STRAW BALES FOR BUILDINGS: MECHANICAL BEHAVIOUR UNDER COMPRESSION

M. Maraldi[1], G. Molari[1], L. Molari[2]*, N. Regazzi[1]

[1] Alma Mater Studiorum Università di Bologna, DISTAL, Bologna, Italy
[2] Alma Mater Studiorum Università di Bologna, DICAM, Bologna, Italy

*Corresponding author; e-mail: luisa.molari@unibo.it

Abstract

The use of straw bales in construction is becoming increasingly widespread in the last years. Straw bale building offers advantages over the use of conventional materials in terms of sustainability, hygro-thermal insulation properties and ensures good mechanical properties. In this paper, a discussion on the behavior of single unrendered straw bales under compressive load is carried out. Starting from the data obtained from an extensive experimental campaign conducted on bales of several materials, a simple interpretation of the deformation of the bales under compression has been proposed.

Keywords:

Straw bale construction; compressive test.

1 INTRODUCTION

The use of straw bales in construction has seen a growing interest in the last decades. Straw bales have excellent insulation capabilities and good breathability combined with good mechanical properties. Moreover, straw is an agricultural by-product, and represents a low-cost and environmental-friendly option, thus (Chaussinanda, 2015; Gupta, 2015; Bainbridge, 2005; Desborough & Samant, 2009; King, 2006).

The increasing use of straw bales as a building material requires a deep understanding of their mechanical performance. In this paper, the behavior of a straw bale under compressive loads is studied starting from the data collected through an extensive test campaign conducted on bales of several materials and different densities. Since the bales are posed both flat and on edge in building walls, the tests were performed in both the configurations.

2 EXPERIMENTAL SETUP

The tested bales were made of 8 different materials: millet, wheat, hard wheat, rice, oat, barley, corn and sorghum. All these straw materials were cultivated locally in the area of Bologna, Italy. Bales have been packed with two Polypropylene twine strings. All the bales were baled using a commercial Gallignani 146 Special baler supplied by a local farmer.

The test setup and the methodology used in the tests are described in details in the paper by Maraldi et al. (2016). In particular, a hydraulic press (MTS 243.35T single ended hydraulic actuator, MTS Systems Corp., U.S.A.) has been used for the compressive tests. Force has been measured through a sandwich load cell (Instron Corp., U.S.A. 250 kN dynamic capacity, 500 kN static capacity) and bales vertical displacement has been measured through the actuator’s linear displacement transducer (LVDT). The longitudinal displacement of the bales has been recorded using digital image correlation (DIC), whereas the transverse displacement has been monitored with a 3D triangulation laser scanner (Vivid 900 laser scanner, Konica Minolta, Inc., Japan).

Bales have been tested both flat and on edge for all the different materials: three bales were tested in each case as reported in Table 1.

Table 1 . Overall tests performed.

material	flat	On edge
wheat	3	3
hard wheat	3	3
rice	3	3
oat	3	3
barley	3	3
corn	3	3
sorghum	3	3
millet	3	3

The dimensions of all the bales tested are reported in the Table A1 and A2 in the Appendix. It can be observed that even if the dimension of the baling chamber is fixed, there is a non-negligible difference in width and height from one bale to another. In particular, the width and the height vary of about the 10% of their mean value, whereas the length (where the baling chamber is not constrained) varies more than the 20% of the mean value.

In Table 2 are reported the mean value of the density for material. The millet and rice have a higher density in respect to the other straws. Wheat and hard wheat present the lower density.

Table 2. Mean value of the densities of the materials.

Material	**Mean value of density [kg/m^3]**
millet	146
rice	120
corn	103
oat	101
barley	98
sorghum	96
wheat	90
h. whaet	87

3 FORCE-DISPLACEMENT DIAGRAMS

The force-displacement diagrams are reported for the bales laid flat and on edge in Figure 1 and 2, respectively.

All the tested bales exhibit a non-linear stiffening behavior as described in several papers (Bou-Ali 1993), (Krick 2008), (Maraldi et al. 2016).

We can analyse the behaviour considering each material separately as reported in Figure 3.

