VISCOELASTIC PROPERTIES OF SEED COTTON

AND THEIR EFFECT ON MODULE SHAPE AND DENSITY

A Thesis

by

ROBERT GLEN HARDIN IV

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

August 2004

Major Subject: Biological and Agricultural Engineering

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Approved as to style and content by:

Stephen W. Searcy (Chair of Committee)	Calvin B. Parnell (Member)
Robert G. Lemon (Member)	Gerald L. Riskowski (Head of Department)

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ABSTRACT

Viscoelastic Properties of Seed Cotton and Their Effect on Module Shape and Density. (August 2004)

Robert Glen Hardin IV, B.S.; B.S., North Carolina State University

Chair of Advisory Committee: Dr. Stephen W. Searcy

Modules for cotton storage and transport should be constructed with a shape that will resist collecting water to maintain the quality of seed cotton during storage. Meeting this specification requires knowledge of the relationship between the applied compressive force, deformation, and time for seed cotton. Several factors were tested to determine their effects on the height and density of seed cotton during compression, creep loading, and recovery. Models were used to describe these processes. These results were used to develop an algorithm capable of providing information on module shape to the module builder operator.

The initial loading density did not affect the compressed density, but a slight effect was observed in the recovered density, due to the weight of the seed cotton. Picker harvested cotton was compressed to a greater density than stripper harvested cotton, but expanded more during recovery, resulting in similar final densities. Multiple compressions increased the density, but this increase was not physically significant after the third compression. Higher moisture content increased the density seed cotton could be compressed to slightly. Viscoelastic behavior was observed; however, the effect on density was small.

Both the compression and creep curves were described using mathematical models. A compression model using an asymptotic true strain measure yielded high R^2 values; however, some aspect of this process remained unexplained and the equation was limited in its predictive ability. Creep behavior was described using a modified Burgers

model. This model was more accurate than the creep model, although a definite trend existed in the creep model residuals.

A feedback algorithm was developed based on the observation that the compressed density was primarily dependent on the mass of seed cotton and not the initial density. By measuring the compressed depth of cotton in a module and the hydraulic pressure of the tramper foot cylinder, the resulting shape of the module can be predicted. Improved loading of the module builder is necessary to produce a desirably shaped module. More seed cotton needs to be placed in the center of the module, resulting in a surface that slopes down towards the outer edges.

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NOMENCLATURE

A	model parameter for nonlinear creep compliance
B	model parameter for nonlinear creep compliance
C	model parameter for nonlinear creep compliance
E	modulus of elasticity
E_1	modulus of elasticity of series-connected spring in a Burgers or related model
E_2	modulus of elasticity of parallel-connected spring in a Burgers or related model
J	creep compliance
K	combined modulus of elasticity and plastic strain constant
m	model parameter for nonlinear creep compliance
t	time
u	asymptotic height ratio
u_0	asymptotic height ratio at initial height
x	measured height
x_0	initial height
x_{min}	asymptotic minimum height
γ	measured density
γ_0	initial density
γ_c	density at the beginning of creep loading
γ_{max}	asymptotic maximum density
ε	strain
$d\varepsilon/dt$	strain rate
ε_c	strain due to creep loading
η	viscosity
η_1	viscosity of series-connected damper in a Burgers or related model
η_2	viscosity of parallel-connected damper in a Burgers or related model
σ	applied stress
σ_0	constant applied stress during creep loading

CHAPTER I

INTRODUCTION

Moisture damage during storage of seed cotton in modules may result in a significant decrease in the quality of seed and lint. This damage may be caused by rain collecting in depressions on top of the module and leaking through the cover. Module covers are designed to resist water penetration, but the covers actually used are often damaged. Weathering and rough handling of the covers over several years of use reduces the resistance of the cover material to water and creates holes, allowing water to leak into the cotton.

Because covers may not provide adequate protection from water, module shapes that prevent the collection of water on the cover are necessary to maintain a higher level of seed cotton quality. Construction of a module with a desired shape requires a better understanding of the behavior of seed cotton when a compressive force is applied. The relationship between force, deformation, and the time-dependent recovery must be known in order to predict the final density and resulting shape of the module. Currently, there is little published data on the physical properties of seed cotton.

This research is conducted as part of a larger project to improve postharvest handling of seed cotton. The primary goal of this research is to determine the viscoelastic properties of seed cotton and their effects on module shape and density. To shed water, modules must be built which have a convex surface. This research aims to determine the physical properties of seed cotton which can be used to predict the density of seed cotton and the resulting surface characteristics of the module.

Objectives

1. The effects of different conditions encountered in harvesting cotton on the density and height of seed cotton after compression will be determined. Factors such as the harvesting method and moisture content are likely to affect the

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physical properties of seed cotton.

2. Models of compression and time-dependent effects will be used to mathematically describe the data from force-deformation and creep curves of seed cotton. An accurate model will allow the prediction of module density and the resulting shape.
3. An algorithm that can be utilized to provide the module builder operator with feedback on module shape will be developed. This algorithm will be used in a system that informs the operator where cotton needs to be moved to result in a module with a desirable shape.

This research will lead to the construction of cotton modules with shapes that preclude water collection on the cover. The identification of problems in module construction and the knowledge of the relationship between applied forces and module shape will lead to further work on reducing storage losses in cotton modules. Knowledge of the physical properties of seed cotton is necessary for the development of a system that can be implemented on a module builder to enable the operator to produce modules with a desired shape.

CHAPTER II

LITERATURE REVIEW

Seed Cotton Handling and Storage

Development of the mechanical cotton harvester allowed cotton to be harvested much faster than it could be ginned. Because of this imbalance, producers' loaded trailers often remained at the gin for three to five days (Wilkes et al., 1974). The availability of the trailers became the limiting factor in harvesting operations. Mechanical harvesters could not be used as efficiently and delays resulting from a lack of trailers could result in yield and quality losses due to unfavorable weather. Clearly, alternative methods of storing seed cotton before ginning needed to be developed.

Early efforts to develop alternative methods of storing seed cotton involved baling cotton using existing equipment. Abernathy and Williams baled seed cotton with a hay baler or a standard gin press to determine the effect of storage method on quality (1961). Seed cotton baled with average moisture content of 6.9% using either method was stored as long as two months with no significant decrease in lint quality. Storage of seed cotton baled in a flat bale press was studied by Taylor and Porterfield (1964). Bales stored under shelter had lint and seed quality comparable to seed cotton samples ginned when the bales were made or stored loose and ginned at the same time as the bales. The only lint quality factor negatively affected by storage was staple length, which decreased by 1/64 to 1/32 of an inch.

While these storage methods did not adversely affect quality, the primary disadvantage to using gin presses to bale cotton was that a large number of trailers would still be required to transport the seed cotton to the gin. Without additional investment in machinery, using a gin press to bale seed cotton would reduce the capacity of ginning operations. Since increases in harvesting rates necessitated the need for temporary seed cotton storage, reducing the gin capacity was highly undesirable. A hay baler could be used to compress seed cotton on the farm; however, not all cotton producers had this equipment. Additionally, seed cotton baled in a hay baler had a density of 144 kg/m^3

(9 lb/ft^3), only slightly higher than the density of seed cotton after tramping in a trailer-about 96 kg/m^3 (6 lb/ft^3) (Abernathy and Williams, 1961).

The cotton-stacking trailer developed by McNeal represented the first major attempt to store cotton on the farm (1966). When the trailer was fully loaded with seed cotton, the bed was tilted towards the rear, and the rear gate opened. The front wall of the trailer was chain-driven towards the rear as the trailer is pulled forward, ejecting the stack of seed cotton. The stacked seed cotton was stored in the turnrows and covered. The trailer was modified so the seed cotton could be stacked on pallets (McNeal, 1967), which could be winched back on to the same trailer for transport to the gin.

An economic comparison was made between a seed cotton handling system utilizing the stacking trailer and one with conventional trailers (McNeal and White, 1970). The analysis demonstrated that the stacking trailer resulted in total savings of $1.55 per bale for a 450-acre farm yielding 1.2 bales per acre harvested with three two-row pickers. The economic savings were due to the reduced investment in equipment necessary with the stacking trailer, as a large number of trailers were necessary in the conventional system. One major disadvantage of this system is that the seed cotton had to be tramped manually so the stack would maintain its shape for efficient reloading and transport to the gin.

The module system of storing and handling seed cotton was developed in the early 1970's to overcome the drawbacks of earlier methods and to completely separate storage and transport activities (Wilkes et al., 1974). A tractor is used to transport the module builder and supply power through the power take-off (PTO) and hydraulic connections. A tramper foot spans the width of the module builder and is capable of applying compressive stresses of approximately 100 kPa (15 psi). The tramper foot is mounted on a carriage that can be moved over the entire length of the module builder.

The module builder dimensions have been standardized by the American Society of Agricultural Engineers (ASAE) to facilitate transport and handling of modules (2001). A standard module builder is 9.75 m (32 ft) long, 2.21 to 2.30 m (7.25 to 7.54 ft) wide at its base, and either 2.74 or 3.35 m (9 or 11 ft) high. The taller version was developed for use with stripped cotton, since stripper harvested cotton is compressed to a lower density than picker harvested cotton in a module. The weight of the resulting module of stripped cotton should be similar to a shorter module of picker harvested cotton. The walls on a module builder are tapered inward 25.4 mm (1 in) for each 304.8 mm (12 in) of rise. After a module is constructed, this taper allows easy removal of the builder from the module and ensures that seed cotton is not lost from the sides of the module.

The module builder is loaded directly from the harvester or boll buggy. Before the cotton is compressed, it is distributed along the length of the module builder by raising or lowering the tramper foot to the desired height and moving the carriage to drag cotton back and forth. Finished modules are protected from rain during storage with a cover, usually made of polyethylene or other synthetic material.

One early improvement on the cotton module builder was the development of an automatic control system (Shelby and Parish, 1975). Solenoid valves were used to control the hydraulic motors driving the tramper foot and carriage and the cylinders that raised and lowered the wheels and end gate. After cotton was loaded into the module builder, the operator raised or lowered the tramper foot to select the height for leveling the cotton. The automatic control system was then activated. The tramper foot moved to the rear at the selected height to level the cotton. Limit switches were used to identify when the carriage reached the front and rear of the module builder. Starting at the rear of the module builder, the tramper foot extended downward until a pressure switch in the hydraulic system was opened. Time delay relays controlled the upward and forward movement of the tramper foot. This cycle of extending and retracting the tramper foot and moving the carriage forward was repeated until the carriage reached the front of the machine. The pressure switch and time delay relays were adjustable to control the maximum compressive force applied, the height the tramper foot was raised, and the distance advanced by the carriage between strokes. The performance of this system was not evaluated in the literature.

The module builder dramatically increased the productivity and efficiency of cotton producers and ginners. However, this system has remained nearly unchanged for the last thirty years. A major problem encountered in building modules is distributing the cotton in the module builder. The only practical methods of moving seed cotton in the module builder are varying the location where the harvester unloads and using the tramper foot to push cotton along the length of the module builder. The tramper foot is designed primarily to compress the cotton, and, consequently, is not highly effective at moving seed cotton.

Visual observation of the partially built module by the operator is the sole basis for making decisions on where seed cotton should be moved in the module and where the module should be tramped. Several factors complicate these decisions. The operator bases his actions on the volume of seed cotton observed a region of the module. However, a module should be constructed with a uniform density across both the length and width. Building modules with uniform density requires that the operator have knowledge of the mass of seed cotton at a particular location in the module. Even accurately judging the volume of seed cotton to move can be difficult because of the large distance from the operator’s platform to the far end of the module builder.

These difficulties result in the construction of modules that deviate from the ideal shape. Researchers generally agree that the elevation of the module should be highest in the center and slope down towards the outer edges to prevent the collection of water on the cover. Willcutt et al. indicated that the collection of water on covers is a serious problem (1992). Brashears et al. postulated that an irregular module surface may be a cause of moisture damage (1993). A commercially available spray-on material was tested to determine its suitability as a module cover. The moisture content of the modules with the spray-on covers was significantly higher at locations on the module surface with lower elevations as compared to regions on the module surface with higher elevations. The spray-on cover shed water from higher locations on the surface, but water was channeled into cracks and depressions in the surface, causing moisture damage.

Effects of Moisture on Seed Cotton Quality

Maintaining seed cotton quality during storage in modules is a prime concern of both producers and ginners. The most important factor affecting the deterioration of quality during storage is the moisture content because excess moisture provides a more desirable environment for microbial growth. Microorganisms degrade the cottonseed, resulting in lower quality seed for oil and feed markets. The microbial activity in modules with high moisture levels increases the temperature. Therefore, high temperatures in modules are often used as an indicator of wet modules.

Griffin found that the germination of cottonseed with seed moisture levels greater than 16% was less than 50% (1975). The milling grade index for seed cotton that was picked before the dew evaporated was 84.1, compared with 95.1 and 96.6 for cotton that was picked wet and dried and cotton that was picked dry. Wilkes further investigated the effects of moisture on seed quality and determined in laboratory tests that cotton with seed moisture levels less than 10% could be stored for at least 30 days with no decrease in seed quality (1978). As the seed moisture level increased, the storage time before seed quality was affected decreased. In modules, a seed moisture content less than 11% did not result in a decrease in quality. This seed moisture content corresponded to an average seed cotton moisture content of 10%. Curley et al. found that germination decreases when the module moisture level is between 13 and 16% and ceases when the moisture level is above 16% (1988).

The degradation of cottonseed results in the release of compounds which discolor the lint. Abernathy and Williams baled seed cotton with higher moisture contents using both a hay baler and a gin press and stored the bales for three weeks to determine the effect of moisture content on lint quality. The seed cotton was classified as low, medium, or high moisture with average moisture contents of approximately 10, 13, and 15 percent. The seed cotton stored at higher moisture contents showed a significant decrease in the USDA color grade index and had a higher yellowness value as measured by a colorimeter.

Parish and Shelby demonstrated that a significant decrease in lint quality occurred when the seed cotton moisture content in a module was greater than 18% (1974). Parish and Shelby also found that lint quality began to decrease when the module temperature rose above 43°C (110°F). Griffin determined that a similar moisture content resulted in a lower lint grade for 9 out of 10 replications when compared with cotton that was picked dry (1975). Curley et al. found that color was the only lint quality measurement influenced significantly by module moisture content (1988). The percent change in yellowness began to increase significantly at a moisture level of 13 to 14%.

Compression of Cotton

Construction of a module with a properly rounded top surface remains difficult. A properly built module is dependent on the operator visually observing the module and making decisions on where the seed cotton should be moved in the module and where the module should be tramped. In order to determine the resulting module shape from these actions, certain physical properties of seed cotton must be known. These properties are necessary for predicting the density and subsequent module shape resulting from a certain pattern of compression strokes.

Brashears et al. investigated the relationship between applied pressure and density in seed cotton (1970). Seed cotton compressed to 481 kg/m^3 (30 lb/ft^3) was found to recover to a final density of 320 kg/m^3 (20 lb/ft^3), indicating a significant inelastic component to the deformation. However, this compressed density is far greater than any density reached in a module builder. Additionally, their research demonstrated that seed damage occurs at this density at lower moisture levels. No research has been conducted with seed cotton to determine the recovery that occurs at lower densities and applied pressures. Additionally, no investigation has been made into the time-dependent properties of seed cotton.

The compressive behavior of cotton lint has been examined more thoroughly as a result of research into cotton baling. Since cotton lint comprises approximately 40% of the mass of seed cotton, parallels should exist between the compressive behavior of lint and seed cotton, especially with low applied stresses. At low stresses, most deformation will be expected to occur in the lint, not in the cottonseed or foreign material. Anthony and McCaskill performed a regression analysis to determine variables that significantly affected the force required to compress lint cotton (1976). The compressed density, moisture content, quantity, and a moisture content-quantity interaction were significant effects on the force required to compress lint cotton. A regression equation relating a logarithmic transformation of force to moisture content and a logarithmic transformation of compressed density explained 99.2% of the variation. While the form of the relationship may be different for seed cotton, density and moisture content should have significant effects on the force required to compress seed cotton.

The effect of multiple compressions on lint cotton has also been tested (Anthony, 1977). Repeated compression of lint cotton to a constant density resulted in a decreasing force with each subsequent compression. However, the reduction in force decreased with each subsequent compression. Multiple compressions with the same applied force resulted in an increase in the final density. Again, the effect decreased with each additional compression. Anthony also determined that the resilient force, the force exerted by the lint cotton when restrained at a constant volume after compression, was decreased by repetitive compression. Understanding how repeated applications of force affect density is necessary to predicting module shape, as numerous compressions occur at various locations in the module builder.

Several measurements have been made of the change over time of the resilient force of lint cotton. Anthony and McCaskill measured the resilient force exerted on bale ties over a 16 hour period (1974). The resilient force increased over time, reaching 88% of the highest recorded value in 20 minutes and 98% of the maximum in 5 hours. Chimbombi also determined that the resilient force of cotton lint has an initial rapid increase and then approaches an asymptotic value (1998). If lint cotton exerts a time-dependent resilient force when restrained, then unrestrained lint would exhibit expansion over time. Determining the magnitude of this expansion in seed cotton is necessary for predicting module shape.

Physical Properties of Biological Materials

In order to reliably predict module shape, an accurate model of the relationship between stress, strain, and time needs to be developed. Deformations resulting from applied stresses can be considered to be elastic or inelastic. For ideal elastic compression, stress is directly proportional to strain, as defined in Hooke's law:

$$\sigma = E\varepsilon \tag{1}$$

where

σ = stress (Pa)

E = modulus of elasticity (Pa)

ε = strain (dimensionless).

This law is generally only valid for small strains in homogenous materials, such as steel (Mohsenin, 1986). However, biological materials, such as seed cotton, may exhibit strains of fifty percent or more and are often of a heterogeneous nature. Upon removing the applied stress, the strain in an elastic material is fully and instantaneously recovered.

Inelastic, or permanent, deformations can be further divided into plastic and viscous components. Plastic strain, such as the deformation in a material after the yield stress is reached, is not dependent on time. Viscous behavior is exemplified by an ideal liquid and is described by Newton's law:

$$\sigma = \eta(d\varepsilon/dt) \tag{2}$$

where

η = viscosity (Pa s)

$d\varepsilon/dt$ = strain rate (s^{-1}).

Applying a constant force to a viscous material results in a value of strain that is directly proportional to the length of time the force is applied.

Materials exhibiting a combination of elastic and viscous behavior are referred to as viscoelastic. Linear viscoelastic behavior has been represented by mechanical models consisting of elastic and viscous elements. These models use springs to represent elastic components and dampers to simulate viscous behavior. By solving the differential equations of motion for a network of springs and dampers, a model for viscoelastic behavior is obtained.

Common viscoelastic tests include determination of creep, recovery, and stress relaxation. Creep is the phenomenon that occurs when a load is applied to a material and maintained at a constant level. Continued deformation occurs over time with a constant load due to the viscous aspect of the material's response. Recovery is a related phenomenon that occurs when a load is removed. Recovery in creep models can be predicted by applying a load equal in magnitude and opposite in direction to the original load. Applying a load to a material and holding the strain constant produces the response known as stress relaxation. The applied stress required to maintain a constant strain decreases with time. These responses are simpler to model because either the strain or stress is constant, resulting in a differential equation that is easier to solve. If the solution to one of these differential equations is defined as the ratio of strain to stress, the result is termed the compliance.

