RESHAPING AND RECOMPRESSING ROUND BIOMASS BALES

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ABSTRACT. Recompressing bales to achieve greater density can reduce biomass storage and transportation costs, but research on recompressing round biomass bales is limited. Bi-axial compression in the radial direction of wheat straw, corn stover, switchgrass, and reed canarygrass was used to reshape round bales into a rectangular cross-section. The process was conducted as a three-stage progression: vertical reshaping to cuboid shape, followed by vertical and then horizontal densification. Density increased by 13% to 23% during vertical densification, and the pressure-density relationship was modeled as a linear function. Linear, power, and exponential models were fit to the pressure-density data collected during horizontal compression, during which density increased by an additional 68% to 83%. The linear and power functions best modeled the horizontal compression data. Although the power model underpredicted the initial density, it closely predicted the final bale density, so this model would have greater utility for future design applications. The target density of 240 kg DM m$^{-3}$ was achieved at the end of compression with all four crops. Corn stover had significantly greater final density than the other three crops and achieved the target density with less applied pressure. Bales were restrained with polyester strapping prior to removal from the chamber. Bale density decreased 19% to 30% due to re-expansion after pressure was released. Although the forces applied were great, the specific energy requirements were low because compression took place over a relatively long time (~30 s). Differences in specific energy between crops were not statistically significant. Reshaping and recompressing large round bales could be an alternative to high-density large square baling to achieve weight-limited transport of baled biomass.

Keywords. Bales, Biomass, Compression, Density.

To minimize transport costs of biomass feedstocks, legal weight limits of the transport vehicle must be achieved (Searcy and Hess, 2010; Miao et al., 2013). Bale density and cross-section (i.e., round vs. square) are crucial to realizing this goal. The large square bale has been the preferred biomass package due to its greater density and more transport-efficient cross-section. To achieve most U.S. road-legal weight limits, square bale density should be at least 240 kg m$^{-3}$ (Miao et al., 2013). However, this goal is difficult to attain when mature biomass crops are baled with conventional large square balers. Large square bale densities between 145 and 200 kg m$^{-3}$ have been reported for switchgrass, straw, and corn stover (Cudiff and Marsh, 1996; Kemmerer and Liu, 2010; Shinners et al., 2007, 2010; Afzalnia et al., 2012). Baler modifications that have been made to produce greater bale density include longer bale chambers, greater chamber convergence, and larger flywheels and drivelines. Although greater bale densities may result from these modifications, bale cost increases substantially. Greater bale density can reduce biomass transport costs (Larasati et al., 2012). However, the bale density-power function is nonlinear, so greater density requires not only a more expensive baler but also a much larger and more expensive tractor, so estimated total delivered cost actually increased with greater bale density (So-khansanj et al., 2014).

Packaging biomass in round bales is another harvest and logistics option. Compared to large square balers, round balers are lower cost, require less power and smaller tractors, and can have comparable productivity. However, biomass round bales typically have lower density than large square bales. Large round bale densities between 120 and 180 kg m$^{-3}$ have been reported for switchgrass and corn stover (Shinners et al., 2007, 2010). Additionally, the round cross-section of the bales results in unoccupied volume on the transport vehicle, reducing total load weight potential.

An alternative biomass logistics system has been proposed that uses low-cost round baling for initial harvest and packaging and then uses a reshaping and recompression process to improve bale density and cross-section. This process could take place on the baler (Olander, 2014) or be a post-baling process (http://www.roundbalepress.com/). The combination of high density (i.e., >240 kg m$^{-3}$) and better utilization of the transport volume by the rectangular shape should help reduce transport costs of round bales.

