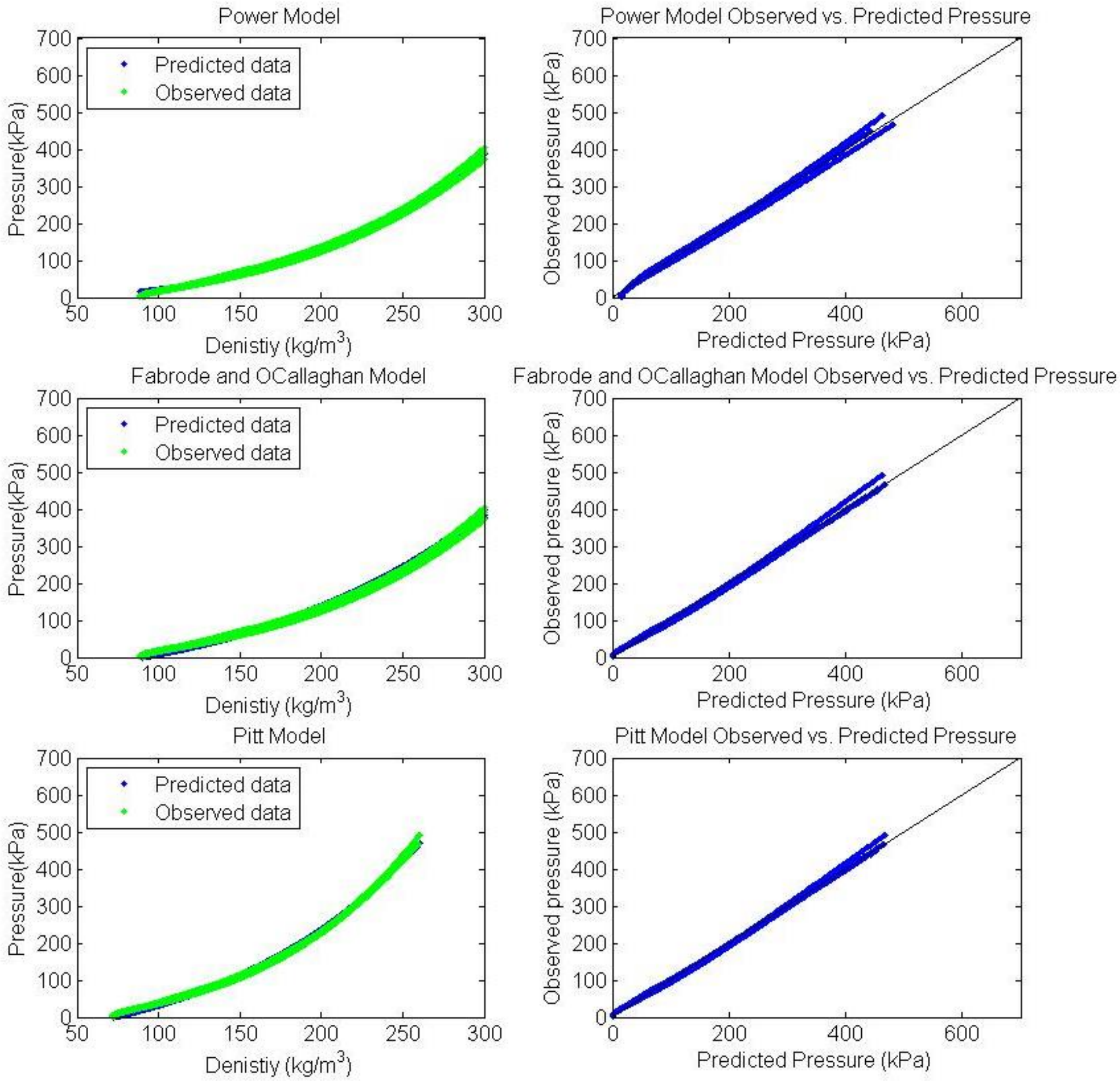


Figure B-11 Fit assessment for intact, high moisture switchgrass

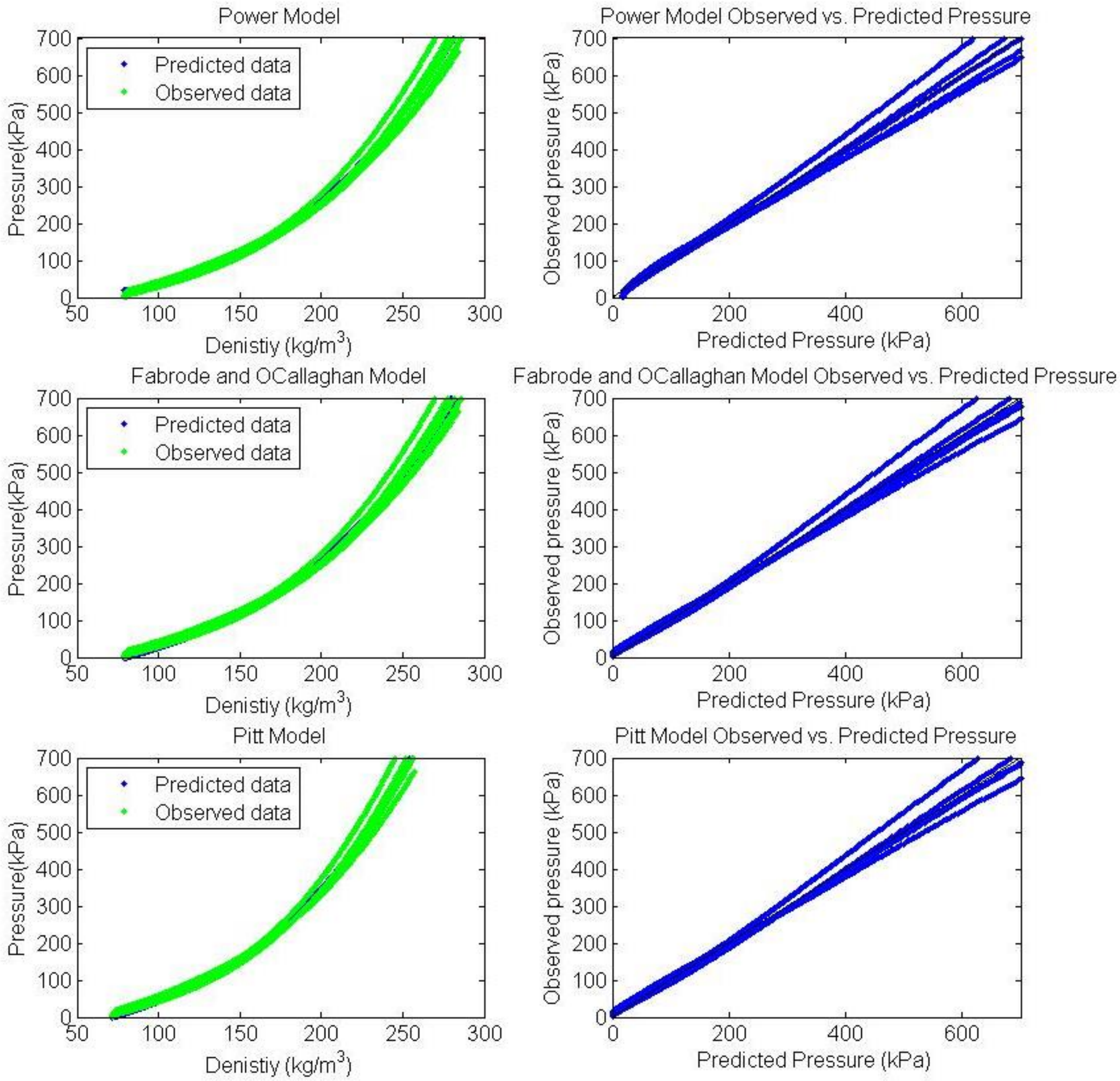