Certain combinations of elastic and viscous elements are commonly encountered in models of material behavior (Figure 1). A Maxwell model consists of a spring and damper connected in series, which results in instantaneous elasticity in the spring and time-dependent permanent deformation in the damper when a load is applied. This mechanical model is generally used to describe stress relaxation as stress decreases exponentially when the material is in a state of constant strain. With only one Maxwell element, the stress will eventually reach zero. Since this response is not usually observed with real materials, a generalized Maxwell model, consisting of a number of Maxwell units connected in parallel with a spring, is often used to describe stress relaxation. Because of the additional elastic element, the stress approaches a value equal to the constant strain multiplied by the modulus of elasticity of the spring.

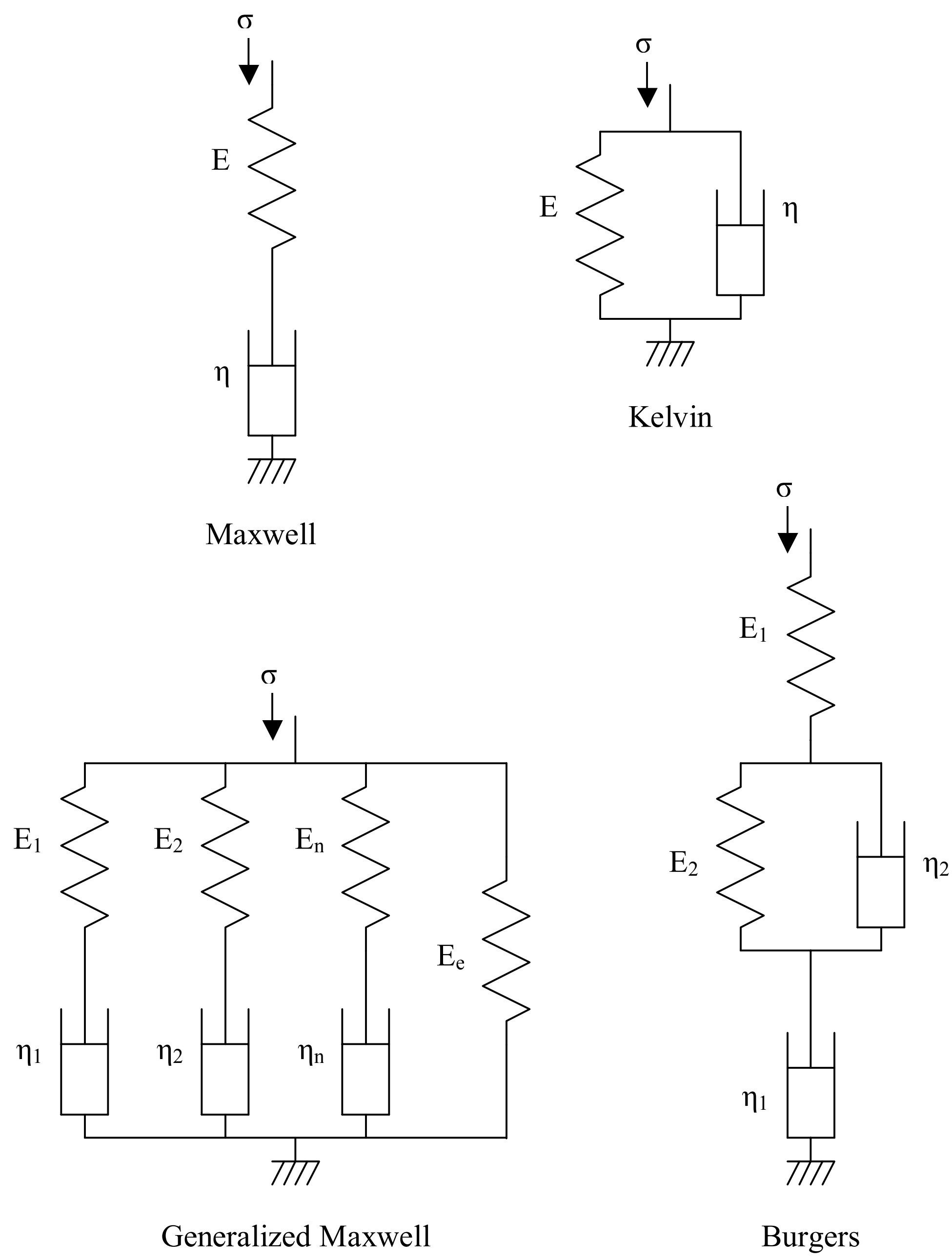

Figure 1. Common viscoelastic models.

Placing a spring and damper in parallel yields a Kelvin model, which is usually used to describe creep. With a constant load applied, a Kelvin model predicts zero instantaneous strain, as motion in the spring is restricted by the damper. As time increases, the strain rate decreases, and a smaller proportion of the load is carried by the damper. Therefore, as the time approaches infinity, the load is carried by the spring, and the strain approaches a value equal to the constant applied stress divided by the modulus of elasticity of the elastic element. However, removal of the load results in no permanent deformation. In order to more accurately describe the creep response of real materials, a Kelvin model is placed in series with a Maxwell model. This combined model is known as the Burgers, or four-element, model. This model has characteristics of both the Kelvin and Maxwell models, predicting instantaneous elasticity, delayed elasticity, and time-induced permanent deformation. The creep response of the Burgers model is described by the following equation:

$$\varepsilon(t) = \sigma_0(1/E_1 + t/\eta_1 + (1/E_2)(1-e^{(-E2/\eta 2)t})) \quad (3)$$

where

$\varepsilon(t)$ = strain, as a function of time (dimensionless)

σ_0 = constant applied stress during creep loading (Pa)

E_1 = modulus of elasticity of series-connected spring (Pa)

t = time (s)

η_1 = viscosity of series-connected damper (Pa s)

E_2 = modulus of elasticity of parallel-connected spring (Pa)

η_2 = viscosity of parallel-connected damper (Pa s).

Rehkugler and Buchele developed a hypothetical model for the behavior of forage under compression (Figure 2) (1969). Their model used fracture elements to represent the permanent deformation of the forage, along with elastic and viscous elements. However, they were unable to develop a mathematical equation directly from their model and performed a dimensional analysis to aid in the determination of the relationship between forage properties, testing specifications, applied stress, and density.

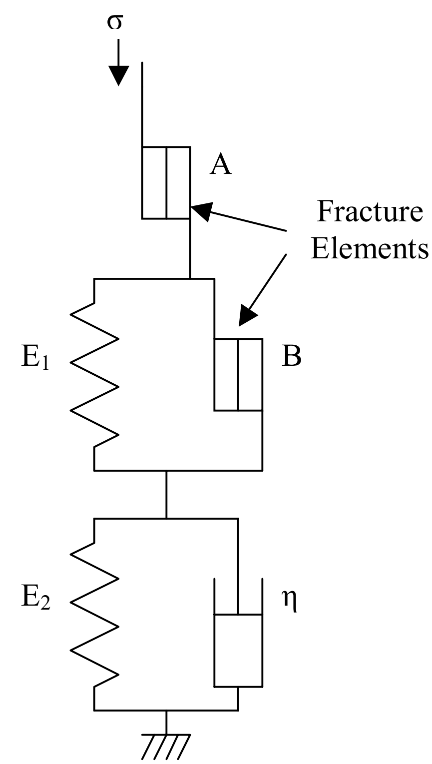

Figure 2. Viscoelastic model developed by Rehkugler and Buchele.

Stress relaxation of bulk biological materials was investigated by Mohsenin and Zaske (1976). A generalized Maxwell model was used to model the stress relaxation behavior of forages and wood byproducts. The materials were compressed in a 38 mm diameter cylinder with a maximum pressure of approximately 48.3 MPa (7000 lb/in^2). The force was maintained for at least 50 s to record the reduction in stress over time. Mohsenin and Zaske found that three Maxwell elements were sufficient to describe the behavior of the forages and wood materials tested.

One major drawback of these models is that they all predict a linear relationship between stress and strain during the initial compression, due to the linear elastic elements used. However, compression tests on a variety of agricultural materials have shown that Hooke's law can not accurately describe the behavior of these materials

(Mohsenin, 1986). Peleg developed a model with nonlinear elastic elements to more accurately predict the stress-strain relationship observed in biological materials (Figure 3) (1983).

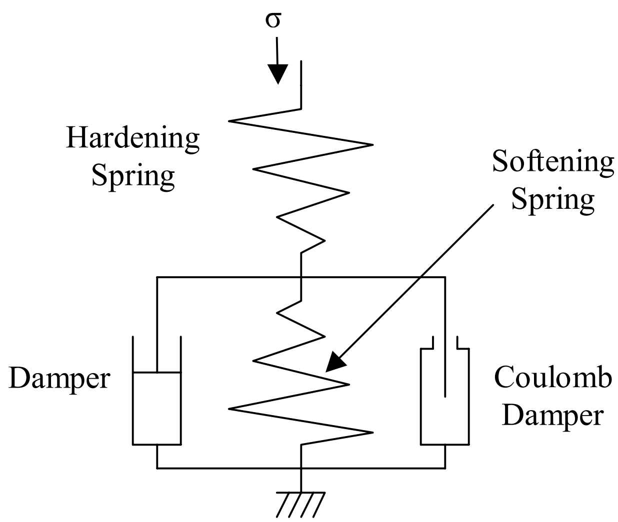

Figure 3. Peleg's viscoelastic model.

Peleg’s model elaborates upon a three-parameter solid model, consisting of a spring in series with a parallel combination of a spring and damper. A hardening spring with cubic elasticity was used for the series-connected elastic element to more accurately represent the increasing slope initially observed on the force-deformation curve of biological materials. A Coulomb damper was added to the parallel elements to model the internal friction of the material, and the parallel-connected elastic element was a softening spring, also with cubic elasticity. This softening spring models the behavior of the material near its yield stress. Both time-dependent and independent permanent deformation result when a force greater than the internal friction force is applied. The model parameters can be easily determined from common rheological tests, unlike previous attempts to model nonlinear behavior.

One major limitation of Peleg's work is that many biological materials, especially unconsolidated bulk materials, exhibit permanent deformation upon application of any force, regardless of the magnitude. Faborode and O'Callaghan developed a model for the compression of fibrous agricultural materials and combined their work with Peleg's model to produce a viscoelastic model for these materials (1986, 1989). Their modification predicts a permanent deformation in the material due to loss of the void spaces in the unconsolidated material.

Faborode and O'Callaghan developed an equation to account for this process of expelling air from the material. The differential rise in applied stress as a function of density was modeled as an exponential function of the compression ratio, the ratio of the compressed density to the initial density. An exponential function was chosen based on empirical evidence. Solving this differential equation resulted in an expression relating the pressure (applied compressive stress) to a function of the initial density, compression ratio, and material parameters. This expression was then used in a piecewise method with Peleg's model to predict the behavior of fibrous materials. The dividing point on the force-deformation curve between use of the equation developed by Faborode and O'Callaghan and Peleg's model was where the Cauchy number reached a maximum. This dimensionless parameter represents the ratio of inertial to elastic forces. Faborode and O'Callaghan theorized that inertial forces dominated the initial deformation due to the loss of void spaces, while elastic forces governed the region described by Peleg's model.

The model proposed by Faborode and O'Callaghan predicts completely inelastic deformation for the initial phase of compression, although real viscoelastic materials exhibit a combination of elastic and inelastic strain. In addition, a time-dependent response occurs only if the applied force is large enough to expel the void spaces and overcome the internal friction of the material. Fibrous agricultural materials generally will exhibit time-dependent responses even if very small forces are involved, as can be observed in the recovery of cotton modules. Additionally, the choice of an exponential function to model the pressure rise is arbitrary, and a power or polynomial function may provide as good a fit.

Another drawback to Faborode and O'Callaghan's model is that inertial forces will not be significant in most compression processes. The Cauchy number varied from approximately 0.012 to 0.024 in the compression tests performed by Faborode and O'Callaghan, indicating that the effects of inertial forces were relatively unimportant compared to compressibility forces. Munson et al. stated that inertial forces can be neglected if the Mach number is less than 0.3, which corresponds to a Cauchy number of 0.09 (1998). Furthermore, the maximum value of the Cauchy number does not indicate the expulsion of all air voids, but rather where the relative effect of the inertial forces is largest. If all air voids are removed, the material should behave more like an ideal solid, and the Cauchy number will be near zero.

Bilanski and Graham presented a viscoelastic model that more accurately predicts the behavior of agricultural materials, particularly with a small applied compressive stress (1984). This model, shown in Figure 4, adds an inelastic strain element in series with a Burgers model. A more rigorous mathematical analysis of the instantaneous response of this model was performed by Bilanski et al. (1985).

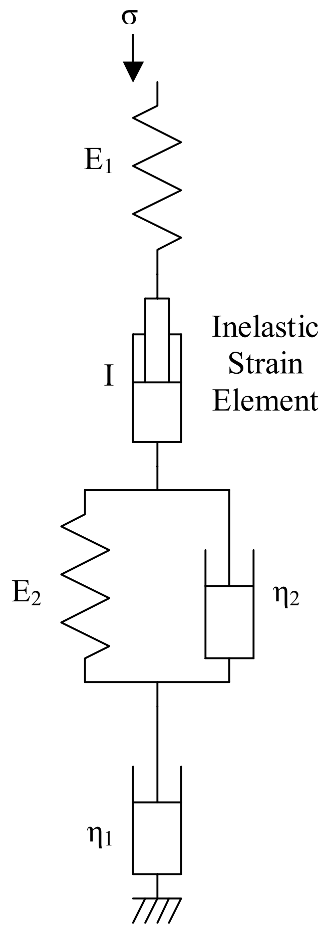

Figure 4. Viscoelastic model developed by Bilanski and Graham.

Bilanski and Graham observed that the compressed height of forage in a die approached an asymptotic value (1984). This observation is physically consistent, as the lateral movement is restrained; therefore the material can not be compressed to zero height. Instead of actually using height in the model, the following height ratio was calculated that varied from one at the initial height to zero at the asymptotic height:

$$u = (x_0 - x_{min})/(x - x_{min}) \tag{4}$$

where

u = height ratio (dimensionless)

x_0 = initial height (m)

x_{min} = asymptotic minimum height (m)

x = measured height (m).

The instantaneous response only occurs in the series-connected spring and inelastic strain elements. A differential change in applied stress will result in a differential strain, with elastic and plastic strain components. The differential elastic strain was assumed to be equal to the applied differential stress divided by the modulus of elasticity, E. Hooke's law is based on this assumption, but because it is generally used for small strains, the solved differential equation can be approximated by the commonly used linear form (eq. 1). The actual solution to the differential equation is referred to as true strain by Mohsenin (1986):

$$ln(x_0/x) = \sigma/E \quad (5)$$

This equation is defined so that compressive stresses and strains are positive.

The differential plastic strain element was also assumed to be proportional to the differential applied stress. Since both the differential elastic and inelastic strains were considered to be proportional to the differential change in applied stress, the modulus of elasticity was combined with the inelastic strain proportionality constant for analysis. Incorporating this combined constant and replacing height with the height ratio defined in eq. 4 resulted in the following relationship:

$$ln(u_0/u) = \sigma/K \quad (6)$$

where

u_0 = height ratio evaluated at initial height, equals 1 (dimensionless)

K = combined modulus of elasticity and plastic strain constant (Pa).

This ratio was converted to a density ratio resulting in the following equation for instantaneous response:

$$(\gamma_{max} - \gamma)/(\gamma_{max} - \gamma_0) = e^{-\sigma/K} \tag{7}$$

where

γ_{max} = asymptotic maximum density (kg/m^3)

γ = measured density (kg/m^3)

γ_0 = initial density (kg/m^3).

While this density ratio varies from 1 at the initial density to 0 at the maximum density, it is not mathematically equivalent to the height ratio described earlier.

The time-dependent response of this model was described in more detail by Graham and Bilanski (1984). In describing the viscoelastic response, this model is essentially a Burgers model with non-linear elements. The model for the creep compliance used was:

$$J = C\sigma^{-m}(1+At+e^{-Bt}) \tag{8}$$

where

J = creep compliance (Pa^{-1})

C = model parameter (Pa^{m-1})

m = model parameter (dimensionless)

A = model parameter (s^{-1})

B = model parameter (s^{-1}).

The power function is used to describe the nonlinear creep behavior, while the remaining terms are a simplified version of the creep compliance of a linear Burgers model. When a constant load is applied, this model predicts a total strain composed of instantaneous, transient, and steady-state components. The instantaneous component is the deformation that occurs in the series-connected elastic and inelastic elements. The exponential term describes the transient response occurring in the parallel combination of a spring and damper in the model. The steady-state creep is the continued deformation that occurs in the series-connected damper and is a linear function of time. The permanent deformation that occurs in this model is the sum of the strain resulting from the inelastic element and the series-connected damper.

CHAPTER III

MATERIALS AND METHODS

Compression Testing Apparatus

Compression of seed cotton in a manner similar to the action in a module builder was simulated in the laboratory. A compression testing apparatus was mounted on an existing frame, and force was applied using a hydraulic cylinder attached to a circular steel plate. The plate had a thickness of 1.90 cm (0.75 in) and a cross-sectional area of 699.4 cm^2 (108.4 in^2). A Hottinger Baldwin Measurements* shear beam load cell with a rated capacity of 22240 N (5000 lb) was mounted on the opposite end of the cylinder to record force. The combined error of the load cell was 8.9 N (2.0 lb), and the rated change in the force measurement due to creep loading for 20 minutes was 6.7 N (1.5 lb).

The seed cotton was compressed in a PVC cylinder with a depth of 91.4 cm. The cylinder was split into two halves and held together with quick-release hose clamps around the circumference. This design allowed the walls of the cylinder to be easily removed without disturbing the mass of seed cotton. Removing the sides of the cylinder after compression allowed recovery of the seed cotton uninhibited by the effects of wall friction.

An 1850-030 Houston Scientific string potentiometer was used to measure the height of the column of seed cotton within the PVC cylinder. The base of the position transducer was mounted to the frame of the testing apparatus, and the cable was connected to the top surface of the steel plate. The maximum travel of the string potentiometer cable was 762 mm (30 in). Nonlinearity of the potentiometer, determined from an actual calibration performed on July 22, 2003, was found to be 0.64 mm (0.025 in). The reported repeatability was 0.38 mm (0.015 in), resulting in a total maximum height error of 1.02 mm (0.040 in). After the seed cotton was removed from the PVC cylinder, height of the column was measured manually.

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*Brand names are provided for informative purposes and their use does not constitute an endorsement of any product.

