Summary Report:

Compression Modulus of Hemp Fiber Construction Bales

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Submitted to:

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1.0 Executive Summary:

- Since at least the late 1800's, conventional wheat, barley or oat straw bales have been used extensively in North America, and globally, to construct low rise building walls. Due in significant part to their limited compression modulus and related load bearing capacity, conventional straw bales are mostly used as non-load bearing building elements and the structural load is carried by timber or steel post and beam structural frames. The conventional straw bales are generally limited to providing thermal and acoustic insulation.

- Based on a cursory review of the conventional straw bale state of the art, it appears the straw bale construction industry would benefit from the commercial availability of renewable, insulating, construction bales with substantially higher compression modulus and bearing capacity.

- Canadian Greenfield Technologies Corp. (CGT) manufactures a line of 14" x 18" x 36" construction bales produced from high quality, industrial hemp bast fiber (not straw) using their innovative, proprietary bale manufacturing process. CGT engaged Diacem Technologies Inc. (Diacem) to conduct an evaluation of the compression modulus and bearing capacity of the hemp fiber bales, relative to the straw bale market convention (i.e.: control.)

- Structural engineers and building designers design structures to safely carry structural loads with serviceable deflection of the structural elements, such as load bearing walls. The modulus of elasticity in compression (i.e.: compression modulus) is a fundamental material mechanical property and describes the relationship between the material compressive stress and strain. That is, the load carrying capacity versus the deflection of the material under compression. The compression modulus is a critical engineering input to the design of safe and serviceable structural elements in compression, such as load bearing construction bales.

- Based on the scope of work undertaken, the conventional straw bales are comprised of relatively large diameter, hollow tube-like discrete elements bundled together in the bale structure. Due to their hollow nature, the discrete elements in the bale are highly compressible, resulting in a relatively soft, ductile, sponge-like construction bale with relatively low compression modulus and bearing capacity.

- By comparison, hemp fiber bales are comprised of smaller diameter, high aspect ratio, high tensile strength bast fibers that are highly intertwined in the bale structure. Due to their highly intertwined, fibrous structure, hemp fiber bales are substantially less compressible than straw bales, resulting in substantially higher compression modulus and bearing capacity. Additionally, CGT's unique, proprietary hemp bale production process appears to facilitate the development of high compression modulus during bale manufacturing.

- After compression of the straw and hemp fiber bales to ≈ 0.20 compressive strain, ≈ 60 +/- 5% of the strain (≈ 0.12) was fully elastically recoverable within 5 minutes of bale unloading. The remainder of the residual strain appears to be semi-elastic and recoverable with additional time, with perhaps some plastic, permanent deformation.

- Up to a compressive strain of 0.20, on average, the control straw bales possessed a compression modulus of approximately 113 kPa, when compressed with a flat bale orientation (i.e.: compression along the short cross section axis). This value is within the range of published compression modulus values for straw bales.

- Up to a compressive strain of 0.20, on average, the hemp fiber bales possessed a flat bale compression modulus of approximately 400 kPa. That is, the hemp fiber bales typically possess 3.5 times higher compression modulus than the straw bale market convention. The hemp fiber bales exhibited as much as 4.1 times higher compression modulus as the straw bale control during testing.

- Both the straw and hemp fiber bales exhibited anisotropic compression modulus properties. Significantly higher compression modulus and bearing capacity was generally observed when the bales are loaded flat, as opposed to on edge.

- Under equivalent compressive strain, the flat hemp fiber bales possess 3.5 to 4.1 times higher bearing capacity than the straw bale convention. The commercial availability of CGT's hemp fiber construction bales represents a substantial advancement in the load bearing capacity of natural fiber construction bales, previously unavailable to the straw bale building construction industry.

2.0 Introduction:

Canadian Greenfield Technologies Corp. (CGT) is a leading manufacturer of industrial hemp processing equipment and products derived from industrial hemp. CGT manufactures 14" x 18" x 36" compressed bales of industrial hemp bast fiber for use in construction applications. CGT engaged Diacem Technologies Inc. (Diacem) to provide materials testing and analytical technical services to evaluate the compression modulus of CGT's hemp fiber bales, relative to the market convention, which is typically wheat, barley or oat straw bales. Diacem has 23 years of construction materials engineering experience.