Figure B-12 Fit assessment for intact, low moisture switchgrass

B.4. Normalized relaxation

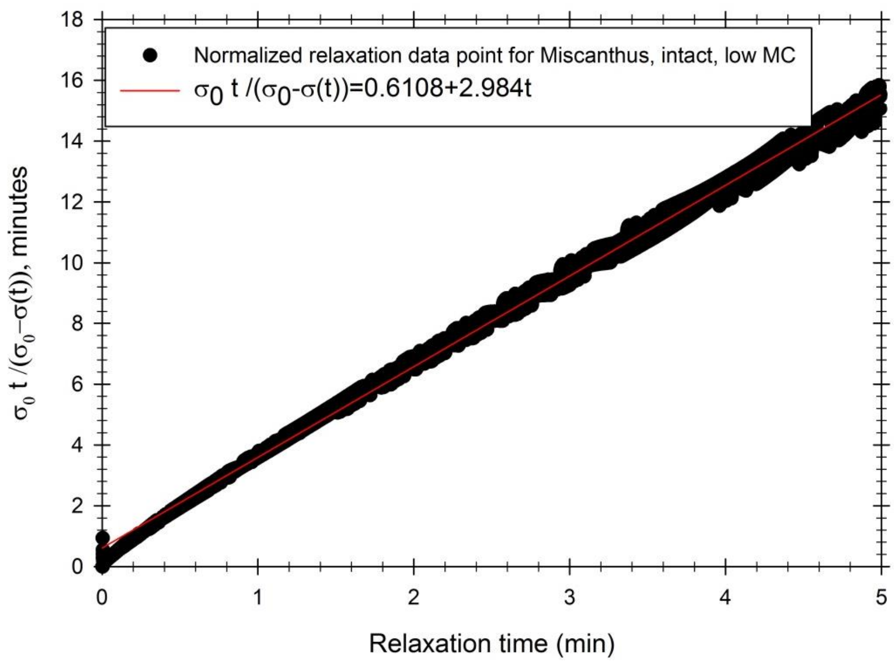


Figure B-13: Normalized stress relaxation fit to Equation 2-9 