The output of each sensor was sampled at 3.33 Hz using an Agilent 34970A data acquisition unit equipped with the 34901A module, a 20-channel multiplexer. The maximum voltage measurement error was calculated based on the actual reading and the voltage range used by the analog-to-digital converter within the data acquisition system. The maximum force measurement error ranged from 2.5 N (0.56 lb) at zero force to 3.6 N (0.81 lb) at the rated load. The resulting total error in the force measurement ranged from 11.4 N (2.6 lb) to 12.5 N (2.8 lb), with an additional 6.7 N (1.5 lb) of error possible during creep loading. Because of the larger output voltage of the string potentiometer, the voltage measurement error in the data acquisition system was insignificant compared to the actual sensor error.

Two compression processes were examined to accomplish the objectives of this research. Compressing seed cotton samples with a constant force simulated tramping at different locations along the length of the module builder. The hydraulic system of the module builder will supply a constant maximum pressure, so the tramper foot cylinder will generate the same force regardless of carriage position. A constant force was achieved in testing by adjusting the position of the pressure relief valve in the hydraulic system.

Tests involving compression to a constant volume modeled the behavior of seed cotton across the width of the tramper foot. The compressed volume under the tramper foot does not vary across the width of the module. As the mass of the seed cotton changes across the width of the tramper foot, the distribution of applied compressive stress on the seed cotton will change as well. Regions with greater mass should experience a greater applied stress and vice versa. Compression proceeds until the applied stress integrated over the area of the tramper foot equals the maximum force supplied by the tramper foot hydraulic cylinder. In testing, compression to a constant volume was done using an adjustable mechanism mounted on the top surface of the circular steel plate that opened a limit switch when the desired volume was reached.

Sample Description and Preparation

The seed cotton used in all tests was harvested in the fall of 2002. The picked cotton was obtained from the Texas A&M University IMPACT Center on the Brazos River in Burleson County, TX and stored in a trailer under shelter until its use. While the picker harvested cotton was protected from rain, it was still in equilibrium with the outdoor atmospheric conditions. Stripped cotton was harvested in the High Plains and transported to College Station in large canvas bags. These bags were stored in the laboratory until samples were removed for testing.

The moisture content of all samples tested was determined by drying in an oven for 24 hours at 105°C. Initially, attempts to vary the moisture content of the seed cotton were made by placing samples in an airtight container above a saturated solution of $NaCl$. This saturated salt solution should produce a relative humidity of 75% in the container (ASTM, 2002). Brashears et al. found that the equilibrium moisture contents of seed cotton stored at 60 and 80% relative humidity were 6.7 and 14.7%, respectively (1970). A linear extrapolation to 75% relative humidity yields an expected moisture content of 12.7%. However, the average moisture content achieved using this treatment was only 0.5% greater than the mean moisture content of all unconditioned samples. Therefore, moisture content was not used as a treatment, but measured and used as a covariate in the statistical analysis.

Objective 1

Constant Force

The seed cotton was loaded into the PVC cylinder and compressed with a maximum applied force of 7200 N. This value corresponds to an applied stress of 104 kPa (15 psi), which is a typical value observed in module builders. As the seed cotton was compressed, the applied force and height of the column of seed cotton were recorded to develop a force-deformation curve. When the maximum force was reached, this applied stress was maintained for the hold time specified for the particular test. During this time, the height of the seed cotton was recorded to develop a creep curve, a plot of strain against time. The force was removed, and the seed cotton allowed to recover for 120 seconds. A total of five compression cycles were performed. After the final compression cycle, the cylinder was removed, and the height of the column of cotton recorded at several time intervals.

Several independent factors were tested in this experiment. Three initial loading densities, 64, 96, and 128 kg/m^3 (4, 6, and 8 lb/ft^3), and two harvesting methods, picker and stripper harvested cotton, were tested in a factorial design. The cylinder was filled completely with seed cotton and a hold time of 900 seconds during each compression was used. 96 kg/m^3 was cited as the average density of seed cotton in a trailer by several researchers (Abernathy and Williams; Wilkes et al.). The density of seed cotton in a module before compression is likely similar, because of the weight of the cotton and the compression done by the harvester compactor. Therefore, 96 kg/m^3 was used as the intermediate density in these tests. The high and low densities represented the range of capabilities of the testing apparatus- greater densities could not be loaded into the PVC cylinder, and the maximum stroke length of the cylinder was reached with lower densities. This range of initial densities is not likely to be exceeded in a module builder.

Two other effects were tested, although not in a factorial design with the harvesting method and loading density due to limited time and materials. One of these factors was hold time, which was also tested with a level of 15 seconds. Tests with this hold time were done using picker harvested cotton with a loading density of 96 kg/m^3. Testing with two separate hold times was used to verify the viscoelastic nature of seed cotton, since the compressed height and density of a viscoelastic material will change over time.

The other effect tested was the loading method. Repeated loading was done by filling the cylinder with seed cotton to a height of 45.7 cm (one-half the total height) and density of 128 kg/m^3. After one compression cycle, an additional 45.7 cm of cotton at 128 kg/m^3 were added to the test cylinder, and the remaining four compressions were performed. Picker harvested cotton was used with a hold time of 900 seconds.

The experiment was conducted as a completely random design with four replications of each test. Because moisture content was initially a treatment, there were a total of 36 replications. Since adequate moisture content control was not achieved, data from these tests were pooled with the replications with the same levels of other factors- picker harvested seed cotton with an initial density of 96 kg/m^3 and a hold time of 900 seconds.

For each compression cycle, the heights at the end of the initial compression and the change in height during the creep phase were determined. These values were identified by sorting the data recorded from the string potentiometer. The compressed height was defined as the initial height when three consecutive force readings were within 5 N. The end of creep was easily identified as the last height reading before a substantial increase in height (greater than 0.5 mm, indicating retraction of the cylinder). The change in height during creep was the difference between the height at the end if creep and the compressed height. The compressed density and change in density during creep were calculated from these height values.

An analysis of covariance (ANCOVA) using a model that included all interaction terms was performed on this data to compare the effects of treatments and compression cycles, with moisture content as the covariate. The generalized linear models procedure in SAS, PROC GLM, was used for the analysis of covariance. Because a large number of terms were involved, the ANCOVA procedure was performed again with a reduced model consisting of only main effects and interactions that were significant at the 5% level. For factors with significant effects, a comparison of the least-squares means was performed on the height data to identify significant differences in the means of the treatments. Least-squares means are the expected means with a balanced design and all covariates held to their mean values. Using least-squares means allowed comparisons to be made with varying moisture contents and unequal numbers of observations for certain combinations of factor levels.

The heights of the columns of seed cotton were recorded at 0, 1, 2, 3, 4, 5, 10, 15, 30, and 60 minutes and 24 hours after removal from the cylinder. Initially, some of the columns of seed cotton fell over before 24 hours elapsed. Supports were constructed that allowed the columns of cotton to remain upright and expand without significant friction. The recovered height data and calculated recovered densities were analyzed using the same methods as the data from each compression cycle.

Constant Volume

Tests were also conducted where the seed cotton was compressed to a constant volume. Separate volumes were used for the picker and stripper harvested cotton. Using the results of the previous tests, the mean heights when the maximum force was initially reached were determined for picker and stripper harvested cotton with an initial density of 128 kg/m^3. These heights were 392 mm for picker harvested cotton and 463 mm for stripper harvested cotton.

The seed cotton was stored in the testing laboratory for a minimum of two days to reach equilibrium and achieve a constant moisture content between tests. Average environmental conditions in the lab were 21°C (70°F) and 69% relative humidity, although the humidity varied from 30% to 80%. The resulting moisture contents of the picker harvested cotton ranged from 9.4% to 10.0% and averaged 9.7%. The stripper harvested cotton averaged 9.5% moisture content with a range of 8.8% to 10.5%.

Initial densities of 64, 96, and 128 kg/m^3 were tested using picker and stripper harvested cotton. The seed cotton was loaded into the cylinder and compressed once, with the cylinder retracted as soon as the limit switch was triggered. The maximum force required to compress the cotton to the constant volume was recorded. The sides of the cylinder were removed to measure the recovery of the column of seed cotton. Except for the 24 hour measurement, recovery was measured at the same times as the constant force experiment. No measurable difference in the recovered height was observed between 1 and 24 hours.

The experiment was conducted as a completely random design for each harvesting method, with four replications of each test. Because the moisture content did not vary significantly between the replications, an analysis of variance was performed on the maximum recorded force and the recovered height data. Duncan's multiple range test was used to identify differences between the treatment means.

Objective 2

The compression data from the constant force tests were sorted into compression and creep phases for each cycle. The compression phase consisted of the readings for all heights between the points identified as the beginning of a compression cycle and the start of the creep phase. The creep phase consisted of all the readings between the heights identified as the start and end of creep.

The mechanical model presented by Bilanski and Graham was used as the basis for analysis of the compression and creep curves. Initially, the equation developed by Bilanski et al. for this model was used to model the compression data (eq. 7). Since the density ratio (left side of eq. 7) was not equivalent to the height ratio (eq. 4), the density ratio was multiplied by the quantity γ_0/γ. This modified density ratio was equivalent to the height ratio and was used in the following equation:

$$(\gamma_0/\gamma)((\gamma_{max} - \gamma)/(\gamma_{max} - \gamma_0)) = e^{-\sigma/K} \tag{9}$$

This modified equation was used to model all the compression data.

Because creep testing was conducted with only one value of applied stress, observations regarding the nonlinear viscoelastic behavior of seed cotton could not be made. Using linear elements in the model described by Bilanski and Graham resulted in an equation nearly identical to the Burgers model (eq. 3):

$$\varepsilon = \sigma_0(1/K + t/\eta_1 + (1/E_2)(1-e^{(-E2/\eta 2)t})) \tag{10}$$

E_1 in eq. 3 was replaced by the parameter K, which determines the instantaneous strain.

Since the instantaneous deformation was determined by eq. 8 for the compression process, the creep model only needed to predict time-dependent effects.

Removing the *1/K* term that produces instantaneous deformation in eq. 9 yielded the following equation:

$$\varepsilon_c = \sigma_0(t/\eta_1+(1/E_2)(1-e^{(-E2/\eta2)t})) \qquad (11)$$

where ε_c is a dimensionless quantity that equals the difference between total strain and strain at the beginning of creep loading.

A modified form of strain needed to be used because the observed strain was dependent on the initial density of seed cotton. Initially, the logarithmic term in the compression model, an asymptotic measure of true strain, was substituted. However, this term could not be computed for many actual values of density during creep loading. Because the maximum density parameter was generally close to the actual maximum density achieved during compression, the value of this parameter was exceeded during creep loading, resulting in the logarithm of a negative number. Therefore, the true creep strain was used instead, resulting in the following model for creep behavior:

$$ln(\gamma/\gamma_0) - ln(\gamma_c/\gamma_0) = ln(\gamma/\gamma_c) \qquad (12)$$

$$ln(\gamma/\gamma_c) = \sigma_0(t/\eta_1+(1/E_2)(1-e^{(-E2/\eta2)t})) \qquad (13)$$

where γ_c is the density (in kg/m^3) at beginning of creep loading. Eq. 12 was used to describe all creep data.

The nonlinear regression procedure in SAS, PROC NLIN, was used for all regression analyses. Each replication and compression cycle was modeled separately for both compression and creep. The data from multiple replications could not be pooled due to the fact the regression equations were nonlinear. When performing a regression analysis on the pooled data, the asymptotic nature of the equation resulted in the model basically describing the replication with the highest density at the maximum stress for compression or the highest time-dependent elastic strain (specified by the exponential term) for creep. Any data points to the right of the asymptote resulted in extremely high least-squares values; therefore the asymptote was generally to the right of almost all the data points.

The accuracy of these models was examined to determine their suitability for use in predicting module shape and density. The R^2 values and residual distributions were determined, and possible adjustments to the models to improve their predictive ability were developed based on these measures of accuracy. The variation in model parameters due to the different treatments was also investigated.

Objective 3

Results from compression testing were used to develop an algorithm capable of predicting the module shape. Since the force applied by the module builder tramper foot is known, the resulting density of the seed cotton could be predicted. The height of the seed cotton at this density was determined by measuring the extension of the cylinder. Multiplying the predicted density by the measured height and the area of the tramper foot will result in an estimate of the mass under the tramper foot.

An algorithm was developed to provide the module builder operator feedback on the mass and density of cotton along the length of the module builder. This algorithm provides the operator with feedback on the distribution of seed cotton in the module builder, so the operator knows where seed cotton needs to be moved to result in a desirable module shape. Variables tested in the compression experiments with significant effects were included in the design of the algorithm. For example, the module builder operator can select if the cotton is picker or stripper harvested. This algorithm should enable the operator to produce modules with more desirable shapes and ensure that the modules are compressed to an adequate density.

CHAPTER IV

RESULTS AND DISCUSSION

Objective 1

Constant Force

Harvest Method-Loading Density Treatments

The experimental design allowed for determination of interactions between harvesting method, loading density, and compression number for the constant force testing. Moisture content was tested as the covariate in the analysis of covariance (ANCOVA) procedure. This analysis was completed for variables indicating the compression, creep, and recovery responses.

Compression Analysis

The height measured at the end of the compression phase and the calculated density corresponding to this height were the dependent variables used in the ANCOVA procedure for the compression phase. Height and density measurements for each replication are displayed in Appendix A. For the analysis of compressed height, the harvesting method-loading density and loading density-moisture content interactions were significant in the full model and were included in the reduced model. All main effects and the interaction between harvesting method and loading density were significant factors in the reduced model at the 5% level. R^2 for the reduced model with compressed height as the dependent variable was 0.998. In analyzing the compressed density, no interactions were significant in the full model. Reducing the model to the main effects resulted in all effects being significant at the 5% level. R^2 for the reduced model for compressed density was 0.979. The analysis of variance tables with the degrees of freedom, F-statistic, and P-value for each reduced model are shown in Appendix B.

Statistically significant differences existed for the mean compressed height and density between the levels of all three factors tested, although these differences were not all practically significant or greater than the measurement error. Table 1 illustrates the mean compressed height and density for the three loading densities. In all tables, means in a column followed by the same letter were not significantly different at the 5% level unless otherwise noted.

Table 1. Least-squares means for compression response of different loading densities.

Loading Density (kg/m^3)	Compressed Height (mm)	Compressed Density (kg/m^3)
64	202^a	293^a
96	302^b	295^b
128	403^c	293^{ab}

Although the difference in compressed density between the low and intermediate loading densities was significant, this difference would not be of practical consequence in a module builder. Additionally, given the mass of cotton and the range of heights tested, the height measurement error of 1 mm resulted in a density error of approximately 1 kg/m^3, which is one-half of the difference between the two means. No trend was apparent, either, since the highest loading density resulted in basically the same compressed density as the first. The mean for the highest loading density was actually slightly higher than for the lowest loading density; therefore, it was not significantly different than either mean compressed density. Rounding to reflect the measurement error resulted in the significance levels displayed here. Therefore, for this applied stress and range of loading densities, it can be safely concluded that no significant variation in the compressed density was due to differences in loading density, and the variation in compressed height was linearly proportional to the initial density of seed cotton.

Differences in the compressed height and density due to the harvesting method were also observed. These results are shown in Table 2. The picker harvested cotton was compressed to a significantly smaller height and greater density than the stripper harvested cotton. The higher percentage of trash in the stripper harvested cotton resulted in a lower compressed density, presumably because the trash was relatively incompressible compared to the lint. The higher trash content may have also increased the internal friction of the material, resulting in greater resistance to compression.

Table 2. Least-squares means for compression response of different harvesting methods.

Harvesting Method	Compressed Height (mm)	Compressed Density (kg/m^3)
Picker	275[a]	320[a]
Stripper	329[b]	267[b]

The mean height and density after each compression are shown in Table 3. Each compression increased the density, but the magnitude of this change decreased with additional compressions. The differences in the mean density and height between each compression were statistically significant, except for the difference in the average compressed height of the fourth and fifth compressions. However, increases in density after the third compression were not large enough to be physically significant.

Table 3. Least-squares means for compression response of multiple compressions of harvesting method-loading density tests.

Number of Compressions	Compressed Height (mm)	Compressed Density (kg/m^3)
1	320^a	277^a
2	305^b	291^b
3	299^c	297^c
4	295^d	301^d
5	293^d	303^e

To determine the effect of the covariate, moisture content, on compressed density, parameter estimates for effects and interactions in the reduced ANCOVA model were generated. Using compressed density as the dependent variable, instead of compressed height, was more useful because height will vary with the mass of seed cotton, and knowledge of how compressed density is affected by moisture content is applicable to a module builder. The parameter estimate for moisture content was 519 kg/m^3, and it was highly significant, with a standard error of 41 kg/m^3. This estimate indicated that an increase in moisture content of one percent (.01) increased the density by slightly more than 5 kg/m^3.

Creep Analysis

The analysis of covariance was also performed on the change in height and density resulting from creep loading. No interactions were significant in the full model, so a reduced model consisting of only main effects was used for analysis. This model had R^2 values of 0.907 for the change in height and 0.965 for the change in density. Loading density, harvesting method, and the number of compressions were significant effects at the 5% level on both the change in height and density. The moisture content was significant at the 5% level in the model of the change in density and significant at the 10% level in describing the change in height.

For all factors tested, the changes in height and density that occurred during creep were relatively small compared to the change in these values during the initial compression. This observation has important implications for building modules. Creep loading is not a practical method of increasing the density of modules. The increase in density is not large enough to justify the additional time required for creep loading.

A clear trend, shown in Table 4, was present in the average change in height associated with different loading densities. As the loading density increased, the change in height during creep increased as well. While the density changes across loading densities were statistically different, these differences were not physically significant. This result was illustrated by the mean change in density of the low and intermediate loading densities, which round to the same value, although they were statistically different.

Table 4. Least-squares means for creep response of different loading densities.

Loading Density (kg/m^3)	Change in Height-Creep (mm)	Change in Density-Creep (kg/m^3)
64	6[a]	8[a]
96	8[b]	8[b]
128	10[c]	7[c]

The height of the column of picker harvested seed cotton decreased less than the height of the stripper harvested cotton during creep, although the increase in density was greater, as shown in Table 5. Because the picker harvested cotton was compressed to a greater density initially, a smaller decrease in height resulted in a larger change in density due to the inverse relationship between height and density.

Table 5. Least-squares means for creep response of different harvesting methods.

Harvesting Method	Change in Height-Creep (mm)	Change in Density-Creep (kg/m^3)
Picker	7^a	9^a
Stripper	9^b	7^b

Multiple compressions caused decreases in the changes in height and density during creep testing, with the rate of change of these variables decreasing as well (Table 6). The decreasing changes in height and density were partially explained by the restraint of the material in the PVC cylinder, which prevented full recovery between compressions. Therefore, the time-dependent elastic strain was not fully recovered, resulting in decreased changes in height and density during additional creep cycles. An additional reason for this behavior was that seed cotton is a work-hardening material, as the slope of the force deformation curve increased as the material was compressed (Figure 5). If the elements in a mechanical model of viscoelastic behavior are work-hardening, then creep strain will decrease as the total deformation of the material increases.

Table 6. Least-squares means for creep response of multiple compressions of harvesting method-loading density tests.

