Journal of Building Engineering 9 (2017) 84–90

Contents lists available at ScienceDirect

Journal of Building Engineering

journal homepage: www.elsevier.com/locate/jobe

Mechanics of straw bales for building applications

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ARTICLE INFO

Keywords:
Straw bales
Building
Stiffness
Anisotropy
Compression
Granular packing

ABSTRACT

Straw bales are seen as increasingly viable for building insulation and even for the construction of small load-bearing straw houses in the last decades, especially in view of the need to seek low environmental footprints. Straw bales can be used as load-bearing structures but they are currently mainly used as a filler insulation material associated with a timber structure. Up to present, very few studies are available concerning the mechanical behaviour of straw bales in buildings. This study aims at investigating the behaviour of straw bales and leads to recommendations for required bales densities. This allows to derive compression models which describe their behaviour in a wall. Therefore, the results show that, in the density range 90–110 kg/m^3, the elastic and strength characteristics are similar whatever the position of the bales (laid flat or on their edge).

The behaviour of the straw bales is found to be in correlation to the straw wisp density and to the initial wisp packing into the bales. The bale should therefore be considered has a system consisting out of the straw and the polymer links: when laid flat, it exhibits a particular type of deformation under single compression leading to a constant perimeter. In this position, the mechanical properties are controlled by two factors: (1) the packing density induced by the machine during the baling process, and by the elasticity and creep of the links; (2) the solid volume fraction of straw wisps, conditioned by the agronomic parameters and the pressure level in the baler.

1. Introduction

In Europe, about 40% of natural resources are currently used in the construction and building industry [1]. Agricultural by-products can be used as a resource to reduce the environmental footprint of building materials and also provide supplementary income for harvesters.

Apart from representing an agricultural by-product basically used for animal feed or litter, straw can be re-grown annually, and can be considered as a local building material with very few processing transformation steps and low fertilizer input. Over the past twenty years, the scientific interest in straw as a building material increased (Fig. 1) to develop this material from both the architectural and scientific points of view [2].

Construction rules regarding insulating materials have even been recently validated in several countries, such as in France [3] and the U.S.A. [4]. In the United Kingdom, some low-cost bale house concepts have been developed [5] and are now on the market [6]. These concepts use prefabricated straw and timber hybrid systems.

Straw bales are generally made directly on the cereal field, just after the grain harvest. Three principal formats exist: round bales, small oblong bales of low to medium density (50–150 kg/m^3) and large oblong bales with high densities (> 150 kg/m^3). For building, the straw bales are generally laid flat, by hand. Thus, the small bale is the most commonly used format, with a weight of barely more than 15 kg and maximal dimensions of approximately 40×50×100 cm.

During harvesting of the cereal crop, the combine harvester collects the grains, and pours straw windrows onto the field. After an optional tedding step, baling consists of picking up the windrows and pressing the straw wisps together. In small balers, the wisps are picked up from the field and oriented by the feeding screw (Fig. 2). During the baling process, the main pressure is applied according to the long axis of the bale and is maintained at the desired compaction state by strings (generally two or three strings, made of thermoplastic polymer).

Straw bales are currently considered as an insulation filling material for construction applications. In the so called hybrid systems, specific prefabricated panels are added to bear the load. However, some self-builders and municipalities are attracted by using the bale itself as load bearing structure in small building. Such load bearing structures are made up of vertical walls of straw bales laid flat and associated with horizontal timber frames. The timber frames and straw walls are held together with tensioning wires that also pre-stress the straw bales. This structure is sometimes supplemented with wooden bracing. The coating of such constructions can be made up of render (plaster, lime or earth) or timber cladding. The building generally has a maximum of

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http://dx.doi.org/10.1016/j.jobe.2016.12.001
Received 6 June 2016; Received in revised form 14 November 2016; Accepted 1 December 2016
Available online 05 December 2016
2352-7102/

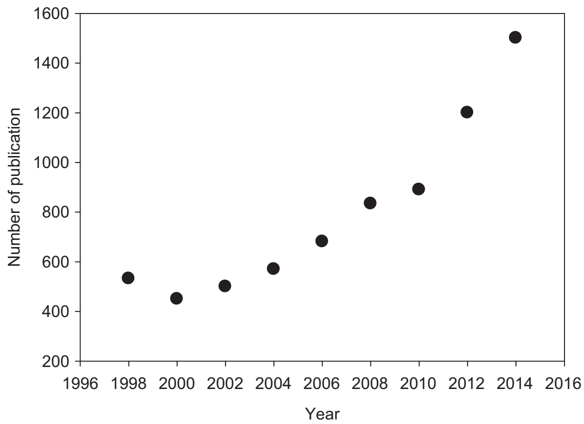

Fig. 1. Evolution of number of publications in Elsevier® with keywords (straw + building).

two floors (ground+1), with a light roof. This technique raises some new questions about the stiffness, creep and stability of straw-bale walls and, more generally, the influence of straw-bale mechanics.