for low moisture intact miscanthus

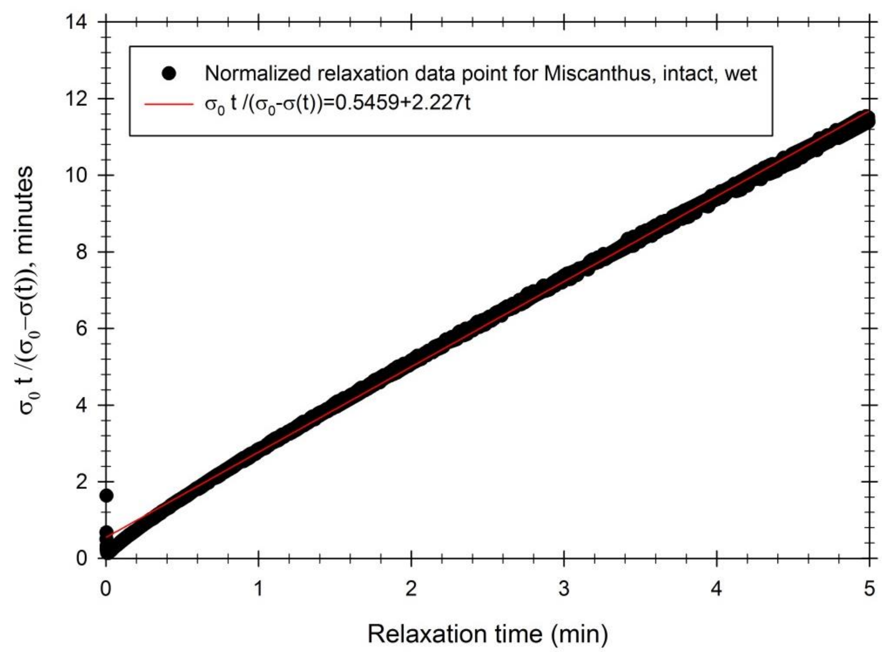


Figure B-14: Normalized stress relaxation fit to Equation 2-9 for high moisture intact miscanthus