Number of Compressions	Change in Height-Creep (mm)	Change in Density-Creep (kg/m^3)
1	16^a	15^a
2	8^b	8^b
3	6^c	6^c
4	5^d	5^d
5	4^d	4^e

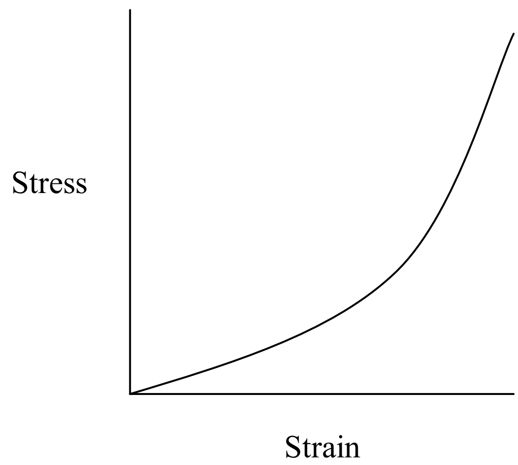

Figure 5. Stress-strain curve of a work-hardening material.

The parameter estimate for the effect of moisture content on the change in density during creep was determined to be 56 kg/m^3. This result implied that a one percent change in moisture content increased the change in density during creep loading (for 900 seconds) by approximately 0.6 kg/m^3. The effect of creep loading and the range of seed cotton moisture contents encountered during harvest are too small for this result to have practical significance in the construction of modules.

Recovery Analysis

The effects of harvesting method and loading density on recovery were determined from the measured height of the column of seed cotton one hour after the seed cotton was removed from the cylinder. The measured height, calculated density, and change in height and density during recovery were examined using the same ANCOVA procedure, except that the number of compressions was not a factor because all samples were compressed five times before the recovery process started.

No interactions were significant in the full model for the change in height, change in density, final height, or final density. R^2 values for the reduced model were 0.615, 0.524, 0.985, and 0.878 for the change in height, change in density, height, and density, respectively. The lower R^2 values for the change in height and change in density during recovery were likely due to several experimental difficulties. These values were affected by inaccuracies in measuring the initial height after the column of seed cotton was removed from the cylinder. Consistent measurement of this value between tests was difficult because the cotton initially expanded quite rapidly. Manual measurement of the height of the column of seed cotton also possibly resulted in additional error. The top surface of the column of seed cotton was generally irregular, so an average height had to be estimated. Some recovery data from early replications was not obtained because the columns of seed cotton fell over.

The harvesting method was a significant effect at the 5% level on the change in height and the change in density during recovery. The loading density and moisture content were significant at the 5% level for the final height and density. For the final height, the harvesting method was significant at the 10% level, while this effect was significant at the 5% level for the final density.

Increased loading density resulted in an increased final density, although the compressed density was nearly identical for each loading density (Table 7). These differences were an expected outcome of the experiment, since increased mass will result in additional compression due to the weight of the seed cotton itself. This result is of greater importance in a module builder where the seed cotton is compressed to a much greater depth with a corresponding increase in weight.

Table 7. Least-squares means for recovery of different loading densities.

Loading Density (kg/m^3)	Final Height (mm)	Final Density (kg/m^3)
64	366^a	160^a
96	512^b	172^b
128	637^c	184^c

The picker harvested seed cotton showed significantly greater recovery than the stripper harvested cotton during recovery (Table 8). This resulted in final mean heights and densities of the picker and stripper harvested cotton that were more nearly equal than the compressed heights and densities. The same physical mechanisms that resulted in a lower compressed density of stripper harvested cotton relative to picker harvested cotton likely explain the observed recovery behavior as well. The lower degree of compressibility or the increased internal friction due to higher trash content resulted in less recovery with stripper harvested cotton.

Table 8. Least-squares means for recovery of different harvesting methods.

Harvesting Method	Change in Height-Recovery (mm)	Change in Density-Recovery (kg/m^3)	Final Height (mm)	Final Density (kg/m^3)
Picker	57^a	22^a	512^a	169^a
Stripper	42^b	16^b	498^a	175^b

Hold Time Treatment

The length of time that the force was maintained during creep testing, referred to as the hold time, was varied using picker harvested cotton with a loading density of 96 kg/m^3. The hold time should not directly affect the compressive behavior of the seed cotton. However, because it affected the time-dependent permanent deformation of the material, the compressed height and density were affected for multiple compressions.

Compression Analysis

Using an ANCOVA model with the hold time and number of compressions as independent factors and moisture content as the covariate resulted in no significant interactions for the compressed height or density. Therefore, the model with only main effects was used to explain the variation in the compressed height and density. R^2 was

0.894 for the compressed height and 0.885 for the compressed density. All main effects were significant sources of variation.

The mean compressed height was significantly greater and the mean compressed density was significantly lower with the reduced hold time (Table 9). This result was expected due to the decreased viscoelastic deformation with a 15 second hold time. Despite the fact that the longer hold time was 60 times greater, the compressed density achieved with this hold time was not physically much different than the compressed density observed with the shorter hold time. This result was another indication that creep loading can not be used to practically increase the density in a module.

Table 9. Least-squares means for compression response of different hold times.

Hold Time (s)	Compressed Height (mm)	Compressed Density (kg/m^3)
15	280^a	314^a
900	272^b	323^b

The effect of additional compressions paralleled the behavior observed in the harvesting method-loading density tests (Table 10). The actual mean density values were greater than the densities observed in the harvesting method-loading density tests, because those results included stripper harvested cotton.

Table 10. Least-squares means for compression response of multiple compressions of hold time tests.

Number of Compressions	Compressed Height (mm)	Compressed Density (kg/m^3)
1	290^a	303^a
2	279^b	316^b
3	274^c	321^c
4	270^d	326^d
5	269^d	328^d

Creep Analysis

Only main effects were present in the reduced ANCOVA model used to explain the variation in the change in height and density during creep loading for the hold time tests. R^2 values of 0.846 and 0.842 were obtained for the models of change in height and change in density, respectively. The hold time and the number of compressions were significant effects at the 5% level for both the change in height and density.

The mean change in height and density during creep loading for each hold time is shown in Table 11. The longer hold time was 60 times longer; however, the change in density was not quite double the change observed with the shorter hold time. The rate of creep strain was much greater at the beginning of creep loading and rapidly decreases. As with the harvesting method-loading density tests, the total deformation due to creep loading was much smaller than the instantaneous deformation. Multiple compression cycles resulted in a response similar to that observed in the harvesting method-loading density tests (Table 12).

Table 11. Least-squares means for creep response of different hold times.

Hold Time (s)	Change in Height-Creep (mm)	Change in Density-Creep (kg/m^3)
15	4^a	5^a
900	7^b	9^b

Table 12. Least-squares means for creep response of multiple compressions of hold time tests.

Number of Compressions	Change in Height-Creep (mm)	Change in Density-Creep (kg/m^3)
1	11^a	12^a
2	6^b	7^b
3	5^c	6^c
4	4^{cd}	5^{cd}
5	3^d	4^d

Recovery Analysis

The recovery data for the hold time tests was analyzed using an ANCOVA model with hold time as a main effect and the moisture content as a covariate, since the interaction was not significant. This model produced R^2 values of 0.762, 0.865, 0.949, and 0.965 for the change in height during recovery, change in density, final recovered height, and final recovered density, respectively. The hold time was significant at the 10% level in explaining the variation in the change in height and change in density. Moisture content was a significant effect at the 5% level for both the final height and final density, while the hold time was significant at the 10% level for the final density.

The mean values of the recovery variables for the two hold times are shown in Table 13. While the differences were not significant at the 5% level, the means for the change in height, change in density, and final recovered density were significantly different at the 10% level. Because of the missing recovery data, few degrees of freedom were available for estimating error. Further investigation would be necessary to confirm that these differences are not due to experimental error, although these results were expected. The longer hold time should increase the time-dependent elastic strain, so increasing the hold time will result in greater recovery when the load is removed. Conversely, the time-dependent permanent strain is also increased with longer hold times, so the final recovered density will still be greater with longer periods of creep loading.

Table 13. Least-squares means for recovery response of different hold times.

Hold Time (s)	Change in Height-Recovery (mm)	Change in Density-Recovery (kg/m^3)	Final Recovered Height (mm)	Final Recovered Density (kg/m^3)
15	38[a]	12[a]	548[a]	161[a]
900	64[a]	24[a]	522[a]	169[a]

Loading Method Treatment

Compression Analysis

The loading method treatment was compared to the picker harvested cotton with a loading density of 128 kg/m^3. One replication of the partial loading method treatment was not used in the analyses because the test was conducted incorrectly. No interactions were significant in explaining the variation of the compressed height or density. Using the ANCOVA model with only the main effects, R^2 was 0.745 for the compressed height and 0.736 for the compressed density. All factors had a significant effect on both the compressed height and density.

The average compressed height and density of each loading method is shown in Table 14. This result was expected, since half of the seed cotton in the partial loading test is compressed one less time. Multiple compressions resulted in a similar response in both the harvest method-density and loading method tests (Table 15).

Table 14. Least-squares means for compression response of different loading methods.

Loading Method	Compressed Height (mm)	Compressed Density (kg/m^3)
Full	367[a]	319[a]
Partial	376[b]	312[b]

Table 15. Least-squares means for compression response of multiple compressions of loading method tests.

Number of Compressions	Compressed Height (mm)	Compressed Density (kg/m^3)
2	381[a]	308[a]
3	372[b]	315[b]
4	368[bc]	319[bc]
5	365[c]	322[c]

Creep Analysis

The loading method-moisture content and number of compressions-moisture content were significant interactions in the full ANCOVA model used to analyze the change in height during creep. Therefore, these interactions were included with the main effects in a reduced model, resulting in an R^2 value of 0.919. However, no effects were significant in this reduced model.

For the change in density during creep loading, the loading method-moisture content interaction was a significant effect in the full model. Including this interaction with the main effects resulted in a model of the variation in the change in density during creep with an R^2 of 0.906. The number of compressions was significant at the 5% level, and the loading method was significant at the 10% level in explaining the variation in the change in density during creep testing.

Partial loading resulted in a statistically significant change in density during creep testing, although the differences in density between the full and partial loading methods were small and not practically significant (Table 16). Because half the cotton in the partial loading test has been compressed one less time, the resulting change in density should be slightly greater than with the full loading test. The change in density with additional compressions was similar to the results observed in the harvest method-loading density tests (Table 17). An analysis of the effect of loading method on recovery was not performed due to insufficient data.

Table 16. Least-squares means for creep response of different loading methods.

Loading Method	Change in Height-Creep (mm)	Change in Density-Creep (kg/m^3)
Full	6^a	6^a
Partial	8^b	7^b

Table 17. Least-squares means of the creep response of multiple compressions of different loading methods.

Number of Compressions	Change in Height (mm)	Change in Density (kg/m^3)
2	12^a	10^a
3	8^b	6^b
4	6^c	5^c
5	5^c	4^c

Constant Volume

Differences in the loading density explained most of the variation observed in the constant volume tests. For the picker harvested cotton, the model R^2 values were 0.997, 0.993, and 0.998 for the maximum applied stress, final recovered height, and final recovered density, respectively. The model R^2 values with stripper harvested cotton were 0.998, 0.971, and 0.992 for the maximum stress, final height, and final density. Both picker and stripper harvested cotton showed similar trends in compression and recovery (Table 18). The maximum applied stress varied significantly between all three loading densities and increased dramatically between the intermediate and highest loading density. The recovered density and height also varied significantly between all three loading densities.

Table 18. Least-squares means for cotton compressed to a constant volume. Significant differences shown are only for values with the same harvesting method.

Loading Density (kg/m^3)	Maximum Stress (kPa)	Final Recovered Height (mm)	Final Recovered Density (kg/m^3)
Picker Harvested			
64	7.6^a	672^a	87^a
96	33.1^b	775^b	114^b
128	107.7^c	849^c	138^c
Stripper Harvested			
64	6.9^a	659^a	89^a
96	35.6^b	767^b	115^b
128	114.2^c	833^c	141^c

Objective 2

Compression Model

The modified version of the model used by Bilanski et al. (eq. 8) was used to model the stress-density relationship. Regression was performed on each replication resulting in a minimum R^2 value of 0.924, although the average value was 0.980. Appendix C lists the parameter values and their standard errors for each replication. The values of *K*, the proportionality constant for the combined elastic and inelastic strain, were averaged over the replications of each combination of treatments and are summarized in Table 19.

Table 19. Average values of *K* (in kPa) for each treatment combination and compression.

	Compression Number				
Treatments	1	2	3	4	5
64, Picker	15.47	21.37	20.37	19.92	19.65
96, Picker	20.24	24.07	23.14	22.55	22.53
128, Picker	28.27	26.55	25.44	24.69	24.05
64, Stripper	17.68	25.78	24.57	24.18	23.55
96, Stripper	25.25	28.56	27.42	26.23	25.24
128, Stripper	40.10	29.89	27.77	26.84	26.27
15 s Hold Time	20.27	25.23	24.13	24.00	23.38
Partial Loading	23.19	23.71	25.22	24.33	23.91

A clear trend was observed in the value of *K* at different loading densities, with *K* increasing as the loading density increased. This increase was largest for the first compression. The value of *K* was slightly higher for stripper harvested cotton than picker harvested cotton for the same loading density and compression number. This observation indicated that stripper harvested cotton required a greater applied stress to compress to a given density, which agreed with the experimental results. Moisture content did not have a significant effect on the value of *K*.

The shorter hold time treatment resulted in an increased value of *K* for all compressions except the first, when compared to the picker harvested cotton with a loading density of 96 kg/m^3. The value of *K* for the first compression was nearly identical because there was no difference in the compression processes at this point. For subsequent compressions, the decreased hold time reduced the creep strain; therefore, a greater compressive stress was required to reach the same density.

The only large differences in the value of *K* between the partial loading treatment and the picker harvested cotton with a loading density of 128 kg/m^3 were in the first two compressions. Because only half the seed cotton was loaded in the cylinder for the first compression, the reduction in *K* was likely due to the different masses of seed cotton. *K* was also reduced during the second compression, presumably because of differences in density in the two layers of seed cotton in the partial loading tests.

The behavior of the value of *K* with the number of compressions was more complex. For all tests except partial loading, the value of *K* decreased from the second through the fifth compression. With partial loading, *K* decreased after the third compression, which was the second compression for the top layer of seed cotton. The *K* values for the first compression of tests with a loading density of 64 or 96 kg/m^3 were lower than the values for all additional compressions. However, the *K* values determined for the first compressions of tests with the highest loading density were larger than all other values of *K*. These values may have occurred because the 128 kg/m^3 loading density was closer to the highest density achieved in testing. The compression model may not be able to adequately describe the stress-density relationship over a small range of densities.

The asymptote in the model was specified by the maximum density parameter, γ_{max}. The values of γ_{max} for each replication were determined, and the average values for the replications of each unique set of test conditions were calculated (Table 20). The different test conditions affected the value of this parameter as well.

Table 20. Average values of γ_{max} (in kg/m^3) for each treatment combination and compression.

	Compression Number				
Treatments	1	2	3	4	5
64, Picker	295.7	310.4	316.1	319.5	322.3
96, Picker	308.9	323.2	328.9	333.5	335.4
128, Picker	308.9	316.4	321.8	324.8	326.9
64, Stripper	255.2	271.0	276.9	280.5	283.1
96, Stripper	255.7	266.5	271.6	274.7	276.7
128, Stripper	273.8	269.3	273.8	276.6	278.7
15 s Hold Time	304.1	314.2	317.7	320.9	322.5
Partial Loading	302.4	305.1	313.5	317.5	320.3

Loading density had no physically significant effect on γ_{max}. The value of γ_{max} for picker harvested cotton was generally 40 to 50 kg/m^3 higher than the parameter value for stripper harvested cotton, corresponding to the greater compressed density observed in testing. Reducing the hold time decreased the maximum density parameter, with the effect more pronounced with additional compressions. Because the time-dependent strain was smaller with a shorter hold time, the highest compressed density for later compressions was less. The value of γ_{max} was reduced with partial loading of the cylinder, although this effect diminished with a greater number of compressions. Because each additional compression increased the density less than the previous one, the measured density of the partial loading treatment approached the density of the full loading treatment.

Multiple compressions generally increased the value of γ_{max} due to the increased density from time-dependent strain. The exception to this trend was the first compression of the stripper harvested cotton with a loading density of 128 kg/m^3. This maximum density value for the first compression was greater than the value for the second compression, although the second compression actually had a higher recorded density. Because the K value for the first compression of these tests was significantly larger than any other value, this increased the likelihood that these values resulted from a range in densities that was too small to robustly estimate the parameters, as mentioned previously.

Higher moisture content increased the value of the maximum density parameter, as shown in Figure 6. The linear regression equations were fit to the parameter estimates of maximum density for each replication of picker harvested cotton with a loading density of 96 kg/m^3 and a hold time of 900 seconds. The slope of the fitted lines shown varied from 282.3 to 448.7, indicating that a one percent change in moisture content increased the value of the maximum density parameter by 2.8 to 4.5 kg/m^3. This value was comparable to the parameter estimates for the effect of moisture content in the ANCOVA models. The parameter estimates for the other tests showed a similar response to changes in moisture content.

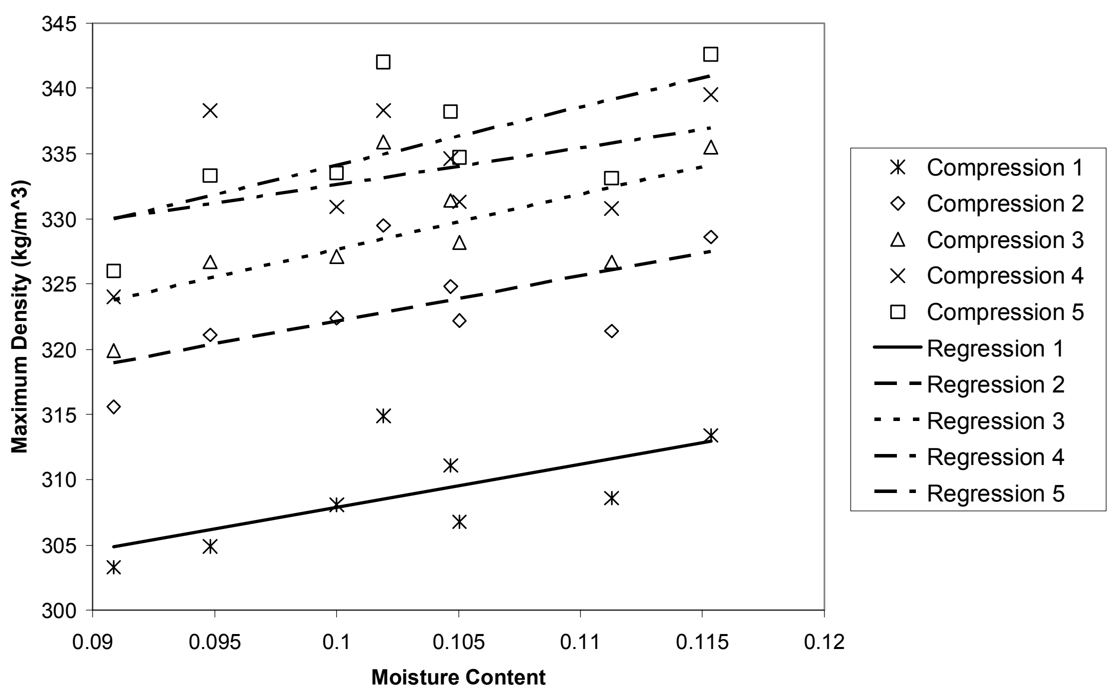

Figure 6. Effect of moisture content on the maximum density parameter.