Until now, studies of straw building materials have been almost exclusively concerned with their hygro-thermal characteristics. The durability of straw insulation materials against moisture has been demonstrated [9,10] and their hygro-thermal properties are now well known [11–14]. However, there are only very few studies on the mechanical behaviour of straw subjected to a compressive load. Some studies have considered the compressibility of straw as a raw material in silos or during a compression process [14,15] or the mechanical behaviour of individual stems [16]. Nona et al. [17] have investigated the compression characteristics of bulk straw, fitting its compression and stress relaxation behaviour with models such as the Maxwell model.

Studies of the mechanical behaviour of straw bales used as a building material are always associated with a given construction technique. For example, Arnaud et al. [18] studied a specimen containing a combination of load-bearing timbers and straw bales reinforced by nails and straps, while Rakowski and MacDougall [20] and Vardy and MacDougall [21] considered straw-bale plastered walls. To our knowledge, there is a lack of available data in the literature about the compression behaviour and properties of individual straw bales. The only articles on this subject [13,18] deal with a low number of samples combined with a narrow range of densities, which is hardly representative of the natural variability of such a building material. In addition, the main identified weakness in straw-bale construction is the highly variable geometry and density of the bales arising from the baling process.

The aim of the present study is to establish a baseline on compressive strength and elasticity characteristics (behaviour and properties) of small straw bales, using two different batches with densities varying from 65 to 115 kg/m^3 processed by two different straw balers, supplemented with literature data [13,19]. The target application is the use of wall filling as a load-bearing material, even associated with other materials. The further goal is understanding the levers for assessing straw building technology.

The anisotropic behaviour is also studied by loading some bales laid flat and others laid on their edge. The analytical models of compression tested here are based on the mechanics of granular media, allowing us to explore the relationship between permanent loading and deformation for the current load-bearing technique.

2. Materials and methods

2.1. Material

The straw making up the bales comes from wheat stems harvested in South Brittany, France. The two batches described in Table 1 display a large range of densities, allowing us to investigate the influence of both density and process on the mechanics of straw bales.

Batch 1 was harvested in the summer of 2013 and batch 2 in 2014, in different fields, and by two different farmers. The wheat sowing density was the same: 280 seeds/m^2. The density distribution of each batch is given in Fig. 3. These distribution curves show the importance of the choice of the agricultural machines in the aim of a use for building.

Building regulations for straw [3] used essentially for insulation applications in timber structures recommend bale densities of between 80 kg/m^3 and 120 kg/m^3, which therefore includes our samples. Batch 1 will never be used in construction as its average density is too low. But it permits to enlarge the investigation range and raise the trends and correlations on a mechanical point of view.

Indeed, as illustrated in Fig. 3, most of the variability arises from the differences between processing machines and agricultural practices, while a marked variability is also observed within each batch (coefficient of variation of 6% in each batch), i.e. within bales specimens produced with the same baler and tractor and on the same field. This variability within the same batch can come from different baler tunings during harvesting and from the variability of the straw itself in a field, due to differences of the soil nature or wind and sun exposures.

The density and moisture of the wisps also varies between batches: even if both batches come from wheat that was sowed at 280 seeds/m^2, the first batch was derived from organic farming, with no chemical treatment, whereas the second was provided by a conventional farmer who also used some stem-shortening agent. This can lead to differences in the stem cross-section, particularly affecting the amount of woody core in the inner part [16]. Furthermore, the first batch was drier (about 9% moisture content by mass of dry material, measured by heating in a drying oven until weight stabilization) and the second was

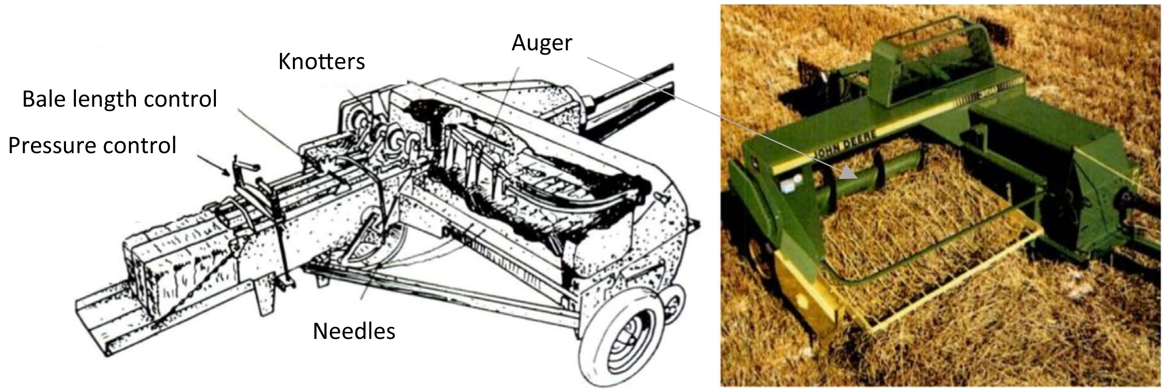

Fig. 2. operating principle of small square straw baler [7,8].