In particular, for flat bales there is a first part of loading in which the force-displacement curve is approximately linear; after this first stage, the behaviour is non-linear and bales stiffness progressively increases. For on-edge bales, there is an initial linear stage qualitatively similar to that of flat bales, while at the beginning of the non linear stage string burst generally occurs.

In Figure 3, the graphs are reported following the order of Table 2 (considering the decreasing mean value of density). The experimental results show that the initial slopes of the force displacement diagrams are influenced by the density of the material. In particular it is evident the trend that the slope is decreasing with lower density.

In this trend the rice seems to have the best performance showing the highest stiffness, while the millet perform less well than expected.

Oat is the weakest material and behaves worse than expected.

All the other straws show the relation between initial slope and density.

In the following Sections, an explanation of strings failure on the basis of bale deformation process is provided.

4 DEFORMATION IN THE LONGITUDINAL AND TRANSVERSE DIRECTION

Images from DIC analysis are reported in Figures 3 and 4. Markers have been placed on one face of the tested bale and their movements have been tracked using VIC-3D 2012 software (Correlated Solutions, Inc., SC, USA). All the bales are tested with strings bindings on the same side of the picture.

From the analysis of the position of the markers, it is possible to assess that flat bales and on-edge bales exhibit different deformation patterns, but all flat bales deform in the same way and all on-edge bales deform at the same way regardless of the material, their density and the loading rate. This means that the deformation pattern is mainly influenced by the baling process only.

The characteristic pattern for a bale loaded flat is shown in Figure 3. It can be observed that as load increases, the vertical lines connecting the markers tend to bend in one direction everywhere except for the right hand side. The characteristic deformation pattern of on-edge bales is shown in Figure 4, instead. It can be observed that lines tend to bend mostly in the same direction.

For monitoring bales transverse deformation, the shape of the bale during the compressive test has been acquired with the laser scanner (one acquisition every 10 mm of vertical displacement of the bale). The Polygon Editing Tool software (Konica Minolta, Inc., Japan) has been used to process the images. Results show that during the compressive tests there is no transverse deformation of the bales, both for flat and on-edge orientation (Maraldi et al., 2016).

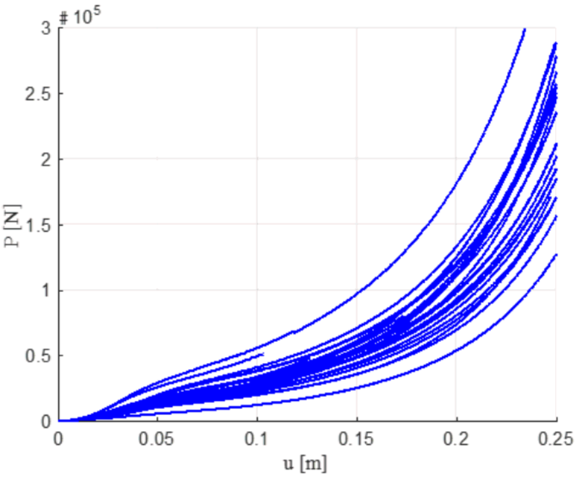


Figure 1. Force-displacement diagram for all the flat bales.

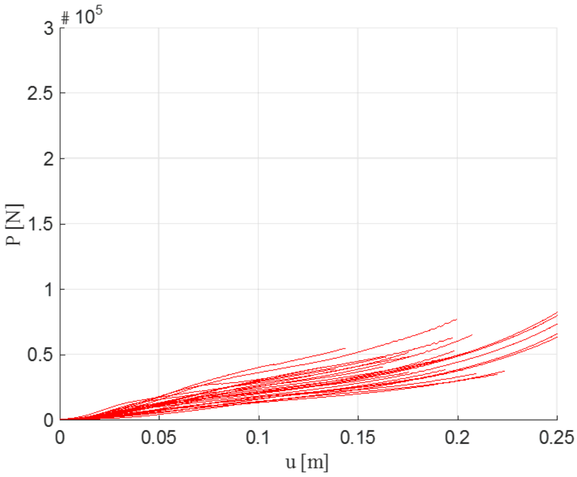


Figure 2. Force-displacement diagram for all the on-edge bales.