One of the common construction applications for agricultural straw bales is building walls. The compression modulus relates the compressive stress carried by the bale (i.e.: load bearing capacity) to its elastic or semi-elastic deformation under load. The compression modulus is an important material mechanical property required by designers utilizing bales in load bearing wall construction. Relative to materials with lower compression modulus, materials with higher compression modulus are stiffer and will have higher load bearing capacity under equivalent deformation (i.e.: compressive strain.)

3.0 Scope of Work:

The scope of Diacem's engagement encompassed materials testing and evaluation of the compression modulus of CGT's hemp fiber bales, relative to the straw bale market convention (i.e.: control) and a basic, cursory review of the state of the art related to agricultural straw bales in building walls.

CGT manufactured the 14" x 18" x 36" hemp fiber bales used in this work at their Calgary, Alberta facility. The conventional barley straw bales of similar size were sourced from an Alberta based supplier. Both types of bales have two twine ties.

4.0 Preliminary State of the Art Review:

4.1 Compression Modulus in General:

When subject to an external load such as tension or compression, materials experience stress and strain. ***Stress*** (6) is defined as follows:

$$\sigma = \frac{F}{A}$$

Where F = normal force applied to the material, A = cross sectional area of the material perpendicular to the direction of the load.

Normal ***strain*** (ε) is defined as the relative change in the material dimension in the direction of the applied load as follows:

$$\varepsilon = \frac{\Delta l}{l_0}.$$

Where: Δl = change (deflection) in dimension under load, l_0 = original un-deflected dimension. Strain is dimensionless.

Each material has its own unique relationship between stress and strain. Most materials behave elastically under conditions of relatively low stress and strain. That is, the material returns to its original dimensions when the load is removed. Such materials obey Hooke's law and the amount of elastic strain a material undergoes is proportional to a constant called the ***modulus of elasticity*** or ***Young's modulus*** **(E).** The modulus of elasticity describes the stiffness or ductility of a material, within its elastic limits. The modulus of elasticity is a fundamental material mechanical property defined as follows:

$$\frac{\sigma}{\varepsilon} = E$$

When the elastic deformation limits of a material are exceeded, plastic strain occurs and the material is permanently deformed to some degree. Figure 1 below illustrates the mechanical principles of elastic modulus, elastic and plastic strain and strength for a generic material under tension [1]:

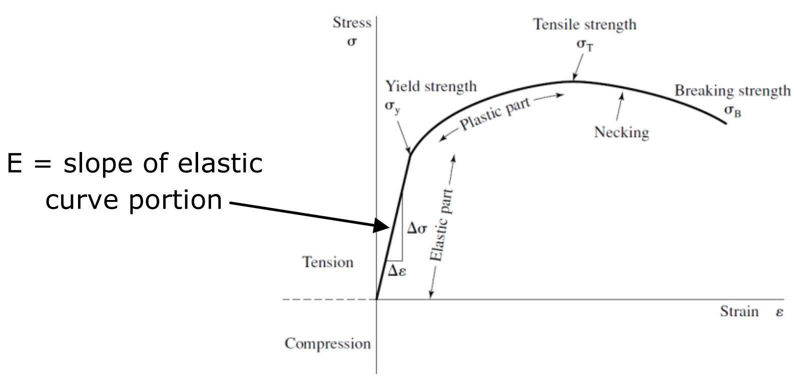


Figure 1: Generic Tension Stress Strain Curve (reprinted from Hummel)

For some materials, particularly metals such as steel, the modulus of elasticity in tension and compression are very similar. However, other materials, particularly highly ductile materials such as rubber and synthetic elastomers, exhibit very different stress-strain relationships under tension or compression as seen below [2], [3]:

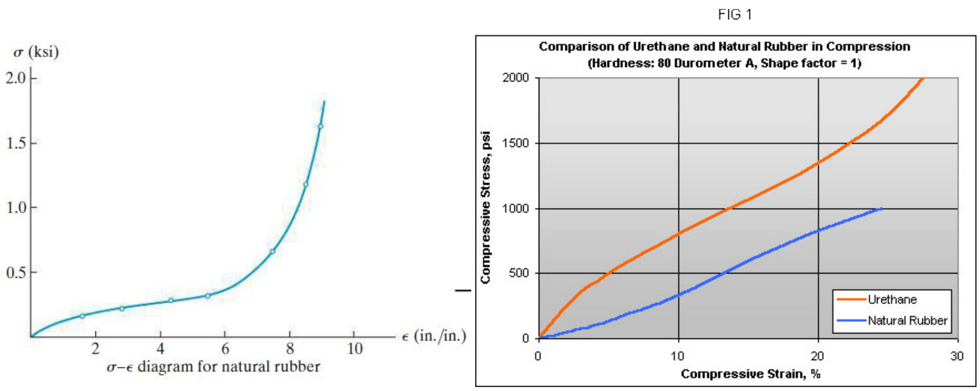


Figure 2: Soft, Ductile Natural Rubber Stress-Strain Under Tension (Left) (reprinted from Hibbeler). Natural Rubber and Polyurethane Stress-Strain Under Compression (Right).

In general, very soft, ductile materials, such as hemp and straw bales, do not exhibit a well defined yield point under compression. For the purpose of this report, the ***compression modulus of elasticity (or compression modulus)*** describes a linear stress-strain relationship over a strain range encompassing elastic, semi-elastic (recoverable with time) and some limited degree of plastic deformation of the bale under compression. As discussed later in this report, the elastic strain is recovered immediately upon unloading the bale. Semi-elastic strain recovery is time dependent and is partially recovered to varying degrees over time, after unloading.

4.2 Compression Modulus of Conventional Straw Bales:

There are several studies that have measured the compression modulus of straw bales. Ashour et. al, measured stress-strain relationships for German straw bales compressed horizontally (i.e.: laid flat) and vertically (i.e.: laid on edge) as seen below [4]:

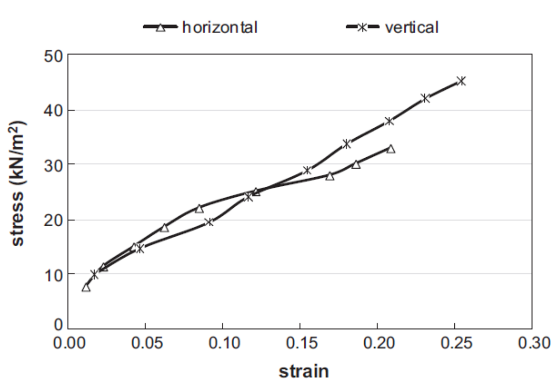


Figure 3: Compressive Stress Strain Relationship of Straw Bales Used for Wall Construction in Germany (reprinted from Ashour et. al.)

As seen above, at a compressive strain of 0.20 the compressive bearing stress borne by the horizontally oriented bale reached approximately 30 kPa. It can be inferred from this data the compression modulus from 0 to 0.20 strain was approximately 150 kPa. The straw bales tested had an average bulk density of 102.6 kg/m^3.

Konecny et. al., measured the compressive stress-strain relationship of wheat straw bales from the Czech Republic. The researchers determined the modulus of elasticity of most of the wheat straw bales to ranged from 109 to 188 kPa [5]. The researchers recommend that load bearing straw bales have a bulk density of at least 90 to 120 kg/m^3.

Watts et. al., measured the compression modulus of elasticity of Canadian oat, barley and wheat straw bales oriented flatly in the range of 83 to 237 kPa [6].

Based on the state of the art referenced in the literature, the typical range of the conventional straw bale compression modulus appears to be approximately 80 to 240 kPa.