Our objective was to quantify and model the pressure-density relationships for reshaping and recompressing round biomass bales to a rectangular cross-section. To achieve this goal, we developed and instrumented a recompression test fixture; recompressed round bales of switchgrass, reed canarygrass, wheat straw, and corn stover; modeled the pressure-density relationships; and quantified the energy requirements.
MATERIALS AND METHODS

A test fixture was designed and fabricated to compress round bales that were nominally 122 cm diameter and 61 cm wide (details below). Although the width of the bales was uncommon, the results are scalable to any bale width. The first iteration of the test fixture used uni-axial compression in which the round bales were compressed solely by the vertical displacement of a single horizontal platen (Lacy, 2016). The results were considered unacceptable because the compressed bales had non-uniform density and shape. Two-stage, bi-axial compression in the radial direction was then used to reshape and recompress bales (fig. 1). The horizontal platen first compressed the bale vertically to a $79 \times 137$ cm ($H \times W$) cross-section (compression ratio of 1.08:1 if original bale diameter was 122 cm), and then the two vertical platens compressed the bale horizontally from both sides, typically to a width of 79 cm. The horizontal and vertical platens were actuated with hydraulic cylinders capable of producing a maximum pressure applied to the bale surface of 240 and 620 kPa, respectively. The system relief valve setting sometimes limited the compressed width that could actually be achieved during horizontal compression. The speed of compression was 45 and 20 mm s$^{-1}$ in the vertical and horizontal directions, respectively.

Pressure transducers were used to measure the pressure in the horizontal and vertical platen cylinders (PX305-3KGI and PX305-7.5KGI, respectively, Omega Engineering, Stamford, Conn.). Displacement of the horizontal and vertical platens was measured with displacement transducers (models 6000 and 3000, respectively, Honeywell, Columbus, Ohio). The sensor outputs were collected at 100 Hz using a USB DAQ (model 6216, National Instruments, Austin, Tex.) in conjunction with LabVIEW software. The raw signals were then post-processed to engineering units using appropriate calibration equations. Instantaneous bale volume was calculated from initial bale volume, chamber dimensions, and displacement of the platens.

Dry corn stover, reed canarygrass, switchgrass, and wheat straw were baled at the University of Wisconsin Arlington Agricultural Research Station using a round baler (model RB455, Case IH, Racine, Wisc.). Moisture content ranged from 10% to 19% (table 1). Three layers of mesh net wrap were used to restrain the bales. The baler pre-cutter was not used, so the material was not size-reduced prior to compression. The bales were stored under cover prior to use. To fit into the width of the test fixture, the bales were cut to a nominal width of 61 cm using a 3.6 m bar chain saw (Orrick, 2015). Nine bales each of wheat straw and switchgrass and seven bales each of corn stover and reed canarygrass were recompressed in the test fixture.

Prior to being put into the test fixture, the bales were weighed on a digital platform scale (model 6002, Scale-Tro-nix Mfg., White Plains, N.Y.) to the nearest 0.5 kg. Bale diameter was measured by hand with a tape measure to the nearest 2 cm in four locations (horizontal, vertical, and both diagonal diameters) and an average diameter was calculated.

After compression but prior to release of pressure, the bales were restrained using $0.9 \times 16$ mm polyester strapping with a tensile strength of 6230 N (part number S-3250, U-Line, Pleasant Prairie, Wisc.). Three vertical and three horizontal straps were used. Straps were tensioned with a ratcheting tensioner, and the strap ends were connected with serrated steel clamps. The bales were held under pressure for about 15 min during strapping because strapping was done

![Figure 1. (left) Bi-axial compression test fixture showing (center) vertical reshaping and compression and (right) horizontal compression to rectangular cross-section.](image)

**Table 1.** Average moisture, compression ratio, and dry basis bale density during vertical compression. Average linear model coefficients based on regression analysis of pressure-density data from individual bales.

<table>
<thead>
<tr>
<th>Material</th>
<th>Number of Bales</th>
<th>Moisture Content (% w.b.)</th>
<th>Compression Ratio$^{[a]}$</th>
<th>Density$^{[b]}$ (kg m$^{-3}$)</th>
<th>Linear Model$^{[c]}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wheat straw</td>
<td>9</td>
<td>9.9 c</td>
<td>1.14 b</td>
<td>109 a 124 b</td>
<td>0.99 b 52.6 a</td>
</tr>
<tr>
<td>Corn stover</td>
<td>7</td>
<td>18.7 a</td>
<td>1.23 a</td>
<td>122 a 150 a</td>
<td>1.20 b 52.7 a</td>
</tr>
<tr>
<td>Switchgrass</td>
<td>9</td>
<td>10.5 c</td>
<td>1.20 ab</td>
<td>111 a 134 b</td>
<td>1.15 b 43.9 ab</td>
</tr>
<tr>
<td>Reed canarygrass</td>
<td>7</td>
<td>12.8 b</td>
<td>1.13 b</td>
<td>120 a 135 ab</td>
<td>1.83 a 7.0 b</td>
</tr>
<tr>
<td>LSD$^{[d]}$ (p = 0.05)</td>
<td>-</td>
<td>1.7</td>
<td>0.08</td>
<td>15 15</td>
<td>0.62 43.5</td>
</tr>
</tbody>
</table>

