THE CORIANDER STRAW, AN ORIGINAL AGRICULTURAL BY-PRODUCT FOR THE PRODUCTION OF BUILDING INSULATION MATERIALS

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Abstract

Straw represents 60-80% of the aerial part of coriander. It is cheap (90 €/ton including harvesting, bunching and transportation) and has an availability of 250 tons/year. However, the latter will grow strongly in the next five years due to the increasing use of vegetable oil from the fruits for food, cosmetics or the chemical industry. Due to its high lignocellulose content (62%), coriander straw is an interesting crop by-product for the production of bio-based building materials. Two types of insulating materials are presented here.

Firstly, it is possible to produce bulk materials by thermo-mechano-chemical refining of straw with water using a twin-screw reactor. According to the applied liquid/solid ratio (0.4-1.0), it is possible to control the fiber aspect ratio of the refined straw (22.9-26.5) and thus the tapped density of the resulting bulk material (110-61 kg/m^3). For the lowest density, the thermal conductivity was 47.3 mW/(m.K), corresponding to a 1.06 (m^2.K)/W resistance for a 5 cm thickness of extrusion-refined straw. Twin-screw refining was also successfully conducted with an aqueous borax solution, allowing fire-proofing of the straw. When used as loose fill in housing, refined coriander straw is a promising solution for building insulation.

Medium-density insulation blocks can also be manufactured using compression molding by combining coriander straw (milled or extrusion-refined) and a starch-based binder. The use of a milled straw (7.5 mm sieve) mixed with 15% binder, cold pressed (87 kPa, 30 s) and then dried, resulted in cohesive blocks with a 155 kg/m^3 density and a 55.6 mW/(m.K) thermal conductivity, corresponding to a 0.90 (m^2.K)/W resistance for a 5 cm thickness. Similarly, such blocks could be used for the thermal insulation of buildings, including the filling of walls, interior partitions, etc.

Keywords:

Coriander straw, lignocellulosic fibers, twin-screw extrusion refining, compression molding, building insulation materials

1 INTRODUCTION

Coriander (*Coriandrum sativum* L.) is an annual herb, commonly used as a condiment or a spice. The fruit has been used as a traditional medicine to treat various medical conditions such as indigestion, worms, rheumatism and joint pain. It also contains a vegetable oil which can be extracted through mechanical pressing using a twin-screw extruder [Uitterhaegen 2015]. Pressed oils are of good quality (<1.5% acidity and negligible peroxide value) and show a high petroselinic acid content (73%). They are also pleasantly scented, owing to part of the coriander essential oil being co-extracted from the fruits during the extraction process.

Straw represents 60-80% of the aerial part of coriander and is considered a crop residue, rendering it economically interesting with a low price of 90 €/ton including harvesting, bunching and transportation. Nowadays, its availability is 250 tons/year in the South-West part of France. However, it will grow strongly in the next five years, since vegetable oil from coriander fruits has gained great interest from the food, cosmetic and chemical industries [Uitterhaegen 2016].

Coriander straw was recently used as a reinforcing filler in polypropylene (PP) and bio-based low-density polyethylene (BioPE) composite materials through twin-screw extrusion compounding and injection molding [Uitterhaegen 2018]. Its reinforcing effect was significant, resulting in a 50% increase in the flexural and tensile strengths (from 19 to 28 MPa and from 12 to 17 MPa, respectively, for polypropylene composites) as compared to the native polymer. From a mechanical point of view, the 40% filled thermoplastic biocomposite had comparable properties to those of commercial wood fibers. In addition, its durability was excellent in terms of UV and hygrothermal weathering. Lastly, it revealed high potential for recycling.

Coriander straw has also already been successfully used as a mechanical reinforcement inside renewable binderless fiberboards molded using hot pressing [Uitterhaegen 2016]. The protein-based press cake resulting from the extraction of vegetable oil from the fruits was then used as a natural binder inside the boards, thus at the same time ensuring the valorization of a crop residue and a process by-product. The resulting fiberboard revealed good performance, i.e. a flexural strength of 29 MPa and a thickness swelling of 24%. Produced without the use of any chemical adhesives, such board could thus present a viable, sustainable alternative for current commercial wood-based materials such as oriented strand board (OSB), particleboard (PB) and medium-density fiberboard (MDF), with high cost-effectiveness.