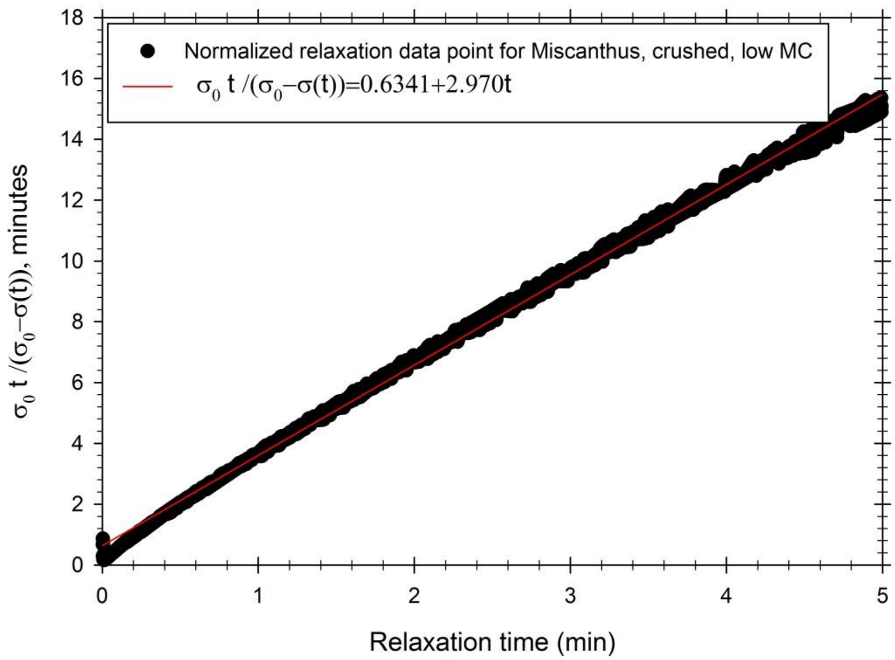


Figure B-15: Normalized stress relaxation fit to Equation 2-9 for processed, low moisture miscanthus

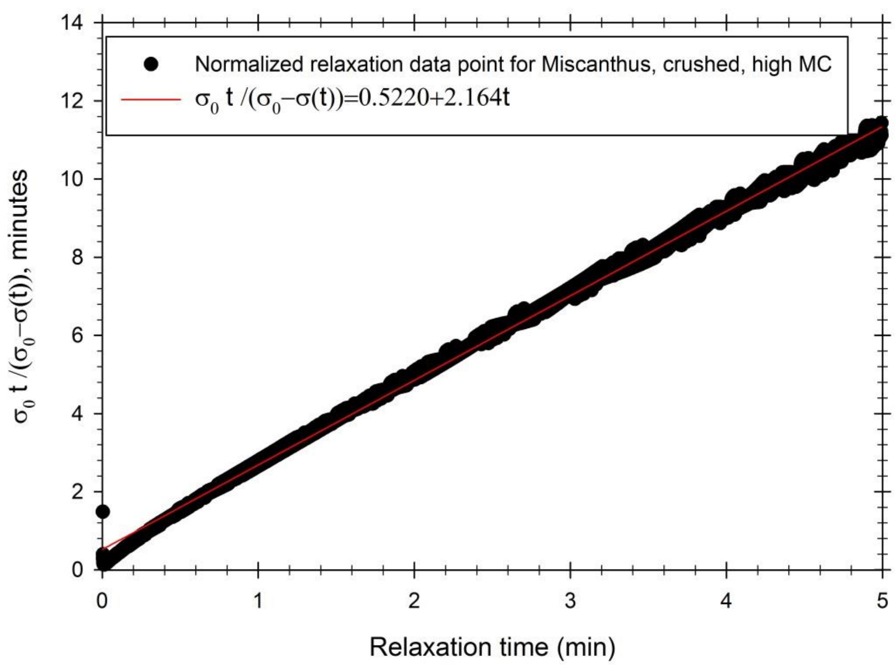


Figure B-16: Normalized stress relaxation fit to Equation 2-9 for processed, high moisture miscanthus