$^{[a]}$ Ratio of initial to final bale volume during vertical compression.
$^{[b]}$ Dry basis density determined when densification started (Start) and at the end of vertical platen displacement (End). Densification started when reshaped bale volume was less than initial uncompressed bale volume.
$^{[c]}$ Average linear model coefficients (eq. 3) determined by regression of the data from individual bales.
$^{[d]}$ Least square difference. Means in the same column followed by different letters are significantly different at 95% confidence.
by hand. It is expected that automated strapping would greatly reduce this dwell time.

After removal from the fixture, two 300 g samples were collected from each bale using a 4 cm diameter boring tool. These samples were then oven-dried in a forced-air oven for 24 h at 103°C in accordance with ASABE Standard S358.3 (ASABE, 2012). Dimensions of the re-expanded bale were taken within 5 min of release of pressure.

**MODEL ANALYSIS**

Round bale recompression was conducted as a three-stage process: vertical reshaping, vertical densification, and horizontal densification (fig. 2). Initial compression reshaped the bale from a round to a cuboid cross-section. The applied pressure actually decreased as the platen descended because of the increasing contact chord length. The transition from reshaping to densification occurred when the instantaneous chamber volume became smaller than the initial bale volume. Vertical displacement was limited to achieve a 79 cm tall bale. The obtainable vertical compression ratio was nominally 1.08:1 (122 cm round to 79 × 137 cm rectangular cross-section); however, actual compression ratios varied based on the initial bale diameter.

Compressing loose plant material in a closed container is considered a two-phase process. Consolidation by void reduction dominates the first stage, so nominal increases in applied pressure create relatively large changes in density. The second phase involves stem crushing and particle rearrangement, so pressure create relatively large changes in density. The second phase involves stem crushing and particle rearrangement, so nominal increases in applied pressure actually decreased as the platen descended because of the increasing contact chord length. The transition from reshaping to densification occurred when the instantaneous chamber volume became smaller than the initial bale volume. Vertical displacement was limited to achieve a 79 cm tall bale. The obtainable vertical compression ratio was nominally 1.08:1 (122 cm round to 79 × 137 cm rectangular cross-section); however, actual compression ratios varied based on the initial bale diameter.

Compressing loose plant material in a closed container is considered a two-phase process. Consolidation by void reduction dominates the first stage, so nominal increases in applied pressure create relatively large changes in density. The second phase involves stem crushing and particle rearrangement, so only nominal increases in density result from large increases in applied pressure (O’Dogherty, 1989). Upon release of pressure, the material rebounds elastically (Mohsenin, 1970), so it is typically restrained with twine or straps. Holding the material under load allows some stress relaxation, resulting in less rebound (Faborode and O’Callaghan, 1989).

The relationship between pressure and density is generally considered exponential, with density leveling off as the process transitions from consolidation to crushing. A simple power function was suggested by O’Dogherty and Wheeler (1984) to model this process:

$$\rho = k \cdot P^n$$

where $\rho$ (kg m$^{-3}$) is the instantaneous bale density, $P$ is the applied pressure (kPa), and $k$ and $n$ are model coefficients.

An exponential model was suggested by Faborode and O’Callaghan (1989) that expressed pressure during compression in terms of the initial density, compression ratio ($\rho/\rho_o$), incompressibility, and porosity:

$$P = \left( \rho_o \frac{A}{B} e^{\left( \frac{B}{\rho_o} \left( \frac{\rho}{\rho_o} - 1 \right) - 1 \right)} \right)$$

where $P$ is the pressure (kPa), $\rho_o$ is the initial density (kg m$^{-3}$), $\rho$ is the instantaneous density (kg m$^{-3}$), $A$ is the incompressibility, and $B$ is the porosity index.