Another industrial application of fiberboards made from crop residues is heat insulation of buildings (e.g. walls, ceilings, etc.), where the main advantages of vegetable fibers are their abundance, low cost, minimal environmental impact, independence from fossil resources, and their natural capacity for thermal insulation [Saiah 2010]. Many different agricultural by-products were used in the two last decades for obtaining innovative and renewable insulation boards, e.g. a mixture of durian peels and coconut coir fibers [Khedari 2003], kenaf fibers [Ardente 2008], flax and hemp fibers [Kymäläinen 2008, Korjenic 2011, Benfratello 2013], cotton stalk fibers [Zhou 2010], jute fibers [Korjenic 2011], coconut fibers [Panyakaew 2011, Alavez-Ramirez 2012], sunflower pith [Vandenbossche 2012, Sabathier 2017], sunflower cake from whole plant [Evon 2014, 2015], date palm fibers [Chikhi 2013], etc.

The thermal conductivity of insulation boards is often influenced by their density [Khedari 2003, Zhou 2010, Panyakaew 2011, Vandenbossche 2012, Benfratello 2013, Chikhi 2013, Evon 2014, 2015], and low-density materials are the best insulating materials, with the lowest thermal conductivities. As an example, the thermal conductivity of an insulation board from sunflower pith having a 36 kg/m^3 density is only 38 mW/(m.K) at 25 °C [Vandenbossche 2012]. It is comparable to that of conventional insulation materials like expanded polystyrene (37 mW/(m.K) with a board density of 50 kg/m^3), rock wool (36 mW/(m.K) with a board density of 115 kg/m^3), and glass wool (35 mW/(m.K) with a board density of 26 kg/m^3).

Thermal conductivity is higher with medium-density materials: 46-68 mW/(m.K) for coconut husk insulation boards with board densities of 250-350 kg/m^3 [Panyakaew 2011], 74-83 mW/(m.K) for insulation boards from sunflower cake with board densities of 338-375 kg/m^3 [Evon 2015], 82 mW/(m.K) for a cotton stalk fibers insulation board with a board density of 450 kg/m^3 [Zhou 2010], 90-108 mW/(m.K) for hemp fibers insulation boards with board densities of 369-475 kg/m^3 [Benfratello 2013], 104 mW/(m.K) for a coconut coir insulation board with a board density of 540 kg/m^3 [Khedari], and 150 mW/(m.K) for a date palm fibers insulation board with a board density of 754 kg/m^3 [Chikhi 2013]. Nevertheless, such boards are viable options for use in building insulation (walls and ceilings).

A strategy to significantly improve the heat properties of insulation fiberboards is the use of natural binders, first solubilized in water and then mixed to the crop residue before compression molding plus drying [Mati-Baouche 2014, Evon 2015]. These external binders are used with physical curing, adhesion being achieved when water has evaporated. It then results in the formation of mostly hydrogen bonds between the biopolymer in the glue and the lignocellulosic compounds (mainly cellulose, and hemicelluloses) in the materials to be joined. When used, natural binders favor both good cohesion and low density for the composite material, thus improving its thermal insulation ability. As an example, it is possible to manufacture insulating bio-based composites according to this technique from sunflower stalks particles and chitosan [Mati-Baouche 2014]. Composites with a thermal conductivity of only 56 mW/(m.K) and a maximum stress of 2 MPa are obtained with a ratio of chitosan of 4.3% (w/w) and a size grading of particles above 3 mm. In the same way, insulation fiberboards made from cake generated during the biorefinery of sunflower whole plant in a twin-screw extruder and three different natural binders (*i.e.* starch, gelatin, and casein) revealed interesting heat insulation properties [Evon 2015]. There, the medium-density board containing 20% starch-based binder was a good compromise between mechanical and heat insulation properties (347 kPa flexural strength and 78 mW/(m.K) thermal conductivity). These thermal and mechanical performances are competitive with those of other insulating bio-based materials available on the market. When placed in walls and ceilings, such boards could thus contribute to the thermal insulation of buildings.

This study aimed to manufacture new thermal insulation fiberboards with improved thermal and mechanical properties, by compression molding at ambient temperature plus drying, from a mixture of a starch-based binder in water solution and coriander straw, and further to evaluate the influence of operating conditions (i.e. straw mechanical pretreatment, binder content, and straw mass) on their density and their flexural and heat insulation properties. The opportunity to use raw materials (i.e. milled or extrusion-refined straw) as loose fill in the attics of houses has been also investigated.

2 MATERIALS AND METHODS

2.1 Raw materials

Coriander straw of French origin (GSN maintenaire variety) was supplied by GSN Semences (France). Prior to the extrusion refining process, the coriander straw was crushed using an Electra Goulu N (France) hammer mill fitted with a 12 mm screen, and then an Electra F3 hammer mill fitted with a 7.5 mm screen. It showed a moisture content of 8.9±0.1%.