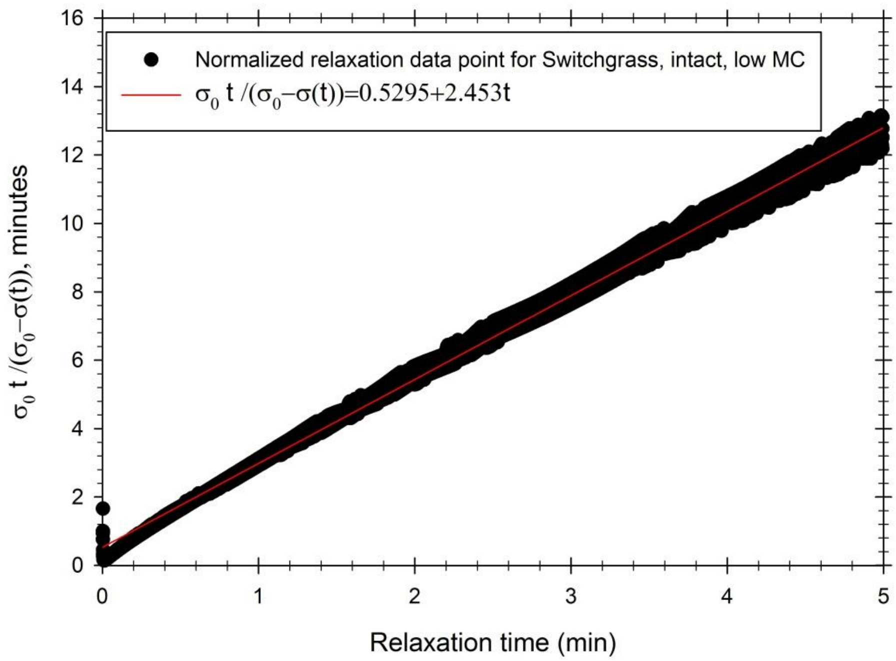


Figure B-17 Normalized stress relaxation fit to Equation 2-9 for intact, low moisture switchgrass

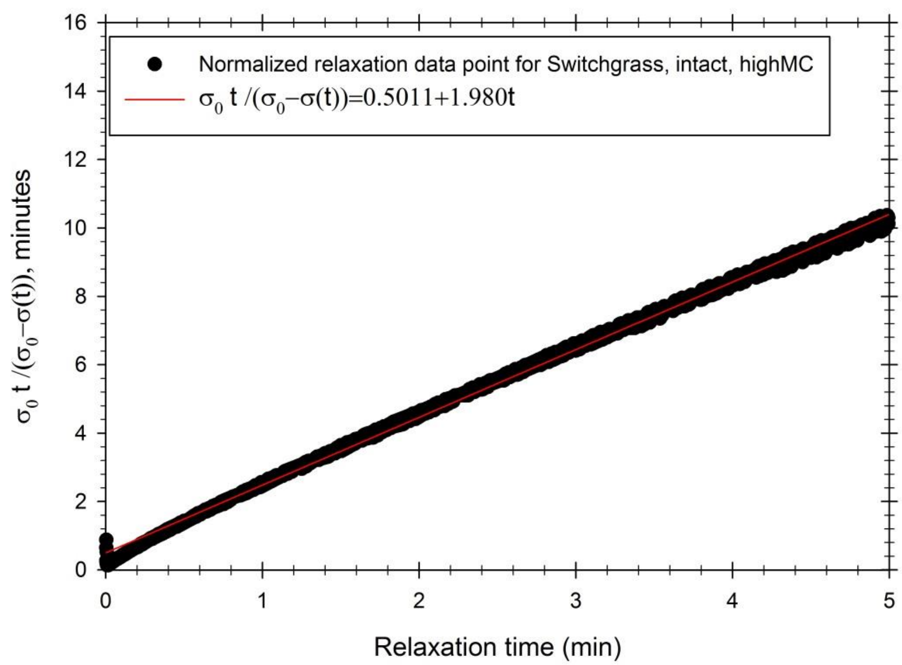


Figure B-18: Normalized stress relaxation fit to Equation 2-9 for high moisture intact switchgrass

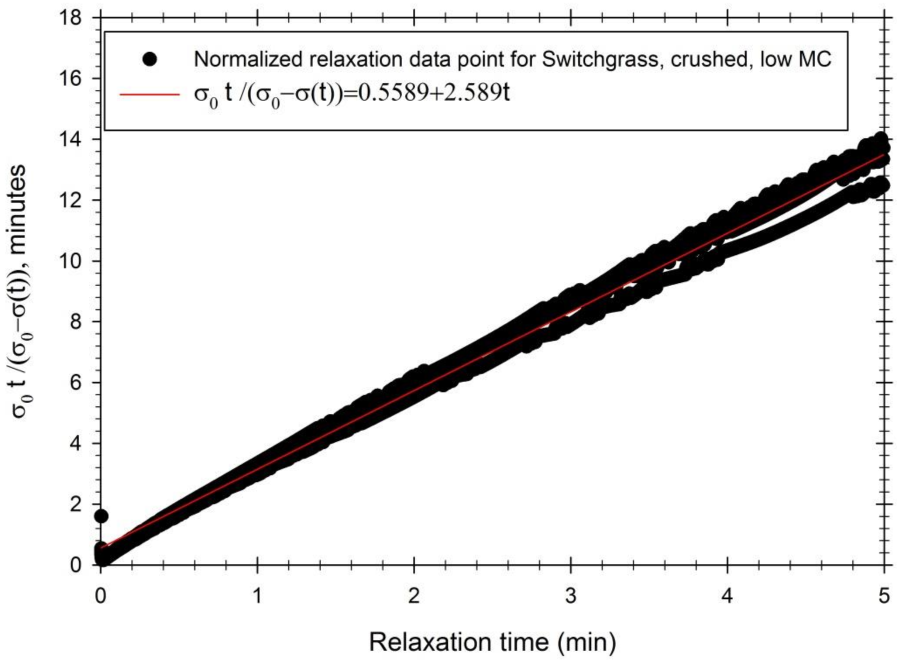


Figure B-19 Normalized stress relaxation fit to Equation 2-9 for processed, low moisture switchgrass