Researchers have applied these models to wheat straw, corn stover, switchgrass, and timothy (Van Pelt, 2003; Hofstetter and Liu, 2011; Tabeli et al., 2011). In these tests, the material occupied the full cross-section of the compression chamber, and no reshaping to fill the fixture cross-section was required.

In this research, the vertical displacement of the horizontal platen was limited to create the desired final bale height of 79 cm. Therefore, most of the platen stroke involved bale reshaping, so densification occurred only near the end of the vertical stroke. Not all bales had the same initial diameter, so the fraction of the total stroke used for reshaping or densification varied. Both linear and power models were considered to describe the pressure-density relationship, but there was almost no difference in the model fit, so a linear model was used:

$$\rho = m \cdot P_v + I$$

where $\rho$ is the instantaneous bale density (kg m$^{-3}$), $P_v$ is the pressure (kPa) in the vertical direction, $m$ is the rate of densification, and $I$ is the intercept.

During horizontal compression, the pressure increased rapidly as densification occurred. Three pressure-density models were considered for this stage:

$$\rho = m \cdot P_h + I$$

$$\rho = k \cdot P_h^n$$

$$P_h = \left( \rho_o \frac{A}{B} e^{\left( \frac{B}{\rho_o} \left( \frac{\rho}{\rho_o} - 1 \right) - 1 \right)} \right) + P_o$$

where $\rho$ is the instantaneous bale density (kg m$^{-3}$), $P_h$ is the pressure (kPa) applied to the bale surface during horizontal compression, and $k$, $n$, $m$, $I$, $A$, and $B$ are model coefficients. The term $P_o$ (kPa) was added to the Faborode and O’Callaghan (1989) model (eq. 6) to account for the initial pressure from the bale pushing against the horizontal platens due to the initial vertical compression.

Microsoft Excel with the Solver data analysis package was used to iteratively solve for all the model coefficients. Initial estimates of the coefficients were made by using those
reported for similar material when compressing square bales (Hofstetter and Liu, 2011). These coefficients were used in the models to estimate either pressure or density, as appropriate. Solver was then used to iteratively minimize the sum of squares of the differences between the actual and model data, and an R^2 value was then calculated. Model coefficients were calculated for each bale, and average coefficients were determined for each crop. An analysis of variance was conducted using Excel to compare the coefficients between different materials.

The model coefficients for the linear and power models (eqs. 4 and 5) were then used to predict bale density by linear interpolation through the range of pressures actually applied to the bale surface during either vertical or horizontal compression. The interpolated values at each pressure were averaged across all bales, the averages and 95% confidence range were plotted, and the new model coefficients were determined.

RESULTS

Round bales are formed by continuously rolling material around the bale core so that the bale is made up of many circumferential layers. During the first stage of compression, these layers were observed to flatten to a rectangular cross-section (fig. 3). When horizontal compression occurred, the layers tended to shear and fold along the bale diagonals where the shear stress was greatest, forming a distinct pattern in the bale (fig. 3).

Figure 3. Concentric rings flattened during vertical reshaping and compression (top). During horizontal compression, the material tended to shear and fold along the bale diagonals where the shear stress was greatest (bottom).
Vertical displacement of the horizontal platen first reshaped the bale and then compressed the bale once the initial bale volume became equal to the instantaneous chamber volume. The pressure-density model for the reshaping stage resulted in a horizontal line (fig. 2) that was equal to the uncompressed bale density. The linear model (eq. 3) was applied to the densification portion of the vertical compression cycle for each bale (table 1). Corn stover had the greatest initial density and compression ratio, so its density at the end of vertical compression was greater than that of the other crops. The differences between coefficients were not statistically significant for wheat straw, corn stover, or switchgrass.