Please note: it is common practice in straw bale wall construction to "plaster" the outside faces of the bales with wire mesh reinforced stucco, Portland cement based mortar, cement-lime mortar, earthen clay mortar, etc. In doing so, the bales are sandwiched between relatively rigid (higher compression modulus) layers approximately 12 to 38 mm thick. According to Vardy and MacDougall, the modulus of elasticity of flat plastered straw bale sections with plaster thickness of 12.7 mm was measured at 12.43 MPa on average, which is two orders of magnitude higher than the bale alone [7]. These values are referenced in the technical literature and do not represent the compression modulus of the straw bales on their own.

4.2 Agricultural Straw Bales in Building Wall Construction:

There is a substantial pool of knowledge related to straw building wall construction and the information below is a cursory introduction.

According to Elsayed, there are three types of straw bale wall construction [8]:

- **Structural Bale:** so called "Nebraska style" straw bale construction, named after the State where the first straw bale homes were constructed in North America in the late 1800's. The straw bales carry structural compressive load from the roof structure and lateral wind load. The bales are stacked and mechanically pinned to each other and the foundation. A wooden roof plate is anchored to the top of the bales and the roof structure is attached to the roof plate.

- **Light-Weight Frame:** uses a timber framework that cannot stand on its own. The straw bales provide structural bracing of the timber frame and shares the roof and lateral load with the frame.

- **Post and Beam or In-Fill Method:** a load bearing, self-supporting timber or steel post and beam structure is constructed and straw bales fill the wall cavity. The straw bales are non-structural and are used primarily for their insulating value. According to King, in-fill construction accounts for the largest segment of the straw bale wall construction applications in order to satisfy building permit authorities, lenders and insurers [9]. This appears to be due in large part to the limited bearing capacity and stiffness of conventional straw bales.

In most cases, the bale wall faces are covered with wire mesh reinforced plaster in order to protect the bales from the elements, improve the fire resistance of the wall structure and to carry some of the structural load to some degree (vertical and lateral loads). The most common plaster systems are based on clay (mud), gypsum, lime, Portland cement and shotcrete. According to King, once plastered, the wall system acts as a composite sandwich of more rigid plaster "skins" on a more flexible straw bale core. Due to the differences in modulus of elasticity between the skin and core, the skin "picks up" significant structural load [9]. The bales act to structurally support and brace the relatively thin plaster skin. Additionally, cracking of the plaster skin is common. Once the relatively thin skin has cracked or deformed, the bales must bear a more substantial portion of the applied load.

Straw bale walls are generally expected to settle and vertically deform under load to some degree. According to United Kingdom designers, a 7 bale high wall with good quality straw bales can be expected to vertically deform by 1.2 to 5 cm (0.5 to 2 inches), depending on the density of the bale and the roof dead load [10]. Assuming a 14" high bale, each bale would normally undergo a compressive strain of 0.005 to 0.02. Higher deformations are expected with other imposed vertical loads such as snow load.

In order to have suitable mechanical properties, insulation value and durability, Cascone et. al. recommend the following straw bale properties [11]:

- **Minimum Dry Bulk Density:** 110 to 150 kg/m^3.
- **Thermal Conductivity:** 0.055 to 0.065 W/m.K.
- **Maximum Moisture Content:** 20% by mass.

In general, it appears that the straw bale building industry would benefit from the availability of high quality, higher compression modulus bales, which would provide more effective load bearing capacity than conventional straw bales.

5.0 Determination of Bale Compression Modulus:

5.1 Methodology:

The following methodology was used to measure bale compression modulus during the course of this work:

- The bales were lightly compressed under a 25 kg plate and the physical dimensions of the bales were measured using a tape measure. An average width (W), height (H) and length (L) for each bale was calculated. The hemp fiber and control barley straw bales have nominal undeformed dimensions of 18" (W) x 14" (H) x 36" (L.) The hemp fiber bales have two polypropylene twine ties. The control barley straw bales have two, natural fiber baling twine ties.

- Each bale was weighed and the bulk density of the bale was calculated using the measured bale volume.

- A Baldwin universal testing machine with 60,000 lbs (267 kN) capacity was used to apply compression load to the bale bearing faces at a controlled rate. The machine cross head travel speed was set to ≈ 0.05 mm/sec.