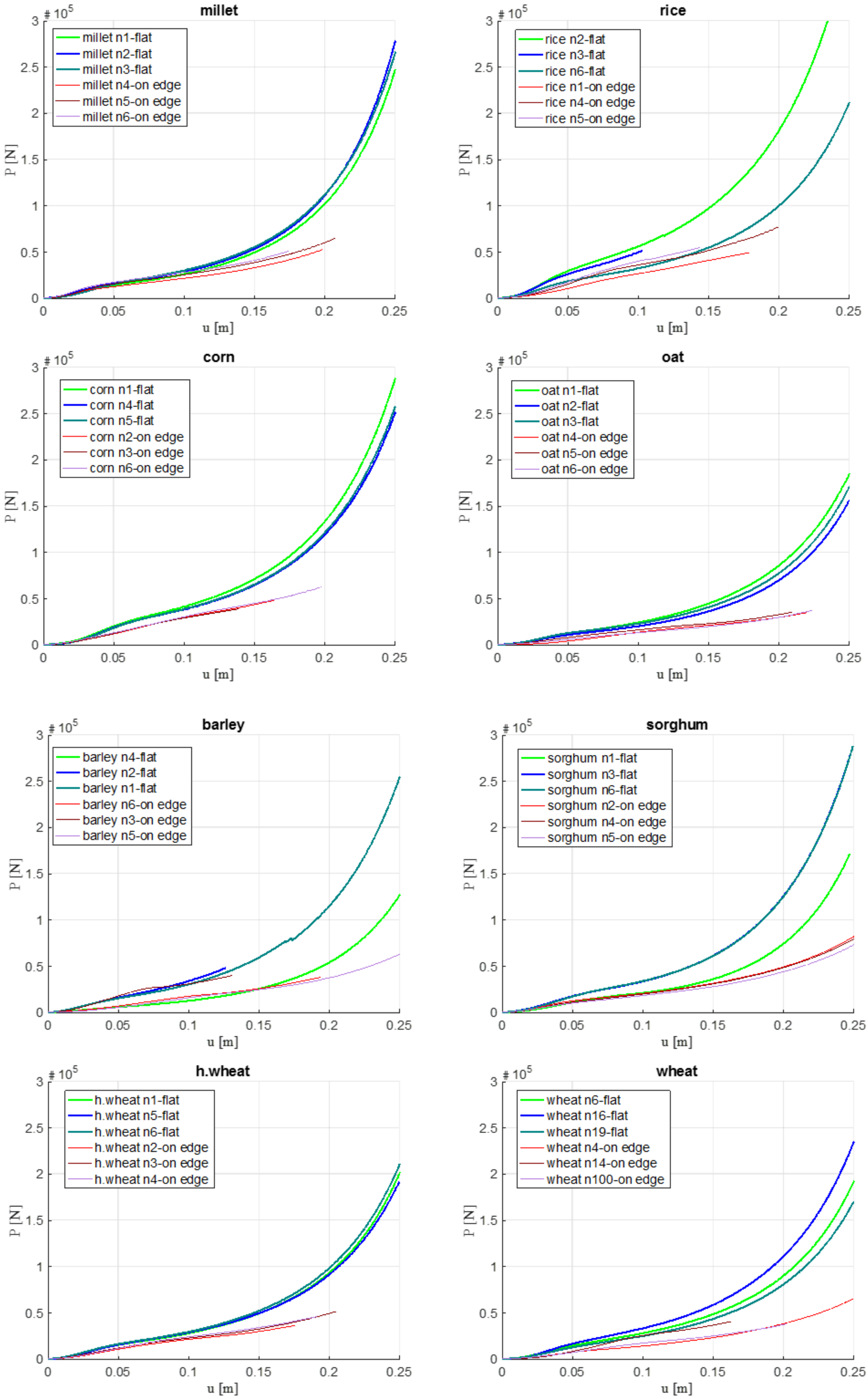


Figure 3. Force-displacement diagram for all the material considered.