The model coefficients were then used to predict the bale density through the range of pressures applied to the bale during vertical compression (table 2). The linearly interpolated values at each pressure were averaged across the bales, and the averages and 95% confidence range were plotted for each crop. The linear model underpredicted initial density and overpredicted bale density at the end of vertical compression. The overprediction of final density might suggest a better fit with a power model; however, this model was no better at predicting final bale density because the model exponent was very close to one (data not presented).

The linear, power, and exponential models (eqs. 4 through 6) were applied to the horizontal compression pressure-density data. All three models fit the data well, with $R^2$ values typically greater than 90% (figs. 4 and 5). However, the $B$ exponent in the exponential model was negative for three crops (table 3), predicting the illogical result that substantial density increases beyond those achieved here would require only nominally greater pressure. Therefore, the exponential model was not considered further.

The slope ($m$) and exponent ($n$) for the linear and power models, respectively, describe the rate of increase of the pressure-density function. Only corn stover had statistically different average model coefficients based on regression of the individual bale data (table 3). Stover bales had the greatest density at the start of horizontal compression because they had the greatest density before reshaping and the largest

### Table 2. Linear model coefficients based on interpolated data from vertical compression.

<table>
<thead>
<tr>
<th>Material</th>
<th>Pressure Range (kPa)</th>
<th>Linear Model (eq. 3)</th>
<th>Density at Start (kg m$^{-3}$)</th>
<th>Density at End (kg m$^{-3}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Start</td>
<td>End</td>
<td>Slope</td>
<td>Intercept</td>
</tr>
<tr>
<td>Wheat straw</td>
<td>49</td>
<td>88</td>
<td>1.26</td>
<td>37.9</td>
</tr>
<tr>
<td>Corn stover</td>
<td>55</td>
<td>107</td>
<td>0.94</td>
<td>73.3</td>
</tr>
<tr>
<td>Switchgrass</td>
<td>54</td>
<td>93</td>
<td>1.36</td>
<td>29.3</td>
</tr>
<tr>
<td>Reed canarygrass</td>
<td>60</td>
<td>89</td>
<td>1.99</td>
<td>-13.3</td>
</tr>
</tbody>
</table>

[a] Average pressure applied to the bale surface when densification started (Start) and at the end of vertical platen displacement (End).
[b] Dry basis density determined when densification started (Start) and at the end of vertical platen displacement (End). Densification started when reshaped bale volume was less than initial uncompressed bale volume.
[c] Measured dry basis density averaged across all bales.
[d] Average dry basis density predicted for each bale based on applied pressure and linear model coefficients.

### Table 3. Average model coefficients for the linear, power, and exponential models based on regression analysis of pressure-density data from individual bales during horizontal compression.

<table>
<thead>
<tr>
<th>Material</th>
<th>Pressure (kPa)</th>
<th>Linear (eq. 4)</th>
<th>Power (eq. 5)</th>
<th>Exponential (eq. 6)</th>
<th>Dry Density (kg m$^{-3}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Initial</td>
<td>Final</td>
<td>$m$</td>
<td>$l$</td>
<td>$k$</td>
</tr>
<tr>
<td>Wheat straw</td>
<td>40</td>
<td>530</td>
<td>0.245</td>
<td>115 ab</td>
<td>39.0 ab</td>
</tr>
<tr>
<td>Corn stover</td>
<td>90</td>
<td>560</td>
<td>0.312 a</td>
<td>118 ab</td>
<td>22.7 ab</td>
</tr>
<tr>
<td>Switchgrass</td>
<td>120</td>
<td>580</td>
<td>0.244 b</td>
<td>100 b</td>
<td>22.1 b</td>
</tr>
<tr>
<td>Reed canarygrass</td>
<td>60</td>
<td>610</td>
<td>0.270 b</td>
<td>122 a</td>
<td>44.8 a</td>
</tr>
</tbody>
</table>

[a] Average pressure applied to the bale surface at beginning (Initial) and end (Final) of compression in the horizontal direction.
[b] Measured dry basis density of bale at beginning (Initial) and end (Final) of compression in the horizontal direction.
[c] Least square difference. Means in the same column followed by different letters are significantly different at 95% confidence.