The predicted values of stress for one replication of picker harvested cotton with an initial loading density of 96 kg/m^3 and a hold time of 900 seconds are displayed in Figure 7, along with the actual data. Although the model described the data reasonably well and the parameters estimated for nearly all the tests were in agreement with actual data, several improvements could be made upon the model. The model overestimated the value of stress initially and predicted too low a value of stress at higher densities. This trend, also shown in Figure 8 in the plot of residuals, occurred in the data for each compression of all tests. Clearly, the model failed to explain some aspect of the compression process. Based on the distribution of residuals, a quadratic or cubic form of the logarithmic term (which is a modified version of the deformation) in the equation may improve the model. In fact, Peleg's model uses an elastic element with force defined as a function of the deformation cubed. Accounting for the variation displayed in Figures 7 and 8 may result in more consistent values for K.

The slope of the actual stress-density curve appeared to decrease at approximately 95 kPa, while the model predicted that the slope of the curve will increase indefinitely. However, this was an artifact of the algorithm used to sort data into compression and creep phases. Although a specific point in testing was defined as the end of the initial compression and the beginning of creep, this transition actually occurred over a range of stress and density values. Further testing demonstrated that the slope of the curve continued to increase.

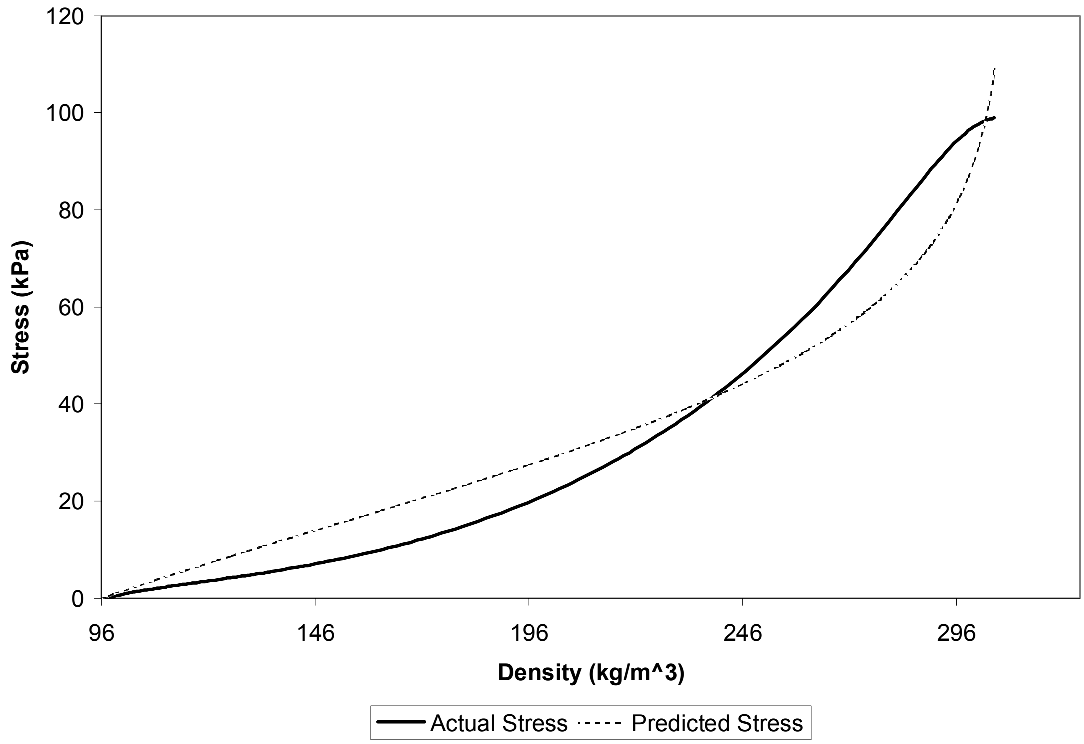

Figure 7. Actual and predicted stress for the 1st compression of replication #3 of picker harvested cotton with a loading density of 96 kg/m^3, a hold time of 900 s, and full loading.

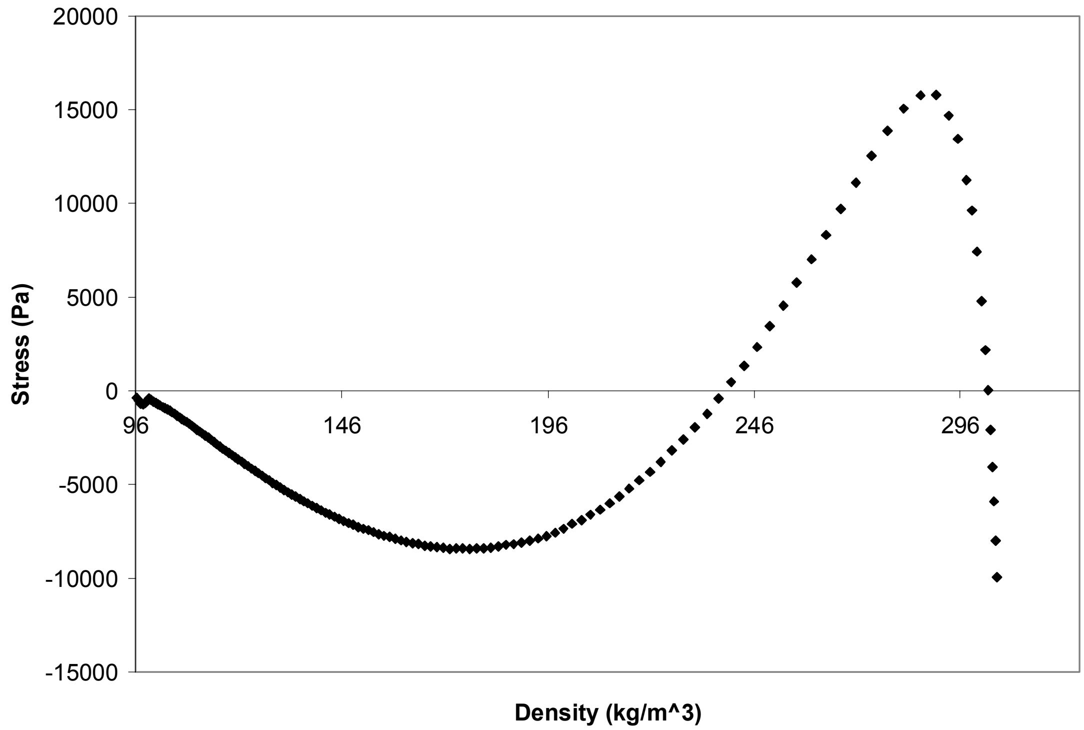

Figure 8. Residuals for the 1st compression of replication #3 of picker harvested cotton with a loading density of 96 kg/m^3, a hold time of 900 s, and full loading.

Another limitation of this model was encountered in the range of densities tested. Seed cotton can be compressed to a greater density than the values estimated for the asymptotic maximum density parameters. A sample of seed cotton was compressed in the lab with an applied stress of 296 kPa to a density of 389.3 kg/m^3. Nonlinear regression of the stress-density data for this sample resulted in parameter values of 60.5 kPa for K and 392.6 kg/m^3 for γ_{max}. Testing at higher densities would be required to generate an estimate for γ_{max} that could be used in making predictions about density over an extended range.

Creep Model

Eq. 12 was used to describe the viscoelastic behavior of seed cotton. The model fit the data extremely well, with an average R^2 value of 0.999 and a minimum R^2 of

0.996. Values for the parameter E_2, representing the elastic element in parallel with a viscous element, are shown in Table 21. The behavior of the series-connected viscous element was described by the parameter η_1, whose values are shown in Table 22. The values of the parameter η_2, the damping coefficient of the parallel-connected viscous element, are shown in Table 23. Analysis of the parameter values for tests with a hold time of 15 seconds was not possible because the model parameters could not be accurately specified with only 15 seconds of creep loading.

Table 21. Average values of E_2 (in MPa) for each treatment combination and compression.

	Compression Number				
Treatments	1	2	3	4	5
64, Picker	2.827	4.724	6.223	7.435	8.948
96, Picker	2.499	4.778	6.381	7.577	9.013
128, Picker	2.897	5.271	7.068	9.009	10.37
64, Stripper	2.386	4.510	6.431	8.369	10.37
96, Stripper	2.529	5.300	7.585	8.855	10.12
128, Stripper	2.522	5.562	7.701	9.935	10.81
Partial Loading	2.854	3.603	6.301	7.903	9.539

Table 22. Average values of η_1 (in GPa*s) for each treatment combination and compression.

	Compression Number				
Treatments	1	2	3	4	5
64, Picker	6.528	9.575	12.57	16.60	18.83
96, Picker	6.099	9.580	12.15	14.35	17.17
128, Picker	6.683	12.32	19.79	19.97	24.42
64, Stripper	4.557	8.263	11.46	15.65	16.04
96, Stripper	5.441	8.975	12.38	18.84	18.37
128, Stripper	5.443	10.62	14.82	18.97	24.89
Partial Loading	6.107	9.406	11.09	18.98	22.45

Table 23. Average values of η_2 (in MPa*s) for each treatment combination and compression.

	Compression Number				
Treatments	1	2	3	4	5
64, Picker	94.87	136.3	189.7	196.0	235.5
96, Picker	81.99	135.2	142.6	149.5	193.2
128, Picker	105.1	154.3	221.4	259.7	268.3
64, Stripper	82.94	154.4	223.5	236.0	342.1
96, Stripper	92.18	168.8	233.9	293.3	319.4
128, Stripper	103.2	186.8	277.6	269.5	313.1
Partial Loading	104.1	116.8	167.2	182.6	309.0

The major difference in parameter values occurred between compressions. E_2 and η_1 increased with additional compressions; therefore, the model predicted decreasing creep strain for subsequent cycles of compression and creep loading. The value of η_2

also increased with repeated compressions and creep loading. The ratio of η_2 to E_2 is known as the time constant and describes the rate at which the exponential term approaches its asymptotic value. While the actual parameter values all increased, the time constant decreased slightly from the first to the fifth compression.

The loading density did not appear to have a large effect on the creep model parameter values, although the highest loading density resulted in slightly larger parameter values for both picker and stripper harvested cotton. Likewise, the harvesting method did not significantly affect the values of E_2 or η_1. The values of η_2 for stripper harvested cotton were similar to picker harvested cotton for the initial compression, but increased more with each additional compression. The parameter values appeared to be unrelated to moisture content.

Partial loading of the cylinder resulted in parameter estimates similar to the full loading data for the first compression. Parameter values increased for the second compression with partial loading, but not as much as with full loading. Because half of the seed cotton was not compressed, this result was expected. This trend continued, as the parameter estimates for a given compression with the partial loading method were between the values for the same compression and the previous compression with full loading.

A plot of the actual and predicted values of the true creep strain, $ln(\gamma/\gamma_c)$, is shown in Figure 9, and the residuals from this regression are displayed in Figure 10. Similar trends were observed in all the data with a 900 second hold time. The model accounted for the delayed elasticity with the exponential term and the time-dependent permanent deformation with the linear term. Addition of another Kelvin unit (parallel-connected elastic and viscous elements) may improve the fit of the model. This procedure is analogous to the method used by Mohsenin and Zaske with Maxwell elements for stress relaxation. Examining the data indicated that the additional Kelvin unit would have a longer time constant and the values of all parameters in the original model would increase. Because seed cotton is a heterogeneous material primarily composed of lint and seed, each Kelvin unit may model the behavior of one component.

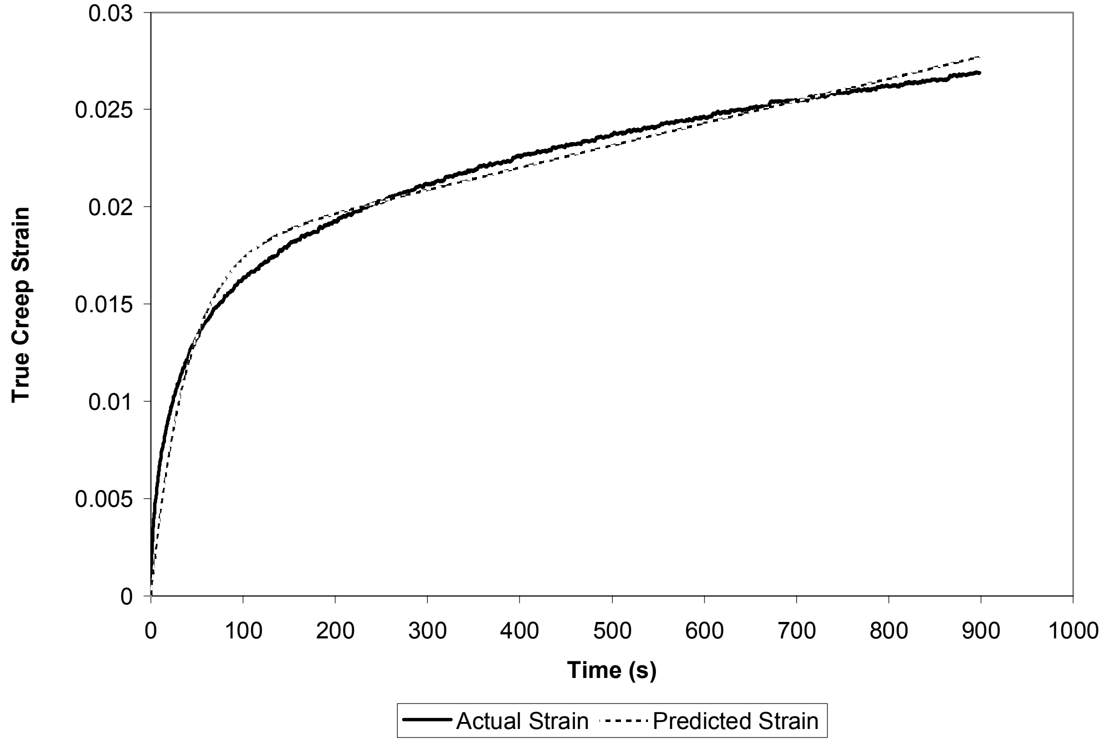

Figure 9. Actual and predicted creep strain for the 2nd compression of replication #1 of stripper harvested cotton with a loading density of 96 kg/m^3, a hold time of 900 s, and full loading.

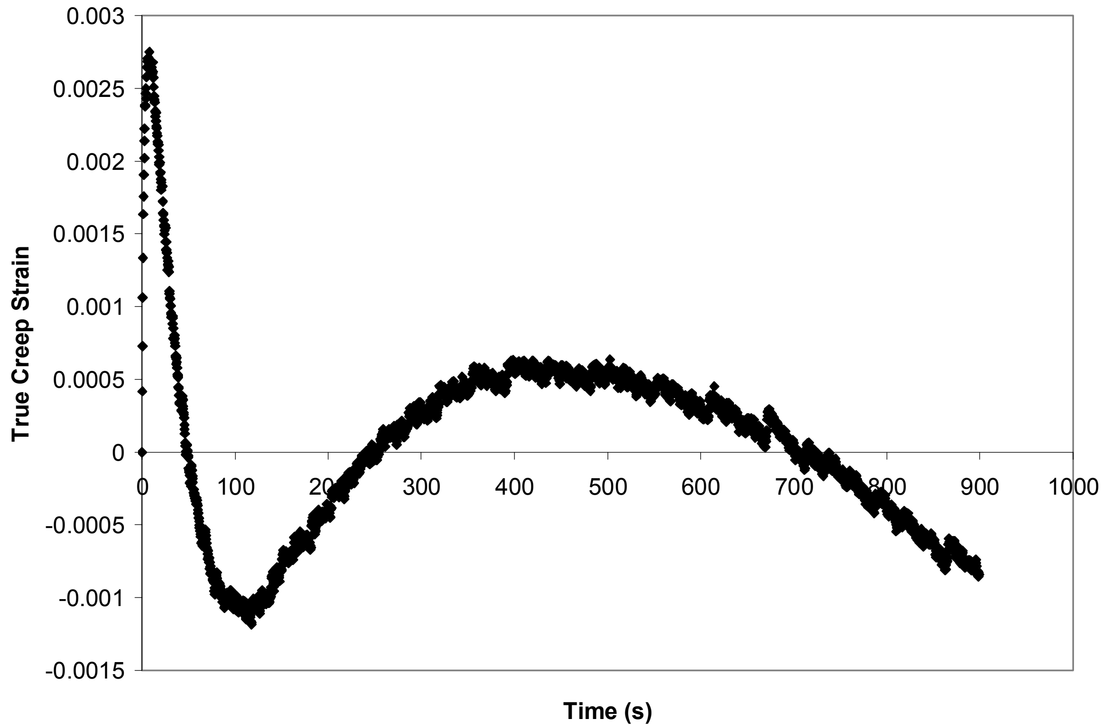

Figure 10. Residuals of creep model for the 2nd compression of replication #1 of stripper harvested cotton with a loading density of 96 kg/m^3, a hold time of 900 s, and full loading.

Objective 3

The results of these experiments were used to design an algorithm that can provide the module builder operator with the necessary feedback on module properties to construct a module that will not collect water on its surface. Because the operator can not vary the maximum compressive force applied by the module builder and additional compressions do not result in large changes in density, the most practical way to affect the shape of the module is to vary the mass of seed cotton throughout the module.

Directly determining the mass of seed cotton at various locations in a module builder would be difficult because the weight of the seed cotton is supported by the ground. No surface exists for mounting sensing elements. However, the mass under the tramper foot in a module builder can be determined from the density and the extension of the tramper foot cylinder. This research has shown that seed cotton was compressed to a constant density with a constant force, regardless of the mass of seed cotton. Therefore, the compressed depth will vary directly with the mass of cotton when a constant force is applied. Once enough cotton has been loaded into the module builder, a constant maximum force is applied by the tramper foot. The shape can be predicted by measuring the compressed height at different locations in the module builder.

The feedback algorithm will be implemented with a microcontroller-based design. This design provides a simple and inexpensive method of integrating sensors and the user interface and allows the algorithm to be easily modified. Use of a microcontroller will also allow extension of the algorithm to automatic control systems for module builders. The microcontroller can send control signals to solenoid valves, resulting in carriage or tramper foot movement.

A position sensor is required to indicate the location of the carriage. Because the carriage is usually chain driven, the position can be determined by using a rotary encoder or magnetic pickup. Although the absolute position is not known using these sensors, it can be determined by indexing the carriage to one end of the module builder. Alternatively, after the carriage has covered the entire length of the module builder, the relative position can be assigned an absolute location because the length is fixed.