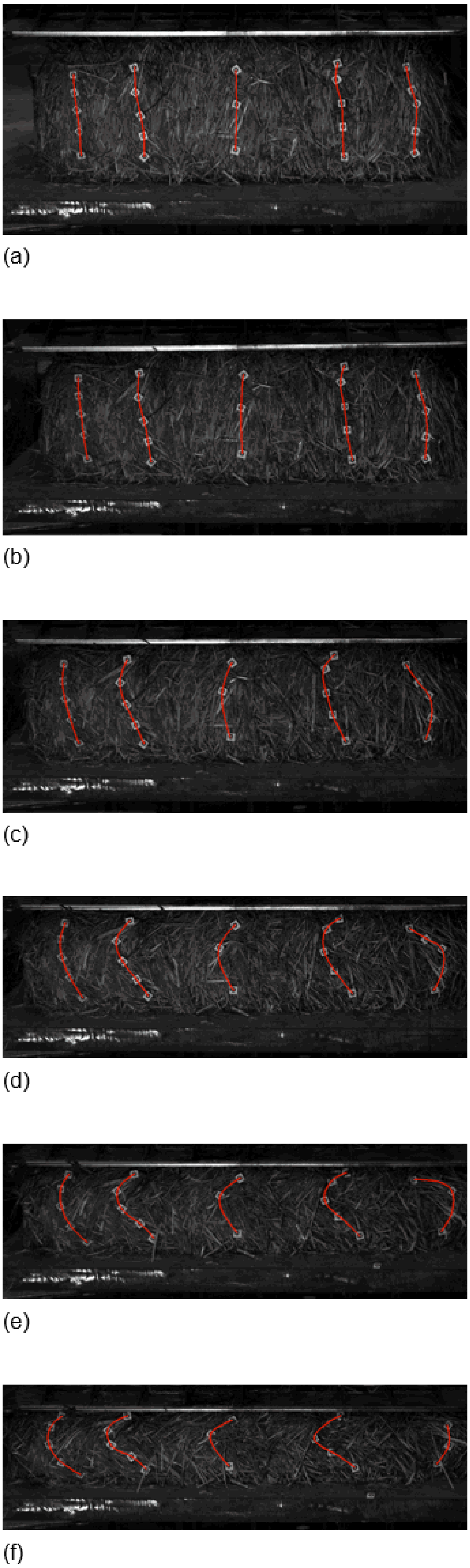


Figure 3. Deformation under compressive tests for millet bales laid flat under progressive vertical deformation: (a) 0; (b) 0.1; (c) 0.2; (d) 0.3; (e) 0.4; and (f) 0.5.