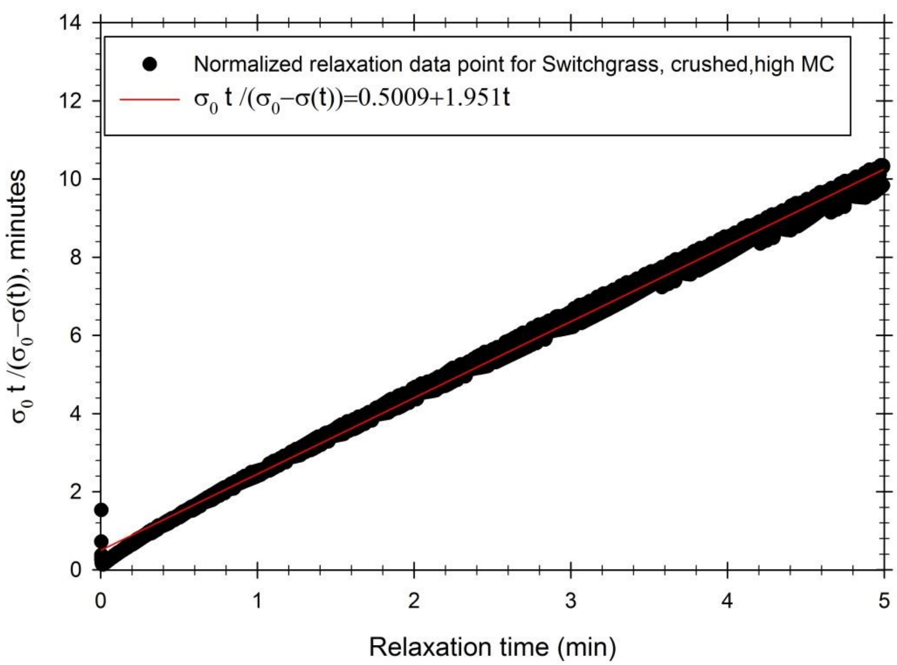


Figure B-20 Normalized stress relaxation fit to Equation 2-9 for processed, high moisture switchgrass

Appendix C. Individual component compression results

C.1. Multiple comparisons for node and internode sections

Table C-1: P value for apparent modulus of elasticity by miscanthus node location. H0: LSMean(node(i))=LSMean(node(j))

i/j	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**internode**
1		0.1948	0.2947	0.0046	0.0119	0.0016	0.0012	0.4284	0.048	0.8098	0.6542	0.7278	0.0892
2	0.1948		0.8062	0.1371	0.2457	0.0709	0.0567	0.6672	0.4031	0.4422	0.6265	0.5583	0.0023
3	0.2947	0.8062		0.0822	0.1575	0.0398	0.0312	0.8435	0.2931	0.5653	0.7583	0.6844	0.0053
4	0.0046	0.1371	0.0822		0.7309	0.7341	0.6558	0.0652	0.659	0.0529	0.1189	0.0972	<.0001
5	0.0119	0.2457	0.1575	0.7309		0.4946	0.4302	0.124	0.8779	0.092	0.1847	0.1538	<.0001
6	0.0016	0.0709	0.0398	0.7341	0.4946		0.9155	0.0321	0.4685	0.0291	0.0737	0.0591	<.0001
7	0.0012	0.0567	0.0312	0.6558	0.4302	0.9155		0.0253	0.416	0.0239	0.0629	0.0502	<.0001
8	0.4284	0.6672	0.8435	0.0652	0.124	0.0321	0.0253		0.2366	0.6913	0.8797	0.8046	0.0165
9	0.048	0.4031	0.2931	0.659	0.8779	0.4685	0.416	0.2366		0.1632	0.2728	0.2348	0.0005
10	0.8098	0.4422	0.5653	0.0529	0.092	0.0291	0.0239	0.6913	0.1632		0.8456	0.9135	0.1341
11	0.6542	0.6265	0.7583	0.1189	0.1847	0.0737	0.0629	0.8797	0.2728	0.8456		0.9349	0.1087
12	0.7278	0.5583	0.6844	0.0972	0.1538	0.0591	0.0502	0.8046	0.2348	0.9135	0.9349		0.1336
internode	0.0892	0.0023	0.0053	<.0001	<.0001	<.0001	<.0001	0.0165	0.0005	0.1341	0.1087	0.1336	