- The bales were placed between the machine loading platform and a rigid lumber bearing platen that distributes the compressive load over most of the bearing face of the bale. The bearing platen measured 20" x 30 " and weighs 25 kg. The compressive stress is applied to 83% of the total bale bearing surface area.

- The bales were compressed to a strain of approximately 0.20. 9 to 12 measurements of the compressive load and bale deflection were taken over the course of the test. The load measurement has a precision of 5 N (1.1 lbs.) The deflection measurement has a precision of 0.01 mm (0.0004".)

- The duration of the test ranged from approximately 25 to 40 minutes per bale depending on the time required to reach sufficient bale deflection to achieve a compressive strain of 0.20 under a constant loading rate.

- The nominal compressive stress was calculated by dividing the measured load by the original, undeformed bale cross sectional bearing area. In actuality, lateral expansion of the bales under compression increases the cross sectional bearing area over the course of the test. The actual applied stress is marginally lower than the nominal compressive stress due to lateral bale expansion.

- At the end of the test, the bale is unloaded and allowed to rest in the machine for 5 minutes to allow for any elastic strain recovery. The bearing platen is then reset and its final position is measured relative to its original reference position before the bale was loaded. The difference in position represents the amount of unrecovered bale strain (i.e.: semi-elastic and/or plastic deformation.)

Figure 4: Control Straw Tube Structure- left. Long Intertwined Hemp Fiber Structure- right

Figure 5: Hemp Fiber Bale Loaded in the Universal Testing Machine

5.2 Bale Physical Properties Summary:

The individual bale dimensions and mass were measured and the bulk density was calculated as summarized below:

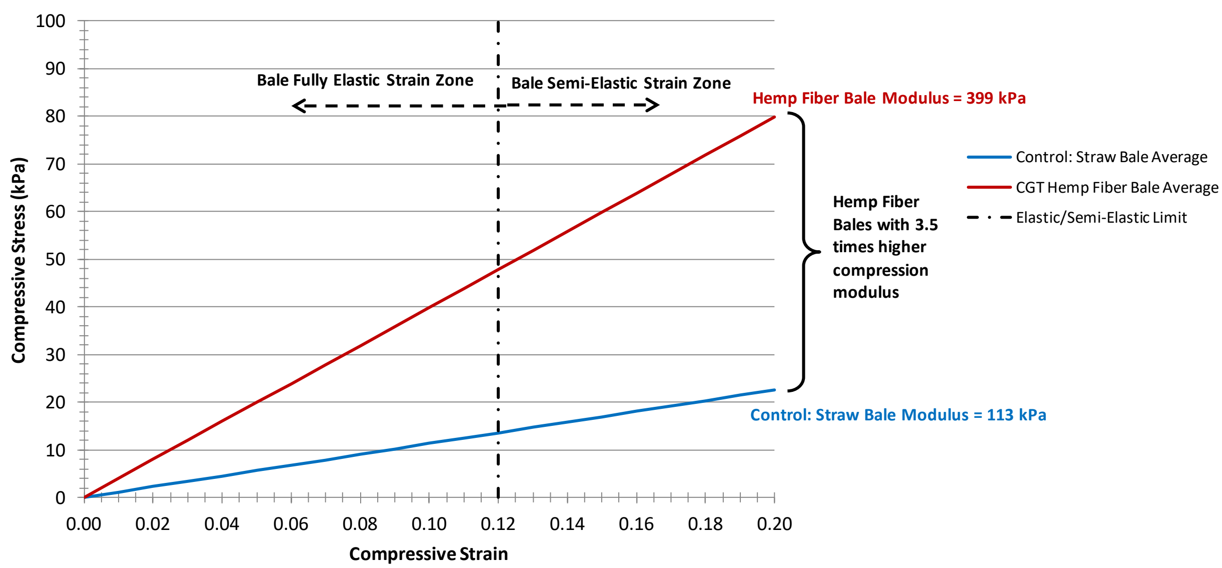
Table 1: Average Dimensions, Mass and Bulk Density of Control Straw and Hemp Fiber Bales										
	Control: Barley Straw Bales					CGT Hemp Fiber Bales				
Test #	W (mm)	H (mm)	L (mm)	Mass (kg)	Bulk Density (kg/m^3)	W (mm)	H (mm)	L (mm)	Mass (kg)	Bulk Density (kg/m^3)
Average:	484	372	914	16.4	100.8	473	361	914	23.9	152.5

The hemp fiber bales were 50% more dense than the control straw bales.