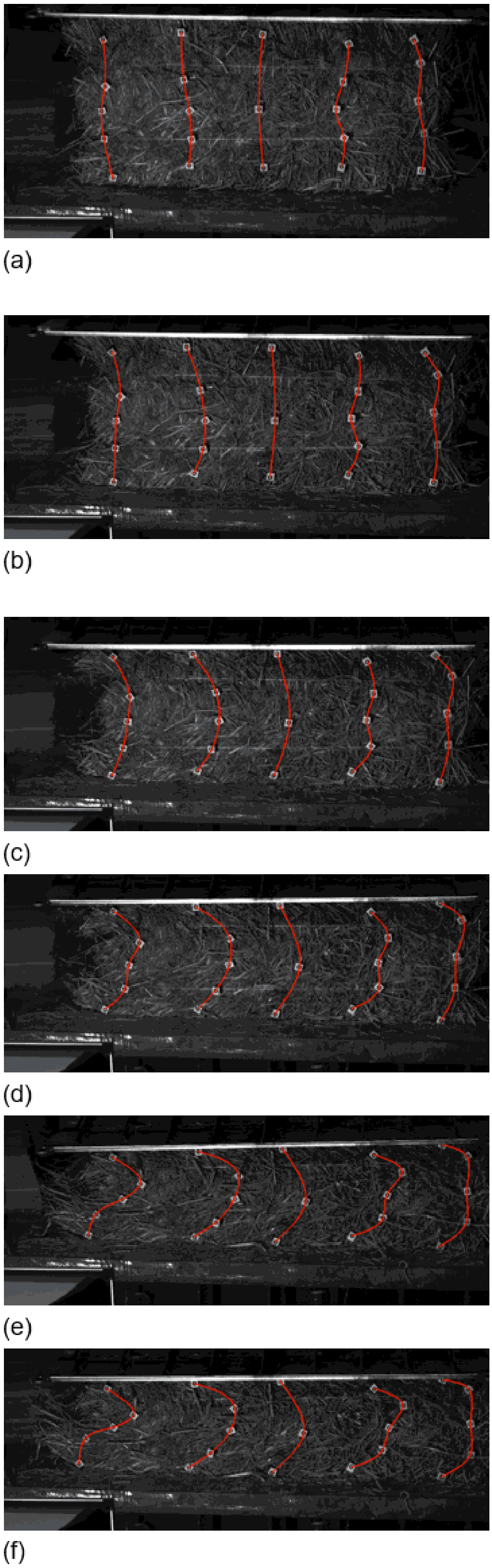


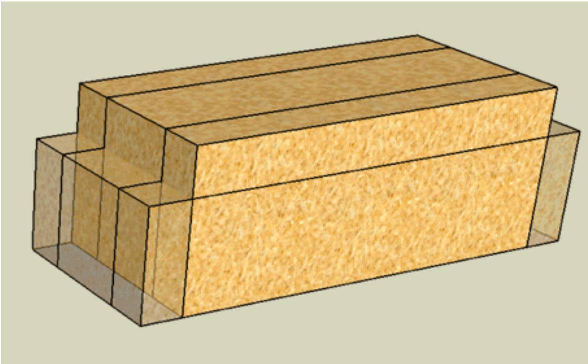
Figure 4. Deformation under compressive tests for millet bales laid on egde uder progressive vertical deformation: (a) 0; (b) 0.1; (c) 0.2; (d) 0.3; (e) 0.4; and (f) 0.5.

5 STRINGS DEFORMATION

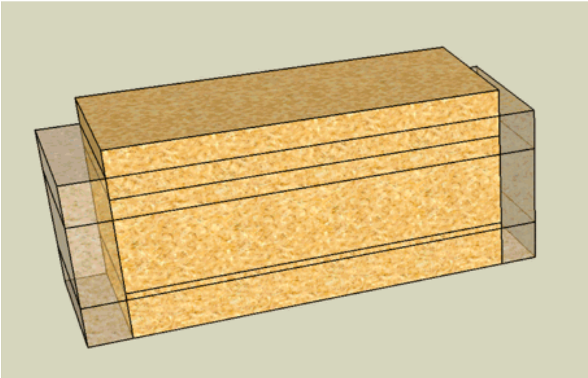
The measurements of the bales lateral displacement indicate that, during the tests, bales are compressed in the loading direction and expand in the longitudinal direction.

Nevertheless, if bales are laid flat, straw fibers can adjust themselves to accommodate the constrain provided by the strings which reduce their length in the vertical direction and increase it in the horizontal direction (Figure 5a and 6a). As a result, the length of the strings during the compressive test remains almost unchanged.

On the other hand, if bales are laid on-edge, straw fibers cannot adjust themselves under loading, since strings deform – and elongate – only in the longitudinal direction (Figures 5b and 6b). For this reason, strings are more stressed in the case of bales loaded on-edge, and strings burst occurs more frequently.



(a)



(b)

Figure 5. Deformation under compressive tests: (a) bales laid flat; (b) bales laid on edge.

(a)

(b)

Figure 6. Strings deformation under loading for: a) flat bales and b) on-edge bales. Orange lines represent the undeformed strings shape, black lines represent their deformed shape.

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APPENDIX

Table A1 – Overall data for flat bales.

