RE-BALING STRAW FOR BETTER INSULATION

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Abstract

Agricultural straw bales, produced as a co-product of cereal crops such as wheat and rice, have been used in construction worldwide for over 100 years, but despite their favourable low environmental impact, sustainable supply chain, and good thermal insulation properties their use has remained largely niche compared with other competing products. However, straw bales have remained sub-optimal for building performance or practically for construction. The current study seeks to improve the insulation qualities of straw by manufacturing bales specifically for construction applications, with the straw stems oriented to maximise available thermal resistance. Technical development and characterisation of an insulating material produced from wheat straw, for use in conjunction with typical timber-framed construction for example, is reported. The paper describes aspects of developing an insulating prototype made from wheat straw, where the thermal properties relative to the orientation of the straw are investigated. Straw orientations other than that produced by traditional baling equipment, and on a scale designed for ease in construction use, require modified equipment. The design and development of small-scale baling equipment for the laboratory is presented. A series of small-scale thermal conductivity tests demonstrate the potential for improved performance through consideration of various straw orientations. Controlling the orientation of the individual straws results in improved thermal resistance, allowing thinner walls than conventional agricultural bales. Straw needs to be baled to specific thicknesses to support uptake in wider construction. With the capability of re-baling the straw into desirable dimensions, the overall width and length of a straw bale can be designed to fit with standard construction. This research will enable greater uptake of a novel low embodied carbon bio-based material into mainstream construction.

Keywords:
Straw bale, fibre orientation, thermal conductivity, insulation materials

1 INTRODUCTION

Straw from cereal crops has been used in construction for millennia, primarily as fibre reinforcement in various earth building materials, as well as roof coverings (thatching), and floor coverings. But since the late nineteenth century straw has also been used directly as bales in both loadbearing and non-loadbearing walls. Straw is derived from the plant stems of agricultural cereal crops such as wheat, oats, barley and rice. A natural co-product of food production, as with other plant based materials, the use of straw in construction provides a bank for photosynthetic sourced carbon dioxide. Straw is composed primarily of cellulose, hemi-cellulose, lignin, and silica.

Straw bale construction dates back more than a hundred years, with the introduction of the first mechanical baling machines in Nebraska, USA [King, 2007]. Following harvest of the cereal crops the cut straw is mechanically compacted and then bound by twine into bales. Agricultural bales come in various shapes and sizes and may have two or more ties binding them together. Round bales are commonly seen in the fields of the UK at harvest time and are more resistant to the weather, whilst rectangular bales are easier for manual handling and better meet requirements for building. Rectangular bales used in construction nominally measure around 1000 mm (long) by 450 mm (wide) and 350 mm (high), with the baling twine laying lengthwise.

Bale density is often used in the specification of straw bales, and whilst thermal resistance is relatively insensitive to density [Shea et al. 2013], mechanical properties, such as compressive resistance, are more dependent on density. The final density, and compactive effort required, is also influenced by straw moisture content at harvest.

During production the small rectangular balers gather the cut straw and transfer it into a compression chamber via an auger or feed fork mechanism. Within the chamber, a plunger moving at 80-100 strokes per minute, compresses the straw into bales with final densities ranging from 60 – 170 kg/m^3. The baling process forms the straw into layers across the bale, sometimes referred to as flakes, of about 100 mm width. The flakes are continuously compressed together along the length of the final rectangular shape [King 2007]. However, the use of traditional bales orients the straw flakes in the least efficient direction for thermal resistance, with the length of the stem folded over and perpendicular to the exposed surfaces [Yin et al., 2018, Sharma and Harries 2016].

The aim of this paper is to present work from research developing the thermal resistance properties and constructability of wheat straw bales for use as non-load bearing insulation material. Initial work investigating the influence of straw bale orientation on thermal resistance is presented, followed by work developing and initial characterisation of prototype functionalised straw bales, The work is part of a larger research project (*Interreg project Sustainable Bio & Waste Resources for Construction*) aimed at developing insulating materials from bio-based and other waste streams.

2 EVALUTING THE DIRECTIONAL THERMAL PROPERTIES OF STRAW BALES

Previous work has shown that the thermal resistance of straw bales is relatively insensitive to their density [Shea et al. 2013]. However, straw bale thermal conductivity is also dependent on moisture content, and most significantly varies depending on heat flow direction relative to straw orientation. FASBA, the German national organisation for straw bale building, have published two values for thermal conductivity based on small scale laboratory tests [FASBA 2009]. For heat flow parallel to the direction of the straw, thermal conductivity is 0.080 W/m K, but when the straw is aligned perpendicular to the direction of heat flow, the thermal conductivity reduces to 0.043 W/m K. These results were derived from small specimens in which all individual straws are placed either parallel or perpendicular to the direction of heat flow. However, the orientation of straw within bales is more randomly distributed. The anisotropic thermal conductivity of straw bales has previously led to proposal for processing during compaction to optimize direction to maximize insulation value [Véjelienė 2012], but to date this has not been realized to any scale.