Another sensor is needed to determine the height of the tramper foot. The tramper foot on some module builders is equipped with a roller chain mechanism to keep the foot level. These models could be equipped with a second rotary position sensor similar to the one for carriage location. If a module builder does not have this mechanism, a wheel could be mounted on the top surface of the tramper foot in contact with the side wall. The wheel mount would need to be spring-loaded to prevent slip and maintain contact with the tapered wall. This wheel could then be instrumented with another rotary position sensor.

To determine the applied stress, the hydraulic pressure can be measured in the line connecting the tramper foot cylinder to the hydraulic pump. The force generated by the cylinder will be equal to this pressure multiplied by the area specified by the cylinder bore diameter. Because the density of seed cotton will depend on the applied compressive stress, this value can be calculated from the ratio of force to the tramper foot area.

After enough cotton is loaded into the module builder so that the tramper foot can not be extended to its maximum depth, the relative mass at various locations in the module can be determined by measuring the height of the tramper foot when the seed cotton is compressed to the greatest density. This density occurs when the pressure required to further compress the cotton is greater than the system relief pressure. By simply comparing the compressed depth of cotton at various locations in the module, the relative mass and resulting shape can be determined. If the seed cotton is compressed to the same height at multiple locations, approximately the same mass of seed cotton is in each location. If the compressed depth of seed cotton is greater at one location, then more cotton is present there. Informing the module builder operator of the compressed height across a module provides information about the relative mass, so the operator can move seed cotton to the appropriate locations.

Density could be predicted if the accuracy of the stress-density relationship was improved. The initial density must be known or estimated for this equation to be used. It would be possible to estimate the density of uncompressed cotton added to the module and predict the compressed density from this initial density and the applied stress. However, the current model is highly sensitive to the initial density at lower applied stresses, resulting in inaccurate predictions of density if the initial density varies slightly.

One potential difficulty that may be encountered in implementing this algorithm is that the distribution of mass along the entire length of the module needs to be determined, but not every location in the module is compressed. This problem can be solved by dividing the length of the module builder into sections of equal length. If further research determines an optimum distance between compression strokes, this value would be incorporated into the algorithm as the length of each section. Otherwise, an arbitrary value consistent with standard operating practices could be assigned. A compression stroke occurring anywhere within the region would result in calculation of the mass and density for that region. This system has the additional benefit of informing the operator if there is a region in the module that has not been compressed.

The resulting mass of seed cotton along the length of the module builder will be displayed to the user. A graphical display, such as an LCD or array of LEDs, will provide an output that is easily understood by the operator. The height of a bar in an LCD or the number of LEDs lighted in a column would indicate the mass of seed cotton at that location in the module builder. Areas with more or less seed cotton would be clearly distinguishable, and the operator could move cotton to or from these areas.

CHAPTER V

RECOMMENDATIONS AND CONCLUSIONS

Objective 1

The primary implication of this research involves loading of seed cotton into module builders, and the resulting module shapes that can be expected. This research indicated that with a constant compressive force, a similar compressed density was reached regardless of the initial density or mass of seed cotton. The mass of seed cotton determined the resulting volume. Therefore, if different masses of seed cotton are loaded into the module builder at different locations and compressed evenly, the module will contain a similar final density of cotton. However, regions with different masses will occupy different volumes, and the resulting top surface will be uneven. This module surface may be subject to water ponding on the cover.

A common practice in forming a module (given that uniform loading is practically impossible) is to tramp until the module has a level or slightly crowned appearance. This operation may result in a module that appears to have a level top surface in the module builder. However, the cotton will continue to expand after the module builder has been removed, resulting in depressions where water will collect. This outcome is the result of several aspects of the physical properties of seed cotton.

The deformation that is observed from repeated compressions is elastic, but not instantaneously recovered because the cotton is restrained from complete expansion in the module builder. Most of the permanent deformation in seed cotton is a result of the time-independent strain that occurs when the void spaces in the material are compressed. A large proportion of this deformation occurs during the initial compression cycle. The differences in volume resulting from additional compression cycles are not practically significant after the third compression. In a module builder, only enough compressions need to be performed so that there is no loose, uncompressed cotton on the surface. This usually requires several compressive strokes to accomplish because uncompressed cotton adjacent to the tramper foot during a compression will fall into the area that has just been compressed.

The time-dependent inelastic strain is small relative to the elastic and instantaneous inelastic strains. This result was evident in the small difference in recovered densities with different hold times, although one hold time was longer by a factor of sixty. The length of time a force would have to be maintained to affect the shape and density of modules is impractical.

With a constant force, the dominant factor affecting the height of seed cotton after compression is the mass of seed cotton. Likewise, the mass of seed cotton is the primary factor in determining the force required to compress seed cotton to a constant volume. Therefore, a module must be loaded according to the desired final shape. If the desired module should be crowned, then more seed cotton should be placed in the center of the module and less near the sides. This action may be accomplished with a mechanical device capable of distributing the seed cotton according to a desired pattern without interfering with the tramper foot.

Improved loading of the module builder is necessary when constructing modules with either picker or stripper harvested cotton. However, because the compressed density of stripper harvested cotton is less when the same pressure is applied, using a higher compressive stress with stripper harvested cotton may be more efficient. While the recovered density was approximately the same, this would not be the case in a module builder. The effect of the weight of the seed cotton is more significant, so more of the elastic deformation is retained.

Objective 2

The equation used to model compressive behavior explained most of the variation in the data. Using an asymptotic form of true strain more closely approximated the behavior than Hooke's law or a true strain measure, but some aspect of the force-deformation curve remained unexplained, as evidenced by the repeated pattern of residuals. This unexplained behavior limits the usefulness of the compression equation for making predictions. A nonlinear relationship between stress and the modified strain may be required. Compression data needs to be obtained over a wider range of stresses and densities to determine a value of the asymptote that is consistent with experimental data at higher stresses as well.

The model accurately described creep behavior, but the deformation due to creep strain was relatively small. Since seed cotton has two primary components, an additional term may improve the accuracy of the model by accounting for the delayed elasticity of the other component. This viscoelastic data may be useful if other methods of seed cotton storage are developed, for example, modifying a harvester to also bale cotton. Knowledge of the viscoelastic properties of seed cotton would be necessary in determining how to optimally restrain the baled material.

Objective 3

The compressed height of seed cotton was used as the basis for the operator feedback algorithm. Because the seed cotton was compressed to a constant density over the entire range of loading densities tested, the compressed height was dependent on the mass of cotton tested. Measuring the compressed height of seed cotton in a module will provide an estimate of the distribution of mass in the module. Development of a feedback system will enable the module builder operator to construct modules that will consistently shed water. The feedback system would also be able to ensure that the operator compresses the module evenly along the length and could be interfaced with an automatic control system.

Future Work

The stress-density relationship of seed cotton needs to be investigated more thoroughly to develop an equation that can be used to accurately predict density. Since the differences between the compression model and the actual data were consistent across tests, a modification to the model or development of a more suitable model should account for this discrepancy. A more accurate model could be used in a feedback system to predict density.

The algorithm developed for the feedback system needs to be implemented on a module builder. The distribution of seed cotton across the width of a module still remains a problem, since the feedback system can only determine the average mass across the entire width. Solving this problem also requires development of a means for moving cotton across the width of the module. This device needs to mount to the tramper foot and be capable of transmitting a compressive force or be moveable, allowing the tramper foot to compress the cotton normally. Investigation of the ideal distribution of mass in a module was not an objective of this research and remains to be determined, but this knowledge is important in constructing modules that will not collect water on their covers.

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APPENDIX A

HEIGHT AND DENSITY MEASUREMENTS

Table 24. Height and density values for compression and creep loading of all replications.

Replication	Moisture Content	Compressed Height (mm)	Compressed Density (kg/m^3)	Change in Height-Creep (mm)	Change in Density-Creep (kg/m^3)
64 kg/m^3 Loading Density, Picker Harvested, 900 s Hold Time, Full Loading 1st Compression					
1	7.8	205	287	9	14
2	9.9	194	302	9	15
3	9.0	200	294	10	15
4	9.8	197	298	10	15
64 kg/m^3 Loading Density, Picker Harvested, 900 s Hold Time, Full Loading 2nd Compression					
1	7.8	195	301	5	8
2	9.9	186	315	6	10
3	9.0	191	307	6	9
4	9.8	189	310	6	11
64 kg/m^3 Loading Density, Picker Harvested, 900 s Hold Time, Full Loading 3rd Compression					
1	7.8	192	306	4	6
2	9.9	182	322	4	8
3	9.0	187	313	4	7
4	9.8	184	318	4	7
64 kg/m^3 Loading Density, Picker Harvested, 900 s Hold Time, Full Loading 4th Compression					
1	7.8	190	309	4	6
2	9.9	180	326	3	6
3	9.0	185	317	3	6
4	9.8	182	322	3	6
64 kg/m^3 Loading Density, Picker Harvested, 900 s Hold Time, Full Loading 5th Compression					
1	7.8	188	312	3	4
2	9.9	178	330	3	5
3	9.0	184	319	3	5
4	9.8	181	325	3	5

Table 24. Continued.

Replication	Moisture Content	Compressed Height (mm)	Compressed Density (kg/m^3)	Change in Height-Creep (mm)	Change in Density-Creep (kg/m^3)
96 kg/m^3 Loading Density, Picker Harvested, 900 s Hold Time, Full Loading 1st Compression					
1	10.2	282	312	15	18
2	10.5	285	308	15	17
3	10.0	288	305	14	16
4	9.5	291	302	16	18
5	9.1	293	300	13	14
6	11.1	288	305	15	17
7	11.5	283	311	15	17
8	10.5	289	304	16	18
96 kg/m^3 Loading Density, Picker Harvested, 900 s Hold Time, Full Loading 2nd Compression					
1	10.2	269	327	8	10
2	10.5	273	323	8	9
3	10.0	275	319	7	9
4	9.5	276	319	8	10
5	9.1	281	313	7	8
6	11.1	276	319	8	10
7	11.5	270	326	8	10
8	10.5	275	320	8	9
96 kg/m^3 Loading Density, Picker Harvested, 900 s Hold Time, Full Loading 3rd Compression					
1	10.2	264	334	6	7
2	10.5	267	330	5	7
3	10.0	270	325	6	7
4	9.5	271	325	6	8
5	9.1	276	318	6	7
6	11.1	271	325	6	8
7	11.5	264	333	6	8
8	10.5	269	326	6	7

Table 24. Continued.

Replication	Moisture Content	Compressed Height (mm)	Compressed Density (kg/m^3)	Change in Height-Creep (mm)	Change in Density-Creep (kg/m^3)
96 kg/m^3 Loading Density, Picker Harvested, 900 s Hold Time, Full Loading 4th Compression					
1	10.2	261	337	5	7
2	10.5	264	333	5	6
3	10.0	267	329	5	6
4	9.5	261	337	5	7
5	9.1	273	322	4	5
6	11.1	267	329	5	6
7	11.5	260	338	5	6
8	10.5	267	330	5	6
96 kg/m^3 Loading Density, Picker Harvested, 900 s Hold Time, Full Loading 5th Compression					
1	10.2	258	340	4	5
2	10.5	261	337	4	5
3	10.0	265	332	4	5
4	9.5	265	332	4	6
5	9.1	271	324	4	5
6	11.1	265	332	4	5
7	11.5	258	341	4	6
8	10.5	264	333	4	5
128 kg/m^3 Loading Density, Picker Harvested, 900 s Hold Time, Full Loading 1st Compression					
1	8.5	391	300	16	13
2	8.0	397	295	18	14
3	10.7	381	308	21	18
4	10.0	397	295	17	13
128 kg/m^3 Loading Density, Picker Harvested, 900 s Hold Time, Full Loading 2nd Compression					
1	8.5	376	312	9	8
2	8.0	380	309	9	7
3	10.7	362	324	11	10
4	10.0	381	308	10	8
128 kg/m^3 Loading Density, Picker Harvested, 900 s Hold Time, Full Loading 3rd Compression					
1	8.5	369	318	7	6
2	8.0	373	314	6	5
3	10.7	354	331	6	6
4	10.0	373	314	7	6

Table 24. Continued.

Replication	Moisture Content	Compressed Height (mm)	Compressed Density (kg/m^3)	Change in Height-Creep (mm)	Change in Density-Creep (kg/m^3)
128 kg/m^3 Loading Density, Picker Harvested, 900 s Hold Time, Full Loading 4th Compression					
1	8.5	365	321	6	5
2	8.0	368	319	5	4
3	10.7	350	335	5	5
4	10.0	370	317	5	5
128 kg/m^3 Loading Density, Picker Harvested, 900 s Hold Time, Full Loading 5th Compression					
1	8.5	362	324	4	4
2	8.0	366	320	5	4
3	10.7	348	337	5	4
4	10.0	367	320	5	4
64 kg/m^3 Loading Density, Stripper Harvested, 900 s Hold Time, Full Loading 1st Compression					
1	10.1	231	254	12	14
2	9.9	231	254	15	17
3	11.6	229	256	15	18
4	10.4	233	251	13	14
64 kg/m^3 Loading Density, Stripper Harvested, 900 s Hold Time, Full Loading 2nd Compression					
1	10.1	219	268	6	8
2	9.9	217	270	7	9
3	11.6	215	272	7	9
4	10.4	222	264	7	9
64 kg/m^3 Loading Density, Stripper Harvested, 900 s Hold Time, Full Loading 3rd Compression					
1	10.1	214	274	4	6
2	9.9	212	277	5	7
3	11.6	210	280	5	6
4	10.4	217	270	5	7
64 kg/m^3 Loading Density, Stripper Harvested, 900 s Hold Time, Full Loading 4th Compression					
1	10.1	212	277	3	4
2	9.9	209	280	5	6
3	11.6	207	284	3	5
4	10.4	213	275	4	5

Table 24. Continued.

Replication	Moisture Content	Compressed Height (mm)	Compressed Density (kg/m^3)	Change in Height-Creep (mm)	Change in Density-Creep (kg/m^3)
64 kg/m^3 Loading Density, Stripper Harvested, 900 s Hold Time, Full Loading 5th Compression					
1	10.1	210	279	3	4
2	9.9	206	284	3	5
3	11.6	205	286	3	4
4	10.4	211	277	3	4
96 kg/m^3 Loading Density, Stripper Harvested, 900 s Hold Time, Full Loading 1st Compression					
1	9.8	352	250	19	15
2	9.7	355	247	18	13
3	10.2	349	252	18	14
4	10.8	350	252	18	14
96 kg/m^3 Loading Density, Stripper Harvested, 900 s Hold Time, Full Loading 2nd Compression					
1	9.8	332	265	9	7
2	9.7	338	260	10	8
3	10.2	332	265	9	8
4	10.8	332	265	9	7
96 kg/m^3 Loading Density, Stripper Harvested, 900 s Hold Time, Full Loading 3rd Compression					
1	9.8	325	270	6	5
2	9.7	330	266	6	5
3	10.2	325	271	7	6
4	10.8	325	270	6	6
96 kg/m^3 Loading Density, Stripper Harvested, 900 s Hold Time, Full Loading 4th Compression					
1	9.8	321	274	5	4
2	9.7	326	270	4	4
3	10.2	321	274	6	5
4	10.8	321	274	5	4
96 kg/m^3 Loading Density, Stripper Harvested, 900 s Hold Time, Full Loading 5th Compression					
1	9.8	319	276	5	4
2	9.7	324	271	4	3
3	10.2	317	277	5	4
4	10.8	318	276	5	4

Table 24. Continued.

Replication	Moisture Content	Compressed Height (mm)	Compressed Density (kg/m^3)	Change in Height-Creep (mm)	Change in Density-Creep (kg/m^3)
128 kg/m^3 Loading Density, Stripper Harvested, 900 s Hold Time, Full Loading 1st Compression					
1	9.6	467	251	23	13
2	9.8	467	251	25	14
3	11.0	459	256	24	14
4	11.1	460	255	26	15
128 kg/m^3 Loading Density, Stripper Harvested, 900 s Hold Time, Full Loading 2nd Compression					
1	9.6	446	263	10	6
2	9.8	444	264	12	8
3	11.0	436	269	11	7
4	11.1	434	270	12	8
128 kg/m^3 Loading Density, Stripper Harvested, 900 s Hold Time, Full Loading 3rd Compression					
1	9.6	438	268	7	4
2	9.8	435	270	8	5
3	11.0	428	274	8	5
4	11.1	426	275	9	6
128 kg/m^3 Loading Density, Stripper Harvested, 900 s Hold Time, Full Loading 4th Compression					
1	9.6	433	271	7	4
2	9.8	429	273	5	3
3	11.0	423	277	6	4
4	11.1	420	279	6	4
128 kg/m^3 Loading Density, Stripper Harvested, 900 s Hold Time, Full Loading 5th Compression					
1	9.6	430	273	5	3
2	9.8	426	275	5	3
3	11.0	420	279	6	4
4	11.1	417	281	5	4
96 kg/m^3 Loading Density, Picker Harvested, 15 s Hold Time, Full Loading 1st Compression					
1	9.3	289	304	6	6
2	9.2	295	298	5	5
3	10.8	290	303	6	6
4	10.3	294	299	7	7

Table 24. Continued.

Replication	Moisture Content	Compressed Height (mm)	Compressed Density (kg/m^3)	Change in Height-Creep (mm)	Change in Density-Creep (kg/m^3)
96 kg/m^3 Loading Density, Picker Harvested, 15 s Hold Time, Full Loading 2nd Compression					
1	9.3	280	314	4	4
2	9.2	288	305	4	4
3	10.8	281	313	5	6
4	10.3	284	309	4	5
96 kg/m^3 Loading Density, Picker Harvested, 15 s Hold Time, Full Loading 3rd Compression					
1	9.3	277	318	4	4
2	9.2	284	310	4	4
3	10.8	277	318	4	5
4	10.3	280	314	4	4
96 kg/m^3 Loading Density, Picker Harvested, 15 s Hold Time, Full Loading 4th Compression					
1	9.3	274	320	3	4
2	9.2	280	314	3	3
3	10.8	273	322	3	3
4	10.3	277	317	3	4
96 kg/m^3 Loading Density, Picker Harvested, 15 s Hold Time, Full Loading 5th Compression					
1	9.3	272	323	3	4
2	9.2	279	315	3	4
3	10.8	272	323	3	4
4	10.3	275	319	3	4
128 kg/m^3 Loading Density, Picker Harvested, 900 s Hold Time, Partial Loading 1st Compression					
1	8.8	200	293	9	15
2	10.0	195	300	9	15
3	7.8	196	299	9	15
128 kg/m^3 Loading Density, Picker Harvested, 900 s Hold Time, Partial Loading 2nd Compression					
1	8.8	393	298	13	11
2	10.0	385	304	14	12
3	7.8	389	301	14	11

Table 24. Continued.