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Figure 4. Applied pressure during horizontal compression versus dry basis density for a single corn stover bale using the linear model (eq. 4, $R^2 = 0.998$) and power model (eq. 5, $R^2 = 0.986$).

Figure 5. Dry basis bale density versus pressure applied to bale during horizontal compression for a single corn stover bale using the linear model (eq. 4, $R^2 = 0.909$) and exponential model (eq. 6, $R^2 = 0.981$).
The linear and power model coefficients were then used to predict the bale density through the range of pressures applied to the bale during horizontal compression (table 4; figs. 6 and 7). Corn stover had the greatest slope (linear model) and exponent (power model). The linear model predicted the initial density better than the power model, while the opposite occurred for final bale density. The power model underpredicted initial density because most of the consolidation occurred during vertical compression. The linear model overpredicted final density because the process was just starting to become asymptotic near the maximum pressure applied. From a design standpoint, predicting the pressure needed to achieve maximum density is more important than the initial pressure, so the power model has more utility than the linear model.

Compared to corn stover, wheat straw and switchgrass required greater pressure to reach a given density (tables 3 and 4). This is contrary to the results reported by Hofstetter and Liu (2011). Bale behavior during compression would be affected by physical properties such as friction coefficient, stiffness (modulus of elasticity), and bending strength. Materials with greater friction coefficients would have more resistance to particles sliding over one another, necessitating greater compression force. Stiffer materials are more difficult to compress and require more pressure to reach the same density. Stems with greater bending strength would be harder to reshape in the compression chamber. Although information is limited on the physical properties of common biomass crops, a review of these properties (table 5) indicates that switchgrass would be the most difficult to compress, followed by wheat straw and corn stover.

The length of stems in the bale could also have an influence on pressure-density relationships when recompressing round bales. The switchgrass and wheat straw bales were formed by progressively layering long stems into the round bale.
bale chamber. Corn stover bales had shorter particles because they were formed with material that had been size-reduced with a flail shredder prior to baling. When compressed horizontally, the material was observed to shear and fold along the diagonals of the bale where the shear stress was greatest. Long material might have been more difficult to fold in this region than short material, contributing to greater pressure requirements to achieve a given density.

The pressure required to achieve density up to 340 kg m⁻³ was estimated using the power model coefficients found in this research for round bales (table 4) and using coefficients for the exponential model (eq. 2) found when compressing small square bales at similar compression speeds (Hofstetter and Liu, 2011). The pressure estimates for corn stover were nearly identical and were similar for switchgrass (fig. 8). Compression pressures were estimated to be greater for wheat straw round bales than for small square bales.

The compression speeds were 45 and 20 mm s⁻¹ during vertical and horizontal compressions, respectively, so compression took approximately 10 and 20 s, respectively. The magnitude of the total power and specific energy requirement for round bale compression (table 6) was similar to that reported by Hofstetter and Lui (2011) for recompressing square bales at similar compression speeds. The power requirement was relatively low because densification occurred over a relatively long time, especially compared to the rapid compression done by the reciprocating plunger in a large square baler (typically less than 0.5 s). Energy requirements for baling switchgrass with a large square baler were 35 to 70 kJ kg⁻¹ (Liu and Kemmerer, 2011). This is one potential advantage of the densification system studied here; although the required forces are large, they can be exerted over a longer time, reducing the total power required. For instance, if recompression occurred at the baler, as suggested by Olander (2014), the process could take place over 30 to 60 s while the next bale is formed. Power requirements would increase proportionally as the time for recompression is reduced.

Bales were strapped with three polyester straps each in the vertical and horizontal directions and were held under pressure for about 15 min during strapping. Dimensions of the re-expanded bale were taken within 5 min after release of pressure. After strapping and retracting the platens, each bale re-expanded in both the vertical and horizontal directions. The average compressed and expanded density and the average percentage of directional expansion for each crop were determined (table 7). Wheat straw tended to expand the most, while the expansion was similar for the other three crops. Based on the reported modulus of elasticity (table 5), switchgrass might have been expected to experience more expansion. The switchgrass stems were very brittle. If these stems failed during compression, less elastic expansion might be expected. It is recognized that it was not possible to strap all the bales to the same pre-tension, which could have affected the amount of re-expansion. The bales tended to re-expand non-uniformly, taking the shape of a square with the sides slightly bulged at the centers.