Table C-2: P value for Smax by miscanthus node location H0: LSMean(node(i))=LSMean(node(j))

i/j	1	2	3	4	5	6	7	8	9	10	11	12	internode
1		0.0205	0.0164	0.0527	0.0585	0.1312	0.0747	0.017	0.0389	0.0111	0.0117	0.0071	<.0001
2	0.0205		0.9334	0.632	0.6001	0.3664	0.5268	0.846	0.9784	0.4678	0.3956	0.3058	0.0442
3	0.0164	0.9334		0.5716	0.5412	0.3223	0.4717	0.9085	0.9628	0.5091	0.4302	0.3353	0.0549
4	0.0527	0.632	0.5716		0.9622	0.6568	0.872	0.5135	0.6553	0.2648	0.2268	0.1658	0.008
5	0.0585	0.6001	0.5412	0.9622		0.6914	0.9094	0.4863	0.6269	0.2501	0.2147	0.1562	0.0069
6	0.1312	0.3664	0.3223	0.6568	0.6914		0.7769	0.292	0.4137	0.149	0.131	0.0917	0.0018
7	0.0747	0.5268	0.4717	0.872	0.9094	0.7769		0.4244	0.5612	0.2171	0.1875	0.1349	0.0048
8	0.017	0.846	0.9085	0.5135	0.4863	0.292	0.4244		0.8829	0.5851	0.496	0.3949	0.0948
9	0.0389	0.9784	0.9628	0.6553	0.6269	0.4137	0.5612	0.8829		0.5179	0.4408	0.3505	0.0901
10	0.0111	0.4678	0.5091	0.2648	0.2501	0.149	0.2171	0.5851	0.5179		0.8759	0.7574	0.4601
11	0.0117	0.3956	0.4302	0.2268	0.2147	0.131	0.1875	0.496	0.4408	0.8759		0.8847	0.6287
12	0.0071	0.3058	0.3353	0.1658	0.1562	0.0917	0.1349	0.3949	0.3505	0.7574	0.8847		0.7668
internode	<.0001	0.0442	0.0549	0.008	0.0069	0.0018	0.0048	0.0948	0.0901	0.4601	0.6287	0.7668	