Replication	Moisture Content	Compressed Height (mm)	Compressed Density (kg/m^3)	Change in Height-Creep (mm)	Change in Density-Creep (kg/m^3)
128 kg/m^3 Loading Density, Picker Harvested, 900 s Hold Time, Partial Loading 3rd Compression					
1	8.8	382	307	9	7
2	10.0	373	315	9	7
3	7.8	377	311	9	7
128 kg/m^3 Loading Density, Picker Harvested, 900 s Hold Time, Partial Loading 4th Compression					
1	8.8	376	312	6	5
2	10.0	367	320	6	5
3	7.8	372	315	7	6
128 kg/m^3 Loading Density, Picker Harvested, 900 s Hold Time, Partial Loading 5th Compression					
1	8.8	373	315	5	5
2	10.0	364	322	5	4
3	7.8	368	319	5	5

Table 25. Height and density values for recovery after one hour. Only replications with data are shown.

Replication	Moisture Content	Change in Height-Recovery (mm)	Change in Density-Recovery (kg/m^3)	Final Recovered Height (mm)	Final Recovered Density (kg/m^3)
64 kg/m^3 Loading Density, Picker Harvested, 900 s Hold Time, Full Loading					
2	9.9	64	30	387	151
3	9.0	44	18	400	147
4	9.8	41	18	387	151
96 kg/m^3 Loading Density, Picker Harvested, 900 s Hold Time, Full Loading					
6	11.1	76	31	508	173
7	11.5	57	23	492	179
8	10.5	57	21	514	171
128 kg/m^3 Loading Density, Picker Harvested, 900 s Hold Time, Full Loading					
3	10.7	51	17	613	191
4	10.0	63	18	676	173
64 kg/m^3 Loading Density, Stripper Harvested, 900 s Hold Time, Full Loading					
1	10.1	38	19	362	162
2	9.9	35	19	346	169
3	11.6	32	18	337	174
4	10.4	44	21	378	155
96 kg/m^3 Loading Density, Stripper Harvested, 900 s Hold Time, Full Loading					
1	9.8	44	17	508	173
2	9.7	51	18	521	169
3	10.2	41	16	502	175
4	10.8	38	14	518	170
128 kg/m^3 Loading Density, Stripper Harvested, 900 s Hold Time, Full Loading					
3	11.0	48	16	622	188
4	11.1	44	15	616	190
96 kg/m^3 Loading Density, Picker Harvested, 15 s Hold Time, Full Loading					
2	9.2	41	11	606	145
3	10.8	41	13	543	162
4	10.3	32	10	546	161
128 kg/m^3 Loading Density, Picker Harvested, 900 s Hold Time, Partial Loading					
1	8.8	63	16	705	166

APPENDIX B

ANALYSIS OF VARIANCE TABLES

Table 26. ANOVA tables for statistical analyses.

Source	**df**	**F-Statistic**	**P-Value**
Harvest-Density Treatments- Compressed Height			
Model	12	4375.30	<.0001
Error	127		
Total	139		
Harvest-Density Treatments- Compressed Density			
Model	8	782.27	<0.0001
Error	131		
Total	139		
Harvest-Density Treatments- Change in Height- Creep			
Model	8	159.55	<0.0001
Error	131		
Total	139		
Harvest-Density Treatments- Change in Density- Creep			
Model	8	453.12	<0.0001
Error	131		
Total	139		
Harvest-Density Treatments- Change in Height- Recovery			
Model	4	5.20	0.0100
Error	13		
Total	17		
Harvest-Density Treatments- Change in Density- Recovery			
Model	4	3.57	0.0356
Error	13		
Total	17		
Harvest-Density Treatments- Final Recovered Height			
Model	4	216.70	<0.0001
Error	13		
Total	17		
Harvest-Density Treatments- Final Recovered Density			
Model	4	23.40	<0.0001
Error	13		
Total	17		
Hold Time Treatment- Compressed Height			
Model	6	74.20	<0.0001
Error	53		
Total	59		

Table 26. Continued.

Source	df	F-Statistic	P-Value
Hold Time Treatment- Compressed Density			
Model	6	67.92	<0.0001
Error	53		
Total	59		
Hold Time Treatment- Change in Height- Creep			
Model	6	48.43	<0.0001
Error	53		
Total	59		
Hold Time Treatment- Change in Density- Creep			
Model	6	46.93	<0.0001
Error	53		
Total	59		
Hold Time Treatment- Change in Height- Recovery			
Model	2	4.80	0.1162
Error	3		
Total	5		
Hold Time Treatment- Change in Density- Recovery			
Model	2	9.58	0.0498
Error	3		
Total	5		
Hold Time Treatment- Final Recovered Height			
Model	2	27.92	0.0115
Error	3		
Total	5		
Hold Time Treatment- Final Recovered Density			
Model	2	40.76	0.0067
Error	3		
Total	5		
Loading Method Treatment- Compressed Height			
Model	5	12.83	<0.0001
Error	22		
Total	27		
Loading Method Treatment- Compressed Density			
Model	5	12.30	<0.0001
Error	22		
Total	27		
Loading Method Treatment- Change in Height- Creep			
Model	9	22.65	<0.0001
Error	18		
Total	27		

Table 26. Continued.

Source	**df**	**F-Statistic**	**P-Value**
Loading Method Treatment- Change in Density- Creep			
Model	6	33.54	<0.0001
Error	21		
Total	27		
Constant Volume- Picked- Final Recovered Height			
Model	2	616.44	<0.0001
Error	9		
Total	11		
Constant Volume- Picked- Final Recovered Density			
Model	2	2081.77	<0.0001
Error	9		
Total	11		
Constant Volume- Picked- Maximum Applied Stress			
Model	2	1293.55	<0.0001
Error	9		
Total	11		
Constant Volume- Stripped- Final Recovered Height			
Model	2	152.17	<0.0001
Error	9		
Total	11		
Constant Volume- Stripped- Final Recovered Density			
Model	2	592.36	<0.0001
Error	9		
Total	11		
Constant Volume- Stripped- Maximum Applied Stress			
Model	2	2703.51	<0.0001
Error	9		
Total	11		

APPENDIX C

PARAMETER VALUES

Table 27. Parameter estimates for compression of all replications.

Replication	Moisture Content	K (kPa)	Standard Error	γ_{max} (kg/m^3)	Standard Error
64 kg/m^3 Loading Density, Picker Harvested, 900 s Hold Time, Full Loading 1st Compression					
1	7.8	15.21	0.46	287.3	0.4
2	9.9	15.42	0.47	302.3	0.4
3	9.0	15.57	0.47	294.7	0.4
4	9.8	15.69	0.47	298.6	0.5
64 kg/m^3 Loading Density, Picker Harvested, 900 s Hold Time, Full Loading 2nd Compression					
1	7.8	20.15	0.99	302.6	0.6
2	9.9	22.49	1.16	317.6	0.8
3	9.0	21.36	1.05	309.0	0.8
4	9.8	21.49	1.10	312.2	0.8
64 kg/m^3 Loading Density, Picker Harvested, 900 s Hold Time, Full Loading 3rd Compression					
1	7.8	18.74	0.98	307.1	0.5
2	9.9	21.34	1.17	323.7	0.7
3	9.0	20.34	1.07	314.4	0.6
4	9.8	21.04	1.14	319.3	0.6
64 kg/m^3 Loading Density, Picker Harvested, 900 s Hold Time, Full Loading 4th Compression					
1	7.8	18.49	0.98	309.5	0.4
2	9.9	21.09	1.18	327.8	0.6
3	9.0	19.46	1.03	317.6	0.5
4	9.8	20.62	1.15	323.2	0.6
64 kg/m^3 Loading Density, Picker Harvested, 900 s Hold Time, Full Loading 5th Compression					
1	7.8	18.24	1.02	312.5	0.4
2	9.9	20.89	1.19	330.8	0.6
3	9.0	19.21	1.04	320.1	0.5
4	9.8	20.27	1.14	325.8	0.5

Table 27. Continued.

Replication	Moisture Content	K (kPa)	Standard Error	γ_{max} (kg/m^3)	Standard Error
96 kg/m^3 Loading Density, Picker Harvested, 900 s Hold Time, Full Loading 1st Compression					
1	10.2	20.16	0.53	314.9	0.8
2	10.5	20.06	0.48	311.1	0.7
3	10.0	20.37	0.49	308.1	0.8
4	9.5	20.02	0.48	304.9	0.7
5	9.1	20.69	0.50	303.3	0.8
6	11.1	21.13	0.53	308.6	0.8
7	11.5	19.50	0.49	313.4	0.7
8	10.5	20.01	0.48	306.8	0.7
96 kg/m^3 Loading Density, Picker Harvested, 900 s Hold Time, Full Loading 2nd Compression					
1	10.2	24.52	1.15	329.5	0.9
2	10.5	22.86	1.09	324.8	0.8
3	10.0	25.51	1.16	322.4	0.9
4	9.5	23.43	1.07	321.1	0.8
5	9.1	23.85	1.04	315.6	0.8
6	11.1	24.88	1.10	321.4	0.8
7	11.5	23.84	1.09	328.6	0.8
8	10.5	23.70	1.11	322.2	0.8
96 kg/m^3 Loading Density, Picker Harvested, 900 s Hold Time, Full Loading 3rd Compression					
1	10.2	24.44	1.19	335.9	0.7
2	10.5	22.99	1.12	331.4	0.7
3	10.0	23.63	1.11	327.1	0.6
4	9.5	22.46	1.05	326.7	0.6
5	9.1	22.40	0.94	319.9	0.6
6	11.1	22.66	1.05	326.7	0.6
7	11.5	23.39	1.13	335.5	0.7
8	10.5	23.10	1.13	328.2	0.7
96 kg/m^3 Loading Density, Picker Harvested, 900 s Hold Time, Full Loading 4th Compression					
1	10.2	22.54	1.14	338.3	0.6
2	10.5	22.25	1.07	334.6	0.6
3	10.0	22.86	1.19	330.9	0.6
4	9.5	21.70	1.06	338.3	0.6
5	9.1	22.60	0.98	324.0	0.5
6	11.1	23.09	1.12	330.8	0.6
7	11.5	23.27	1.12	339.5	0.6
8	10.5	22.05	1.10	331.3	0.6

Table 27. Continued.

Replication	Moisture Content	K (kPa)	Standard Error	γ_{max} (kg/m^3)	Standard Error
96 kg/m^3 Loading Density, Picker Harvested, 900 s Hold Time, Full Loading 5th Compression					
1	10.2	23.04	1.19	342.0	0.6
2	10.5	22.33	1.10	338.2	0.5
3	10.0	22.86	1.18	333.5	0.6
4	9.5	21.45	1.06	333.3	0.5
5	9.1	22.22	0.93	326.0	0.5
6	11.1	22.57	1.15	333.1	0.6
7	11.5	23.19	1.15	342.6	0.6
8	10.5	22.60	1.16	334.7	0.6
128 kg/m^3 Loading Density, Picker Harvested, 900 s Hold Time, Full Loading 1st Compression					
1	8.5	27.68	0.49	308.1	1.0
2	8.0	28.96	0.50	305.3	1.0
3	10.7	27.92	0.51	317.3	1.1
4	10.0	28.52	0.50	304.8	1.0
128 kg/m^3 Loading Density, Picker Harvested, 900 s Hold Time, Full Loading 2nd Compression					
1	8.5	25.79	1.01	314.9	0.8
2	8.0	26.68	0.96	312.2	0.8
3	10.7	27.72	1.11	327.8	0.9
4	10.0	25.99	0.98	310.8	0.8
128 kg/m^3 Loading Density, Picker Harvested, 900 s Hold Time, Full Loading 3rd Compression					
1	8.5	24.53	0.96	319.6	0.6
2	8.0	25.32	1.02	316.8	0.6
3	10.7	26.59	1.15	334.3	0.7
4	10.0	25.32	0.97	316.3	0.6
128 kg/m^3 Loading Density, Picker Harvested, 900 s Hold Time, Full Loading 4th Compression					
1	8.5	23.75	0.92	322.6	0.5
2	8.0	25.11	1.05	320.7	0.6
3	10.7	25.51	1.13	336.8	0.6
4	10.0	24.41	0.92	319.1	0.5
128 kg/m^3 Loading Density, Picker Harvested, 900 s Hold Time, Full Loading 5th Compression					
1	8.5	23.39	0.97	325.4	0.5
2	8.0	23.51	0.95	321.9	0.5
3	10.7	25.40	1.03	338.8	0.5
4	10.0	23.90	0.97	321.6	0.5

Table 27. Continued.

Replication	Moisture Content	K (kPa)	Standard Error	γ_{max} (kg/m^3)	Standard Error
64 kg/m^3 Loading Density, Stripper Harvested, 900 s Hold Time, Full Loading 1st Compression					
1	10.1	17.59	0.56	255.3	0.6
2	9.9	17.10	0.54	255.4	0.5
3	11.6	17.74	0.55	257.6	0.6
4	10.4	18.30	0.60	252.5	0.6
64 kg/m^3 Loading Density, Stripper Harvested, 900 s Hold Time, Full Loading 2nd Compression					
1	10.1	25.27	1.48	270.1	0.8
2	9.9	24.89	1.53	272.4	0.8
3	11.6	27.35	1.67	275.1	0.9
4	10.4	25.60	1.52	266.4	0.8
64 kg/m^3 Loading Density, Stripper Harvested, 900 s Hold Time, Full Loading 3rd Compression					
1	10.1	23.81	1.43	275.3	0.6
2	9.9	24.03	1.46	278.4	0.6
3	11.6	26.08	1.65	281.8	0.7
4	10.4	24.36	1.42	272.1	0.6
64 kg/m^3 Loading Density, Stripper Harvested, 900 s Hold Time, Full Loading 4th Compression					
1	10.1	22.76	1.35	278.3	0.5
2	9.9	22.45	1.32	281.4	0.5
3	11.6	26.31	1.67	285.7	0.7
4	10.4	25.21	1.44	276.7	0.6
64 kg/m^3 Loading Density, Stripper Harvested, 900 s Hold Time, Full Loading 5th Compression					
1	10.1	22.08	1.30	280.6	0.5
2	9.9	23.78	1.48	285.3	0.5
3	11.6	23.97	1.49	287.5	0.5
4	10.4	24.37	1.43	278.9	0.5
96 kg/m^3 Loading Density, Stripper Harvested, 900 s Hold Time, Full Loading 1st Compression					
1	9.8	25.44	0.59	255.5	1.0
2	9.7	25.90	0.58	253.4	0.9
3	10.2	24.80	0.59	256.9	1.0
4	10.8	24.88	0.58	256.9	1.0

Table 27. Continued.

Replication	Moisture Content	K (kPa)	Standard Error	γ_{max} (kg/m^3)	Standard Error
96 kg/m^3 Loading Density, Stripper Harvested, 900 s Hold Time, Full Loading 2nd Compression					
1	9.8	30.25	1.57	267.9	0.9
2	9.7	27.88	1.47	262.7	0.7
3	10.2	28.95	1.47	267.9	0.8
4	10.8	27.17	1.32	267.3	0.7
96 kg/m^3 Loading Density, Stripper Harvested, 900 s Hold Time, Full Loading 3rd Compression					
1	9.8	28.23	1.46	272.7	0.6
2	9.7	27.16	1.45	268.0	0.6
3	10.2	27.55	1.47	273.1	0.6
4	10.8	26.77	1.29	272.6	0.6
96 kg/m^3 Loading Density, Stripper Harvested, 900 s Hold Time, Full Loading 4th Compression					
1	9.8	26.92	1.42	275.7	0.5
2	9.7	26.61	1.38	271.3	0.5
3	10.2	25.48	1.40	275.7	0.5
4	10.8	25.89	1.27	275.9	0.5
96 kg/m^3 Loading Density, Stripper Harvested, 900 s Hold Time, Full Loading 5th Compression					
1	9.8	25.35	1.31	277.3	0.4
2	9.7	24.79	1.31	272.7	0.4
3	10.2	25.88	1.38	278.7	0.5
4	10.8	24.93	1.23	278.0	0.5
128 kg/m^3 Loading Density, Stripper Harvested, 900 s Hold Time, Full Loading 1st Compression					
1	9.6	42.55	0.62	275.0	1.3
2	9.8	41.05	0.65	272.4	1.3
3	11.0	38.50	0.69	274.1	1.4
4	11.1	38.30	0.69	273.5	1.4
128 kg/m^3 Loading Density, Stripper Harvested, 900 s Hold Time, Full Loading 2nd Compression					
1	9.6	27.11	1.27	265.3	0.6
2	9.8	30.99	1.46	267.1	0.7
3	11.0	31.03	1.46	271.8	0.7
4	11.1	30.42	1.50	273.0	0.7

Table 27. Continued.

Replication	Moisture Content	K (kPa)	Standard Error	γ_{max} (kg/m^3)	Standard Error
128 kg/m^3 Loading Density, Stripper Harvested, 900 s Hold Time, Full Loading 3rd Compression					
1	9.6	25.61	1.23	269.6	0.5
2	9.8	29.67	1.37	272.1	0.5
3	11.0	28.64	1.40	276.2	0.6
4	11.1	27.15	1.32	277.1	0.5
128 kg/m^3 Loading Density, Stripper Harvested, 900 s Hold Time, Full Loading 4th Compression					
1	9.6	24.38	1.12	271.8	0.4
2	9.8	27.87	1.29	274.8	0.4
3	11.0	28.48	1.41	279.4	0.5
4	11.1	26.64	1.38	280.5	0.5
128 kg/m^3 Loading Density, Stripper Harvested, 900 s Hold Time, Full Loading 5th Compression					
1	9.6	23.79	1.13	274.1	0.4
2	9.8	28.02	1.30	276.9	0.4
3	11.0	26.27	1.26	280.7	0.4
4	11.1	26.99	1.40	282.9	0.4
96 kg/m^3 Loading Density, Picker Harvested, 15 s Hold Time, Full Loading 1st Compression					
1	9.3	20.52	0.49	307.3	0.8
2	9.2	21.22	0.51	301.2	0.8
3	10.8	19.79	0.49	306.1	0.7
4	10.3	19.57	0.49	301.8	0.7
96 kg/m^3 Loading Density, Picker Harvested, 15 s Hold Time, Full Loading 2nd Compression					
1	9.3	26.08	1.05	318.0	1.1
2	9.2	24.54	0.91	308.8	0.9
3	10.8	24.80	0.99	316.6	1.0
4	10.3	25.49	1.00	313.2	1.0
96 kg/m^3 Loading Density, Picker Harvested, 15 s Hold Time, Full Loading 3rd Compression					
1	9.3	23.65	0.96	320.5	0.8
2	9.2	24.23	0.93	312.9	0.8
3	10.8	23.85	0.99	320.5	0.8
4	10.3	24.80	1.00	317.0	0.9

Table 27. Continued.