To measure the influence of heat flow direction relative to straw orientation, wheat straw bales form a locally sourced supplier in Somerset, UK, was sourced. The two string bales were nominally 350 x 450 x 700 mm with an initial dry density of 120 kg/m^3. To measure directional influence on thermal resistance bales were subdivided, without significantly disrupting the straw orientation, into three 450 x 350 x 80 mm specimens taken in three orthogonal directions, as shown in Fig. 1 [Yao 2015]. Specimen 2 (width-wise orientation) represents the conventional direction found in straw bales. These naturally orientated specimens were cut from the original natural bale using a handsaw together with a 450 x 350 x 80 mm timber box. The density of the three specimens obtained decreased by approximately 24% compared to the original density of the bale due some relaxation during the cutting.

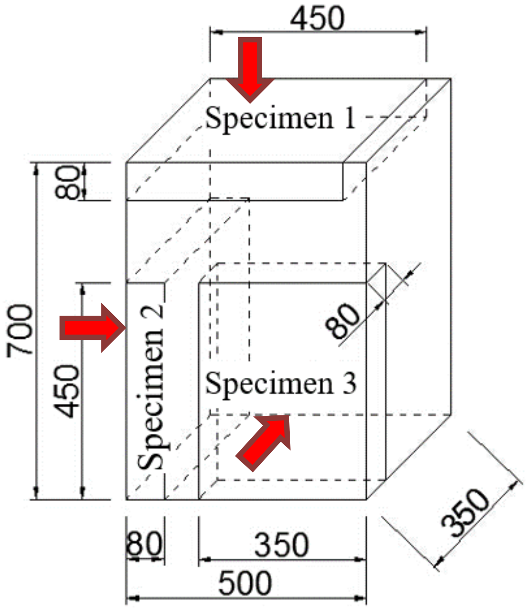

Fig. 1: Specimens cut from the original bale (units are in mm). Red arrows depict heat flux during testing.

An additional set of specimens were created by fabricating 400 x 400 x 80 mm specimens in which the individual straws were aligned by hand either parallel or perpendicular to the heat flow [Lu 2016], allowing comparisons to the FASBA tests and the subdivided straw bale tests. One specimen was manufactured with the straw laid vertically (Vertically oriented), another the straw laid horizontally (Horizontally oriented) and a third specimen comprised randomly orientated chopped straw (Random oriented) (Fig. 2). Each specimen was handmade within a timber frame and tied with strings initially placed in the frame. A thin polyethylene membrane was used to hold the material together, particularly useful in the case of the chopped straw specimen, but also prevented moisture transfer between the specimen and the environment during testing. For the vertically and horizontally orientated specimens, the straw was first tied into smaller bunches in order to hold them in the same direction before cutting them to right length (80 or 400 mm) and placing them into the frame. The chopped straw specimen was made by filling the timber frame with the chopped straw. Each of these process continued until target density was achieved. Tab. 1 provides the specimen characteristics prior to testing.

Vertically oriented Horizontally oriented Randomly (chopped) oriented

Fig. 2: Oriented straw samples.

Tab. 1: Details of thermal conductivity specimen characteristics.

Series	Reference	Description	Dimensions (mm)	Initial density (kg/m^3)	Moisture content (%)
Cut from bale	Specimen-1	Direction of heat flow length-wise	350 x 450 x 80	87	5.0
	Specimen-2	Direction of heat flow width-wise		88	3.3
	Specimen-3	Direction of heat flow height-wise		88	5.0
Oriented straw specimens	Vertical	Vertical straw	400 x 400 x 80	116	10.1
	Horizontal	Horizontal straw		115	8.2
	Random	Chopped straw		116	15.6

Thermal conductivity measurements were carried out using a FOX 600 Heat Flow Meter, from TA Instruments, according to the standards BS EN 12667, ISO 8301 and ASTM C518. WinTherm software was used for control and data handling. Prior to testing, the specimens were dried at 60°C for 6 days until the mass reached steady state. Each specimen was then wrapped in a thin polyethylene membrane (‘cling film’) to maintain a stable moisture content. As the membrane is thin (<20 μm), the effect of its thermal conductivity was ignored. The specimens were framed into expanded polystyrene to ensure a one-dimensional heat flow. The plates are 610 x 610 mm^2 and metering area is 254 x 254 mm^2 (dimensions of the thin-film heat flux transducers). Thickness of each specimen was directly measured by the heat flow meter, with a precision of 0.025 mm.

The influence of temperature on the apparent thermal conductivity values was assessed by performing the measurement at two different mean temperatures: 20°C (upper plate at 10°C and lower plate at 30°C) and 25°C (upper plate at 15°C and lower plate at 35°C). Specimen density at the time of the testing was also measured. The results of thermal conductivity for both mean temperatures 20°C and 25°C as well as the density of the specimens at the time of testing are presented in Tab. 2.