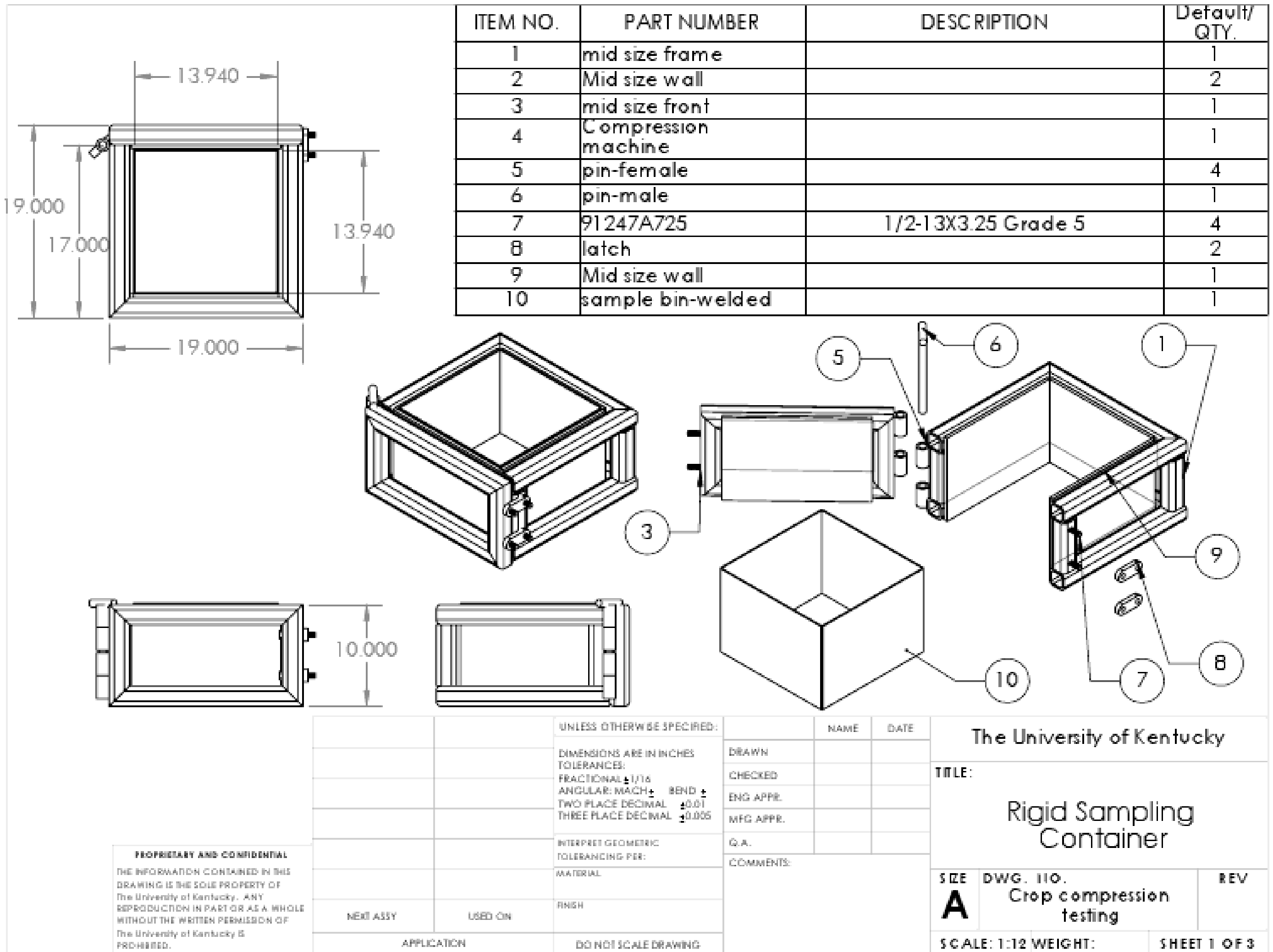
Table C-3: P value for apparent modulus of elasticity by switchgrass node location H0: LSMean(node(i))=LSMean(node(j))

i/j	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**internode**
1		0.0922	0.4461	0.921	0.8159	0.4799	0.2554	<.0001
2	0.0922		0.0134	0.1021	0.0631	0.4029	0.029	<.0001
3	0.4461	0.0134		0.3762	0.6172	0.1571	0.5038	<.0001
4	0.921	0.1021	0.3762		0.7379	0.5269	0.2259	<.0001
5	0.8159	0.0631	0.6172	0.7379		0.3673	0.3309	<.0001
6	0.4799	0.4029	0.1571	0.5269	0.3673		0.1179	<.0001
7	0.2554	0.029	0.5038	0.2259	0.3309	0.1179		0.0145
internode	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	0.0145	

Table C-4: P value for Smax by switchgrass node location H0: LSMean(node(i))=LSMean(node(j))

i/j	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**internode**
1		0.4864	0.7487	0.1296	0.7586	0.7187	0.3918	0.0001
2	0.4864		0.3005	0.3949	0.3244	0.3129	0.1951	<.0001
3	0.7487	0.3005		0.0625	0.998	0.9451	0.5084	0.0003
4	0.1296	0.3949	0.0625		0.0764	0.0782	0.0717	<.0001
5	0.7586	0.3244	0.998	0.0764		0.9492	0.5178	0.0007
6	0.7187	0.3129	0.9451	0.0782	0.9492		0.554	0.0014
7	0.3918	0.1951	0.5084	0.0717	0.5178	0.554		0.1228
internode	0.0001	<.0001	0.0003	<.0001	0.0007	0.0014	0.1228	

Appendix D. Rigid sample container



ITEM NO.	PART NUMBER	DESCRIPTION	Default/ QTY.
1	mid size frame		1
2	Mid size wall		2
3	mid size front		1
4	Compression machine		1
5	pin-female		4
6	pin-male		1
7	91247A725	1/2-13X3.25 Grade 5	4
8	latch		2
9	Mid size wall		1
10	sample bin-welded		1

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TECHNICAL PRESENTATIONS/ABSTRACTS

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