5.3 Summary of Typical Bale Compression Modulus and Stress-Strain Behaviour:

The compression stress-strain relationship of the bales was generally non-linear, but can with be fit with a linear trend line that correlates very well with the data over the compressive strain range tested. The graph below summarizes the typical compression modulus of the hemp fiber bales relative to the straw bale control. The fully elastic and semi-elastic strain zones are also shown:

GRAPH 1: Typical Compressive Stress-Strain Characteristics of Conventional Straw Bales and Hemp Fiber Bales



6.0 Findings and Conclusions:

1. Conventional straw bales are comprised of relatively large diameter, hollow tube-like discrete elements bundled together in the bale structure. Due to their hollow nature, the discrete elements in the bale are highly compressible, resulting in a relatively soft and ductile construction bale with relatively low compression modulus and bearing capacity.

2. Hemp fiber bales are comprised of smaller diameter, high aspect ratio, flexible, high tensile strength bast fibers that are highly intertwined in the bale structure. Due to their highly intertwined, fibrous structure, hemp fiber bales are substantially less compressible than straw bales, resulting in substantially higher compression modulus and bearing capacity. Additionally, CGT's unique, proprietary hemp bale production process appears to facilitate the development of high compression modulus during bale manufacturing.

3. Barley straw control bales had a compressed bulk density of approximately 100 kg/m^3. The hemp fiber bales had significantly higher compressed bulk density of approximately 150 kg/m^3.

4. After compression of the straw and hemp fiber bales to 0.20 compressive strain, 60 +/- 5% of the compressive strain (≈ 0.12) was fully elastically recoverable within 5 minutes of bale unloading. The remainder of the residual strain appears to be semi-elastic and recoverable with additional time, with perhaps some plastic, permanent deformation.

5. Up to a compressive strain of 0.20, on average, the control straw bales possessed a compression modulus of approximately 113 kPa, when compressed with a flat bale orientation (i.e.: compression along the short cross section axis). The maximum control flat straw bale compression modulus measured was 126 kPa. These values are within the range of published compression modulus values for straw bales.

6. Up to a compressive strain of 0.20, on average, the hemp fiber bales possessed a flat bale compression modulus of approximately 400 kPa. The maximum hemp fiber flat bale compression modulus measured was 516 kPa.

7. Under equivalent compressive strain, the flat hemp fiber bales possess 3.5 times higher bearing capacity than the control straw bales on average. The flat hemp fiber bales possessed up to 4.1 times (maximum) higher bearing capacity than the control straw bales, under equivalent compressive strain.

8. The highest compression load borne by a single hemp fiber bale reached 32,000 N or 7,200 lbs under the test conditions. The bale did not rupture under this load.

9. Both the straw and hemp fiber bales exhibited anisotropic compression modulus properties. When compressed on edge (i.e.: compression along the long cross sectional axis), both types of bales exhibited significantly reduced compression modulus relative to flat compression (i.e.: along the short cross sectional axis.)

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8.0 Limitations & Closure:

This report is based on review of the documents, materials test results and Diacem's general knowledge and experience in materials engineering. It has been prepared for the exclusive use of Canadian Greenfield Technologies Corp. Any use which a third party makes of this report, or any reliance on, or decisions made based on it, are the responsibility of such third parties. Diacem accepts no responsibility for damages, if any, suffered by any third party as a result of decisions made or actions based on this report. It has been prepared in accordance with generally accepted engineering practices. No other warranty, expressed or implied, is made.