Replication	Moisture Content	K (kPa)	Standard Error	γ_{max} (kg/m^3)	Standard Error
96 kg/m^3 Loading Density, Picker Harvested, 15 s Hold Time, Full Loading 4th Compression					
1	9.3	23.48	0.97	323.0	0.8
2	9.2	23.87	0.94	316.3	0.7
3	10.8	24.28	1.01	324.3	0.8
4	10.3	24.37	0.98	320.0	0.7
96 kg/m^3 Loading Density, Picker Harvested, 15 s Hold Time, Full Loading 5th Compression					
1	9.3	23.25	0.98	325.5	0.7
2	9.2	22.85	0.89	316.9	0.6
3	10.8	23.56	0.97	325.7	0.7
4	10.3	23.86	0.95	321.8	0.7
128 kg/m^3 Loading Density, Picker Harvested, 900 s Hold Time, Partial Loading 1st Compression					
1	8.8	24.63	0.73	299.3	1.3
2	10.0	22.01	0.71	304.3	1.1
3	7.8	22.92	0.74	303.5	1.2
128 kg/m^3 Loading Density, Picker Harvested, 900 s Hold Time, Partial Loading 2nd Compression					
1	8.8	25.38	0.61	302.9	0.8
2	10.0	23.24	0.58	308.0	0.7
3	7.8	22.51	0.58	304.4	0.7
128 kg/m^3 Loading Density, Picker Harvested, 900 s Hold Time, Partial Loading 3rd Compression					
1	8.8	26.23	0.89	310.0	0.7
2	10.0	25.63	0.97	317.6	0.7
3	7.8	23.81	0.90	312.9	0.6
128 kg/m^3 Loading Density, Picker Harvested, 900 s Hold Time, Partial Loading 4th Compression					
1	8.8	25.23	0.92	314.0	0.6
2	10.0	24.62	0.95	321.8	0.6
3	7.8	23.16	0.86	316.7	0.5
128 kg/m^3 Loading Density, Picker Harvested, 900 s Hold Time, Partial Loading 5th Compression					
1	8.8	24.38	0.90	316.6	0.5
2	10.0	24.17	0.90	324.0	0.5
3	7.8	23.16	0.92	320.3	0.5

Table 28. Parameter estimates for creep loading of each replication.

Replication	Moisture Content	E_2 (kPa)	Std. Err.	η_1 (MPa*s)	Std. Err.	η_2 (MPa*s)	Std. Err.
64 kg/m^3 Loading Density, Picker Harvested, 900 s Hold Time, Full Loading 1st Compression							
1	7.8	2803.6	4.8	7669.4	65.6	81.68	0.65
2	9.9	2817.6	5.0	6579.7	48.4	96.00	0.69
3	9.0	2769.6	4.4	6640.1	44.9	92.56	0.60
4	9.8	2917.3	6.3	5221.1	35.7	109.25	0.90
64 kg/m^3 Loading Density, Picker Harvested, 900 s Hold Time, Full Loading 2nd Compression							
1	7.8	5353.9	9.1	10821.7	68.2	114.77	1.10
2	9.9	4549.8	7.9	9485.6	62.2	126.42	1.04
3	9.0	4612.1	8.7	10285.4	77.0	164.23	1.23
4	9.8	4381.9	9.5	7705.8	52.8	139.89	1.31
64 kg/m^3 Loading Density, Picker Harvested, 900 s Hold Time, Full Loading 3rd Compression							
1	7.8	6364.1	11.4	13522.7	92.7	204.53	1.57
2	9.9	5917.9	11.4	12298.9	88.7	172.06	1.52
3	9.0	6390.6	12.2	12118.6	78.3	209.95	1.68
4	9.8	6217.8	11.3	12352.6	80.7	172.36	1.49
64 kg/m^3 Loading Density, Picker Harvested, 900 s Hold Time, Full Loading 4th Compression							
1	7.8	7181.5	12.2	17363.0	130.8	162.61	1.51
2	9.9	7600.7	12.2	18311.5	129.8	171.36	1.50
3	9.0	7076.2	12.8	16444.0	124.2	212.75	1.72
4	9.8	7883.2	14.8	14270.4	87.3	237.25	2.00
64 kg/m^3 Loading Density, Picker Harvested, 900 s Hold Time, Full Loading 5th Compression							
1	7.8	9145.8	15.7	21091.7	153.1	208.74	1.94
2	9.9	10102.5	20.8	17681.2	114.9	297.17	2.79
3	9.0	8095.2	13.9	18435.2	131.5	185.61	1.72
4	9.8	8448.3	14.5	18127.0	120.7	250.42	1.96
96 kg/m^3 Loading Density, Picker Harvested, 900 s Hold Time, Full Loading 1st Compression							
1	10.2	2470.6	5.2	5423.6	44.3	96.03	0.75
2	10.5	2510.7	4.7	6297.1	53.1	85.42	0.66
3	10.0	2638.9	3.9	5797.7	34.2	78.36	0.53
4	9.5	2226.5	3.1	6057.3	42.1	61.27	0.41
5	9.1	2796.7	5.8	8527.4	96.8	99.97	0.83
6	11.1	2637.5	5.1	5269.7	36.0	104.01	0.74
7	11.5	2455.9	3.4	5560.2	31.7	73.21	0.46
8	10.5	2256.8	3.7	5862.2	45.8	57.68	0.48

Table 28. Continued.

Replication	Moisture Content	E_2 (kPa)	Std. Err.	η_1 (MPa*s)	Std. Err.	η_2 (MPa*s)	Std. Err.
96 kg/m^3 Loading Density, Picker Harvested, 900 s Hold Time, Full Loading 2nd Compression							
1	10.2	4656.3	8.0	8888.7	53.2	117.87	1.02
2	10.5	4600.5	7.6	10388.7	70.6	113.62	0.96
3	10.0	4990.2	9.7	10162.6	72.0	162.12	1.34
4	9.5	4836.8	9.5	8516.4	53.1	137.04	1.25
5	9.1	5675.1	9.9	10695.8	63.7	155.79	1.30
6	11.1	4430.7	9.7	9321.9	77.1	151.62	1.36
7	11.5	4394.3	6.5	8426.3	43.9	102.04	0.81
8	10.5	4638.6	7.7	10241.4	67.6	141.13	1.04
96 kg/m^3 Loading Density, Picker Harvested, 900 s Hold Time, Full Loading 3rd Compression							
1	10.2	6804.5	12.6	11520.9	65.9	155.50	1.55
2	10.5	6937.8	11.1	12218.8	63.5	133.72	1.29
3	10.0	6683.0	11.6	11947.0	68.0	139.28	1.39
4	9.5	5820.7	9.4	11140.2	63.2	127.89	1.15
5	9.1	6821.7	10.4	14069.5	81.9	132.06	1.22
6	11.1	5804.8	11.1	11233.9	75.7	142.95	1.41
7	11.5	5769.2	9.4	12496.7	80.3	140.46	1.19
8	10.5	6403.0	10.7	12587.2	74.9	168.97	1.39
96 kg/m^3 Loading Density, Picker Harvested, 900 s Hold Time, Full Loading 4th Compression							
1	10.2	7181.0	10.6	13579.4	70.8	103.92	1.10
2	10.5	7440.4	11.4	13877.1	73.7	113.08	1.21
3	10.0	8091.5	11.4	15005.0	72.2	160.96	1.34
4	9.5	6868.5	9.7	12768.7	62.4	118.26	1.08
5	9.1	8884.1	14.2	18470.6	110.2	279.08	1.94
6	11.1	7274.5	9.4	14630.9	69.5	162.60	1.15
7	11.5	7647.4	12.2	12760.6	62.6	143.96	1.40
8	10.5	7226.2	10.5	13742.1	70.6	114.39	1.13
96 kg/m^3 Loading Density, Picker Harvested, 900 s Hold Time, Full Loading 5th Compression							
1	10.2	9621.9	18.0	15105.4	81.2	228.53	2.26
2	10.5	9377.6	14.7	18236.7	102.8	179.20	1.71
3	10.0	9421.7	15.3	16806.4	90.0	182.85	1.79
4	9.5	8101.4	13.2	14462.1	78.0	154.78	1.54
5	9.1	9168.6	13.2	23774.2	162.9	194.59	1.59
6	11.1	8227.2	12.3	15651.6	82.2	153.05	1.41
7	11.5	8286.1	15.5	17037.7	117.7	255.65	2.11
8	10.5	9899.3	16.6	16260.5	82.7	196.62	1.96

Table 28. Continued.

Replication	Moisture Content	E_2 (kPa)	Std. Err.	η_1 (MPa*s)	Std. Err.	η_2 (MPa*s)	Std. Err.
128 kg/m^3 Loading Density, Picker Harvested, 900 s Hold Time, Full Loading 1st Compression							
1	8.5	3061.4	5.1	8254.6	67.0	89.75	0.68
2	8.0	3123.3	5.8	6175.9	39.9	120.85	0.83
3	10.7	2494.1	5.1	4790.8	33.0	98.30	0.73
4	10.0	2910.9	5.6	7509.0	66.1	111.39	0.81
128 kg/m^3 Loading Density, Picker Harvested, 900 s Hold Time, Full Loading 2nd Compression							
1	8.5	5328.8	11.3	14402.6	146.7	199.26	1.62
2	8.0	5594.9	6.9	15522.6	96.5	130.59	0.85
3	10.7	4984.7	7.9	7494.6	32.3	137.20	1.04
4	10.0	5176.1	8.3	11873.1	79.0	150.16	1.11
128 kg/m^3 Loading Density, Picker Harvested, 900 s Hold Time, Full Loading 3rd Compression							
1	8.5	7094.2	14.6	16831.6	148.8	206.88	1.96
2	8.0	7255.4	9.9	22047.8	165.1	219.27	1.34
3	10.7	7124.8	9.4	19759.6	130.5	211.02	1.26
4	10.0	6798.3	11.1	20534.8	179.0	248.44	1.57
128 kg/m^3 Loading Density, Picker Harvested, 900 s Hold Time, Full Loading 4th Compression							
1	8.5	8510.3	14.7	21045.8	165.4	174.37	1.75
2	8.0	9754.4	17.5	25402.9	209.1	390.88	2.54
3	10.7	9096.8	16.5	16324.9	95.7	275.88	2.23
4	10.0	8674.8	16.9	17124.2	120.9	197.85	2.09
128 kg/m^3 Loading Density, Picker Harvested, 900 s Hold Time, Full Loading 5th Compression							
1	8.5	11765.9	19.1	26505.2	176.2	315.77	2.50
2	8.0	10068.5	13.1	26660.9	167.7	227.29	1.61
3	10.7	9408.9	11.9	22839.1	128.6	222.10	1.49
4	10.0	10226.9	13.7	21660.0	110.9	307.98	1.85
64 kg/m^3 Loading Density, Stripper Harvested, 900 s Hold Time, Full Loading 1st Compression							
1	10.1	2654.0	4.6	4940.0	28.9	85.42	0.64
2	9.9	2121.6	4.4	3996.9	28.1	70.40	0.61
3	11.6	2142.6	3.9	4167.4	26.5	75.69	0.55
4	10.4	2623.7	5.2	5122.4	35.1	100.23	0.74

Table 28. Continued.

Replication	Moisture Content	E_2 (kPa)	Std. Err.	η_1 (MPa*s)	Std. Err.	η_2 (MPa*s)	Std. Err.
64 kg/m^3 Loading Density, Stripper Harvested, 900 s Hold Time, Full Loading 2nd Compression							
1	10.1	4897.7	9.5	9713.3	66.2	182.20	1.35
2	9.9	4136.1	9.7	7326.8	54.1	147.86	1.37
3	11.6	4307.1	6.9	8149.8	44.3	126.55	0.92
4	10.4	4699.2	7.7	7860.9	38.3	161.18	1.07
64 kg/m^3 Loading Density, Stripper Harvested, 900 s Hold Time, Full Loading 3rd Compression							
1	10.1	6830.1	13.5	13416.1	91.9	258.48	1.93
2	9.9	6164.2	14.6	8707.5	52.6	175.30	1.93
3	11.6	6264.3	11.2	13662.9	93.8	263.07	1.65
4	10.4	6466.0	11.7	10073.2	51.1	197.16	1.58
64 kg/m^3 Loading Density, Stripper Harvested, 900 s Hold Time, Full Loading 4th Compression							
1	10.1	9268.8	16.3	16126.5	90.5	212.74	2.02
2	9.9	6054.5	10.1	15247.4	116.8	142.59	1.26
3	11.6	9562.2	19.7	14497.7	81.7	279.22	2.64
4	10.4	8589.2	15.4	16732.8	103.7	309.46	2.18
64 kg/m^3 Loading Density, Stripper Harvested, 900 s Hold Time, Full Loading 5th Compression							
1	10.1	10917.9	23.2	16345.5	92.1	418.15	3.34
2	9.9	9335.1	18.7	15669.4	95.9	229.88	2.37
3	11.6	10046.9	22.5	14949.6	86.9	443.82	3.33
4	10.4	11195.4	20.6	17190.2	88.4	276.42	2.61
96 kg/m^3 Loading Density, Stripper Harvested, 900 s Hold Time, Full Loading 1st Compression							
1	9.8	2475.3	4.8	5029.6	34.8	96.80	0.69
2	9.7	2776.1	5.9	5239.4	37.4	107.49	0.86
3	10.2	2462.0	4.2	5579.6	38.1	86.79	0.59
4	10.8	2402.7	4.0	5916.1	43.6	77.64	0.55
96 kg/m^3 Loading Density, Stripper Harvested, 900 s Hold Time, Full Loading 2nd Compression							
1	9.8	5865.4	10.9	8962.1	45.2	223.67	1.57
2	9.7	5072.5	9.0	9299.4	54.3	164.03	1.24
3	10.2	5123.8	9.9	8525.7	49.3	150.39	1.32
4	10.8	5137.9	8.6	9114.3	49.1	137.16	1.12

Table 28. Continued.

Replication	Moisture Content	E_2 (kPa)	Std. Err.	η_1 (MPa*s)	Std. Err.	η_2 (MPa*s)	Std. Err.
96 kg/m^3 Loading Density, Stripper Harvested, 900 s Hold Time, Full Loading 3rd Compression							
1	9.8	8146.5	15.6	12662.6	66.8	294.55	2.20
2	9.7	7768.0	14.4	12573.5	68.1	224.90	1.92
3	10.2	7369.6	14.0	11295.0	59.0	233.98	1.92
4	10.8	7057.3	11.2	13005.4	69.5	182.05	1.45
96 kg/m^3 Loading Density, Stripper Harvested, 900 s Hold Time, Full Loading 4th Compression							
1	9.8	9070.2	18.3	18111.5	127.9	370.54	2.66
2	9.7	9806.6	18.4	23185.7	183.2	336.16	2.57
3	10.2	7905.9	12.6	15630.0	89.5	204.32	1.62
4	10.8	8637.1	13.2	18417.7	108.4	262.25	1.79
96 kg/m^3 Loading Density, Stripper Harvested, 900 s Hold Time, Full Loading 5th Compression							
1	9.8	10295.8	20.3	16898.9	100.5	226.71	2.48
2	9.7	11316.4	21.5	22411.8	152.4	327.81	2.87
3	10.2	9531.0	22.6	18380.5	147.2	404.94	3.31
4	10.8	9333.4	23.0	15782.7	117.5	318.32	3.21
128 kg/m^3 Loading Density, Stripper Harvested, 900 s Hold Time, Full Loading 1st Compression							
1	9.6	2815.7	5.6	5526.5	38.2	116.07	0.82
2	9.8	2624.1	5.1	4738.8	29.2	115.00	0.76
3	11.0	2411.3	4.8	6293.0	57.7	98.62	0.70
4	11.1	2237.0	4.1	5214.6	39.4	83.04	0.58
128 kg/m^3 Loading Density, Stripper Harvested, 900 s Hold Time, Full Loading 2nd Compression							
1	9.6	5696.9	10.6	14738.9	124.4	232.97	1.54
2	9.8	6005.9	10.7	7437.8	29.5	188.02	1.46
3	11.0	5166.3	11.8	11636.6	107.7	163.65	1.62
4	11.1	5377.9	9.4	8651.1	43.9	162.76	1.27
128 kg/m^3 Loading Density, Stripper Harvested, 900 s Hold Time, Full Loading 3rd Compression							
1	9.6	7789.1	15.2	19673.7	166.5	398.59	2.29
2	9.8	8337.4	22.5	11898.9	82.4	261.17	3.07
3	11.0	7552.8	13.4	15750.3	102.7	296.17	1.93
4	11.1	7125.9	11.2	11948.2	57.9	154.56	1.36

Table 28. Continued.

Replication	Moisture Content	E_2 (kPa)	Std. Err.	η_1 (MPa*s)	Std. Err.	η_2 (MPa*s)	Std. Err.
128 kg/m^3 Loading Density, Stripper Harvested, 900 s Hold Time, Full Loading 4th Compression							
1	9.6	8897.9	22.1	17732.6	159.0	241.86	2.89
2	9.8	11231.1	18.0	23311.8	142.7	234.00	2.16
3	11.0	9975.0	22.3	16778.8	112.4	348.26	3.13
4	11.1	9637.4	12.3	18064.1	78.4	253.85	1.59
128 kg/m^3 Loading Density, Stripper Harvested, 900 s Hold Time, Full Loading 5th Compression							
1	9.6	11829.9	15.9	22532.3	107.1	197.09	1.75
2	9.8	11369.3	19.0	30130.5	231.7	520.06	2.82
3	11.0	10016.4	13.3	21107.6	109.1	188.59	1.53
4	11.1	10009.5	17.0	25804.3	201.4	346.57	2.39
128 kg/m^3 Loading Density, Picker Harvested, 900 s Hold Time, Partial Loading 1st Compression							
1	8.8	2854.7	5.7	6347.2	49.9	107.67	0.81
2	10.0	2782.8	5.6	6289.9	51.2	98.77	0.79
3	7.8	2924.5	6.6	5684.9	44.6	105.72	0.94
128 kg/m^3 Loading Density, Picker Harvested, 900 s Hold Time, Partial Loading 2nd Compression							
1	8.8	3684.5	6.5	10232.3	90.1	116.16	0.89
2	10.0	3650.3	6.1	8212.3	55.1	132.91	0.87
3	7.8	3474.2	6.1	9773.1	87.4	101.26	0.82
128 kg/m^3 Loading Density, Picker Harvested, 900 s Hold Time, Partial Loading 3rd Compression							
1	8.8	6027.8	9.8	12426.0	75.5	167.64	1.29
2	10.0	6512.7	9.2	10938.3	47.1	168.63	1.18
3	7.8	6362.0	13.4	9892.8	59.0	165.37	1.73
128 kg/m^3 Loading Density, Picker Harvested, 900 s Hold Time, Partial Loading 4th Compression							
1	8.8	8890.9	13.9	14621.8	68.9	189.60	1.67
2	10.0	7829.4	11.8	26196.0	238.0	224.26	1.56
3	7.8	6989.4	9.7	16117.2	95.7	134.02	1.13
128 kg/m^3 Loading Density, Picker Harvested, 900 s Hold Time, Partial Loading 5th Compression							
1	8.8	8970.2	13.7	20000.0	122.8	276.53	1.87
2	10.0	9739.6	16.0	28718.6	254.1	249.12	2.06
3	7.8	9906.5	22.6	18646.1	141.0	401.23	3.29

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