The orthogonal thermal conductivity of rectangular straw bales is evident from the results for the bale tests. The values for Bale Specimens 2 and 3, in both temperature ranges, are comparable, whilst the thermal conductivity confirms earlier work that orienting straw perpendicular to heat flow is the most beneficial direction to maximise insulation value. The thermal conductivity for Bale Specimen 1 is similar to that reported by FASBA for straw laid cross-wise to heat flow. The thermal conductivities for the vertically and horizontally specimens show stark differences in performance, comparable with those reported by FASBA. These results point to benefits of producing oriented straw bales functionalised to be used as insulation in construction. The experimental results are comparable with findings reported by Douzane et al. (2016). Interestingly, the randomly oriented specimen using chopped straw recorded the lowest thermal

Tab. 2: Thermal conductivity and density at test of the specimens

Specimen	Thermal conductivity at 20°C (W.m^{-1}.K^{-1})	Thermal conductivity at 25°C (W.m^{-1}.K^{-1})	Density at test (kg/m^3)
Bale Specimen-1	0.0446	0.0453	83
Bale Specimen-2	0.0602	0.0610	85
Bale Specimen-3	0.0580	0.0587	84
Vertically oriented	0.0835	0.0855	99
Horizontally oriented	0.0501	0.0512	97
Randomly oriented	0.0414	0.0429	99

conductivity. However, chopped straw is not readily suitable for baling with further concerns about potential settlement and fire resistance to be assessed.

3 MANUFACTURING PROTOTYPE STRAW BALES

The present study is investigating the feasibility of producing functionalised small bales, between 100 and 150 mm thickness, suitable for insulation purposes within conventional timber-framed walls for example. Unlike 450 mm wide agricultural bales, the prototypes are not intended to be load bearing. To date this investigation has used small scale production methods to consider the effect of various shapes, densities, and stem orientation on the thermal performance of wheat straw insulation.

The prototype bales have been compacted within a timber and steel braced former using laboratory Enerpac hydraulic jacks. The low stiffness of loose straw requires large displacements of compacting jacks, which has limited the dimensions of the resultant bales. The initial prototype has undergone several changes during the concept initiation. Following initial design for vertical compaction the current set-up uses a horizontal form (400 mm width with 100 or 150 mm height). Each derivation came from a particular need in the production process. Initially this meant primarily producing prototype based on the physical requirements for thermal conductivity testing. The prototype further evolved to consider methods of construction and still further to incorporate mechanics of the straw and potential upscaling (Fig. 3). Figure 4 shows the set up for bale twine prior to loading the chamber and after compaction. Prototype bales are shown in Fig. 5.

Fig. 3: Set-up for compacting prototype bales.

In the production of these prototypes a compressive pressure of 654 kN/m^2 was applied. In trials it was observed that bales could not be reliably produced with a width to height ratio of greater than two. Beyond this limit the bales curled up when tied with the baling twine.

A series of six specimens for each prototype bale (measuring approx. 400 x 150 x 150 mm; average density = 112 kg/m^3) were produced using wheat straw; these were subject to compressive resistance testing following BS EN 826:2013. Load was applied both parallel and perpendicular to the direction of bale compaction. The results for compressive resistance stress at 10% strain are given in Tab. 3.

Baling twine preloaded

Bale twine tied off

Fig. 4: Trial equipment in vertical and horizontal form

Fig. 5: Prototype bales

Tab. 3: Compressive resistance of prototype bales

	Direction of load parallel to bale compression force kN/m^2 (COV)	Direction of load applied perpendicular to bale compression force kN/m^2 (COV)
Resistance at 10% strain	13.3 (5.3%)	16.0 (11.9%)

The measured compressive resistances are insufficient for any significant loadbearing construction application for the 100-150 mm prototype bale thickness produced. However, loadbearing is not the intended application, and for purposes of in-fill the compressive behaviour should be sufficient to ensure air-tight construction as self-weight pressures in the insulation likely to be around 2.62 kN/m^2 for a 2.4 m high timber framed wall.

4 CONCLUDING COMMENTS

The thermal resistance of straw bales is dependent on how the individual straw stems are oriented with respect to the direction of heat flow. Current agricultural bales do not provide optimal orientation of the straw to maximise thermal resistance in construction applications. Consequently, straw bale walls tend to be thicker than many competing products. By functionally rebaling straw it is possible to improve thermal resistance and reduce necessary insulation thickness by 33%.

By orienting the straw parallel to the exposed surface, with production of small scale construction representative bales, a novel bio-based insulation is entirely viable. The developed prototype production method enables single bale and bale bundles to be produced at a small scale and allows characterisation. The process is currently under further development for scalability in reference to larger production methods.

5 ACKNOWLEDGMENTS

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