### CONCLUSIONS

Bi-axial compression of bales of wheat straw, corn stover, switchgrass, and reed canarygrass was used to reshape round bales into a rectangular cross-section. The process was conducted as a three-stage progression: vertical reshaping to cuboid shape, followed by vertical and then finally horizontal densification. Density increased by 13% to 23% during vertical densification and increased by an additional 68% to 83% during horizontal compression. Although the target density of 240 kg DM m⁻³ was achieved in the compression

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**Table 6. Power and specific energy required for vertical and horizontal compression based on numerical integration of force-displacement data.**

<table>
<thead>
<tr>
<th>Material</th>
<th>Power (kW) Vertical[a]</th>
<th>Power (kW) Horizontal[a]</th>
<th>Total (kW)</th>
<th>Specific Energy (kJ kg⁻¹) Vertical[a]</th>
<th>Specific Energy (kJ kg⁻¹) Horizontal[a]</th>
<th>Total (kJ kg⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wheat straw</td>
<td>1.54 a</td>
<td>3.29 a</td>
<td>4.83 a</td>
<td>0.176 a</td>
<td>0.713 a</td>
<td>0.889 a</td>
</tr>
<tr>
<td>Corn stover</td>
<td>1.59 a</td>
<td>3.52 ab</td>
<td>5.11 ab</td>
<td>0.162 a</td>
<td>0.632 a</td>
<td>0.794 a</td>
</tr>
<tr>
<td>Switchgrass</td>
<td>1.55 a</td>
<td>4.88 a</td>
<td>6.43 b</td>
<td>0.169 a</td>
<td>0.802 a</td>
<td>0.971 a</td>
</tr>
<tr>
<td>Reed canarygrass</td>
<td>1.54 a</td>
<td>4.38 ab</td>
<td>5.91 ab</td>
<td>0.129 b</td>
<td>0.681 a</td>
<td>0.810 a</td>
</tr>
<tr>
<td>LSD³ (p = 0.05)</td>
<td>0.09</td>
<td>1.68</td>
<td>1.69</td>
<td>0.025</td>
<td>0.212</td>
<td>0.227</td>
</tr>
</tbody>
</table>

[a] Power or specific energy to compress bales in vertical or horizontal directions.

[b] Least square difference. Means in the same column followed by different letters are significantly different at 95% confidence.

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**Table 7. Expansion of the recompressed bales after restraint by three straps each in the vertical and horizontal directions and release of platen pressure.**

<table>
<thead>
<tr>
<th>Material</th>
<th>Density (kg m⁻³) Compressed</th>
<th>Density (kg m⁻³) Expanded</th>
<th>Dimensional Expansion (%) Vertical</th>
<th>Dimensional Expansion (%) Horizontal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wheat straw</td>
<td>233 b</td>
<td>163 c</td>
<td>16 a</td>
<td>19 a</td>
</tr>
<tr>
<td>Corn stover</td>
<td>278 a</td>
<td>219 a</td>
<td>12 b</td>
<td>18 a</td>
</tr>
<tr>
<td>Switchgrass</td>
<td>225 b</td>
<td>183 bc</td>
<td>13 ab</td>
<td>10 b</td>
</tr>
<tr>
<td>Reed canarygrass</td>
<td>250 b</td>
<td>200 ab</td>
<td>10 b</td>
<td>10 b</td>
</tr>
<tr>
<td>LSD³ (p = 0.05)</td>
<td>27</td>
<td>26</td>
<td>3</td>
<td>4</td>
</tr>
</tbody>
</table>
chamber, density of the strapped bales decreased 19% to 30% due to re-expansion after pressure was released. To achieve the target density, greater in-chamber density and improved restraint systems are likely needed. The model best predicted the final pressure-density relationship, so for design purposes it should be used to predict the pressures needed to achieve maximum density. Reshaping and recompressing large round bales could be an alternative to high-density large square baling to achieve weight-limited transport of baled biomass.

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