Material	n. bale	H [cm]	L [cm]	W [cm]	G [kg]	rho [kg/m^3]	HUM_core [% WB]	HUM_surf [% WB]	v_press [cm/min]
Millet	n.1	40,0	102,0	48,9	26,031	131	16,3	16,6	1
	n.2	38,9	101,8	48,9	26,868	139	17,5	15,8	1
	n.3	39,6	102,9	49,2	27,262	136	16,5	15,0	1
Oat	N	41,0	115,2	50,1	23,268	98	18,2	14,7	1
	n.2	40,4	109,4	49,7	21,572	98	19,3	20,5	1
	n.3	40,0	110,8	50,9	21,581	96	19,6	14,7	1
Sorghum	n.3	39,0	104,9	48,3	19,119	97	14,3	13,9	1
	n.1	39,1	100,3	48,7	16,542	87	14,9	14,2	1
	n.6	38,6	102,6	48,2	19,314	101	13,8	13,3	1
H wheat	n.5	38,5	102,6	50,2	16,946	86	15,8	14,7	1
	n.1	39,1	107,3	49,6	18,400	89	15,4	14,6	1
	n.6	38,9	110,8	49,6	18,570	87	15,5	15,0	1
Corn	n.1	40,4	101,4	48,7	21,348	107	12,5	12,4	1
	n.4	40,7	108,2	49,3	22,262	103	14,8	14,6	1
	n.5	40,5	107,4	50,4	21,732	99	14,7	14,6	1
Barley	n.4	41,1	107,5	49,2	16,811	77	16,4	15,9	1
	n.2	41,0	108,3	50,4	23,870	107	15,1	15,8	1
	n.1	40,2	114,5	49,1	23,404	104	16,0	16,6	1
Wheat	n.19	40,5	112,9	49,2	17,258	77	16,5	15,6	1
	n.6	39,9	111,3	49,4	18,582	85	16,8	14,6	1
	n.16	40,3	110,7	48,9	21,177	97	15,4	13,9	1
Rice	n.6	39,8	113,4	49,3	22,019	99	19,7	16,9	1
	n.2	38,6	103,9	49,6	25,996	131	15,4	16,7	1
	n.3	38,9	103,5	49,8	27,536	137	14,6	12,5	1

Table A2 – Overall data for on-edge bales.

Material	n. bale	H [cm]	L [cm]	W [cm]	G [kg]	rho [kg/m^3]	HUM_core [% WB]	HUM_surf [% WB]	v_press [cm/min]
Millet	n.6	38,5	104,8	49,0	31,869	161	19,9	18,5	1
	n.5	38,7	106,4	48,0	30,685	155	17,3	17,7	1
	n.4	39,5	100,3	48,5	29,643	154	20,3	18,6	1
Oat	n.4	40,0	113,0	51,6	23,907	102	24,6	23,1	1
	n.5	40,0	110,1	49,9	23,780	108	21,7	22,4	1
	n.6	39,7	109,4	49,6	22,716	105	24,3	23,1	1
Sorghum	n.2	38,9	105,8	48,6	19,184	96	15,6	15,5	1
	n.4	38,9	100,2	47,9	19,224	103	16,3	14,8	1
	n.5	39,2	98,3	49,0	17,928	95	15,7	16,3	1
H wheat	n.4	38,7	109,7	48,7	20,165	97	16,8	15,4	1
	n.2	38,9	109,0	49,2	18,848	90	16,4	16,4	1
	n.3	39,4	110,8	48,8	19,506	92	17,2	17,5	1
Corn	n.6	41,4	109,0	48,7	22,672	103	15,1	16,4	1
	n.2	40,7	108,0	48,5	21,633	101	15,2	14,7	1
	n.3	39,7	107,9	49,1	21,981	105	14,3	14,2	1
Barley	n.5	39,5	115,0	51,7	21,073	90	17,2	15,8	1
	n.6	41,3	106,1	49,1	20,686	96	19,6	17,9	1
	n.3	41,3	115,6	49,2	26,332	112	16,4	15,9	1
Whaet	n.14	39,8	111,9	50,0	22,070	99	13,1	12,7	1
	n.100	38,9	114,2	48,6	17,161	79	15,7	15,5	1
	n.4	39,5	100,2	48,2	16,660	87	14,4	14,2	1
Rice	n.4	38,7	108,9	49,6	24,624	118	17,0	14,8	1
	n.1	38,7	115,5	49,2	27,094	123	17,4	15,3	1
	n.5	38,1	103,5	49,9	22,236	113	18,2	17,1	1