The natural binder used in this study has been chosen because of its commercial availability. It was a starch-based binder supplied by Bostik (France) with reference number 28474, and commonly used as a glue for wallpapers. Its starch content was 85%.

2.2 Analytical methods

The moisture content of coriander straw was determined according to French standard NF V 03-903. The mineral content was determined according to French standard NF V 03-322. The oil content was determined according to French standard NF V 03-908. The protein content was determined according to French standard NF V 18-100. The three parietal constituents (cellulose, hemicelluloses, and lignins) were estimated using the ADF-NDF method of Van Soest & Wine [Van Soest 1967, 1968]. Similarly, the water-soluble components were estimated by measuring the mass loss of the test sample after 1 h in boiling water. All determinations were carried out in duplicate.

2.3 Twin-screw extrusion refining

A Clextral Evolum HT 53 (France) co-rotating and co-penetrating twin-screw extruder was used for the fiber refining of the coriander straw material. The extruder barrel, with a length of 1.9 m, consisted of eight modules, each 4D in length (with D corresponding to the screw diameter, i.e. 53 mm), except for module 1, which had an 8D length. Barrel modules 2 to 8 were temperature controlled. Feed material (i.e. milled coriander straw) was introduced near the first module with a Coperion K-Tron SWB-300-N (Germany) gravimetric feeder. No outlet restriction was applied and the material exited the extruder barrel at atmospheric pressure. Water was injected with two different flow rates (15 kg/h and 6 kg/h, respectively) at the end of module 3 using a Clextral DKM Super MD-PP-63 (France) piston pump, while the straw feed rate was kept constant at 15 kg/h. Two different extrusion-refined materials were thus produced, A and B, corresponding to L/S ratios of 1.0 and 0.4, respectively. An aqueous solution of borax (47.3 g/L) was also used for the 1.0 L/S ratio only, thus leading to the production of a third extrusion-refined material, A*. The screw configuration that was applied was the same as in a previous study [Uitterhaegen 2017]. The extruder screw speed was 150 rpm and the extrusion temperature was set at 110 °C.

2.4 Particle size distribution

The morphological characteristics of the milled coriander straw fibers were determined through optical microscopy with a Nachet Z 45 P, ×15 (France) binocular magnifier. Five different images were taken using the Archimed 4.0 (France) software and the measurements were made with the ImageJ (USA) software.

A TechPap MorFi (France) Compact analyzer equipped with a CCD video camera was used for the morphological analysis of extrusion-refined materials. About 30,000 fibers were analyzed with MorFi v9.2 software. This software calculated a number of parameters, including mean fiber length, mean diameter and the fines percentage (fibers shorter than 76 µm). A sample of 2.5 g of dry material was diluted in 1000 mL distilled water, with mechanical stirring to break up aggregates. A 100 mL aliquot of the mixture was taken and diluted (1:10) by adding distilled water to make the volume up to 1000 mL. This process was repeated twice until a consistent concentration of 25 mg/L was achieved. In addition, it was evidenced that dilution in distilled water did not induce fiber swelling, thus not disturbing the measurement. All characterizations were performed in duplicate.

2.5 Apparent and tapped densities

For the tapped density of bulk materials (i.e. milled and extrusion-refined straw), the measurement used a Granuloshop Densitap ETD-20 (France) volumenometer, and the corresponding apparent density, i.e. before compaction, was determined at the same time. Determinations were carried out in duplicate.

2.6 Manufacturing of insulation blocks

Dependent on the tapped density of extrusion-refined materials, the minimal mass of straw to be used for compression molding was determined experimentally to reach sufficient cohesion for the insulation block, thus allowing its handling before drying and its cutting after drying without risk to break it. It was 150 g for the A extrusion-refined straw and 210 g for the B one. Two other masses were also tested, representing 133% and 166% of the minimal mass, respectively.

The starch-based binder was first solubilized in distilled water at room temperature for 10 min under stirring. Binder solutions were then mixed manually for 5 min with the extrusion-refined straw, corresponding to binder contents (w/w) of 10, 15, and 20%, respectively. The mixtures were molded at room temperature by compression inside an aluminum mold during 30 sec using a hydraulic press, producing 150 mm × 150 mm fiberboards with 5 cm thickness. Two insulation blocks were manufactured for the eighteen molding conditions tested, including extrusion-refined material, binder content and raw material mass (Tab. 1). They were dried at 60 °C using a France Etuves XL2520 (France) ventilated oven to eliminate the water added for binder dissolution, and they were then equilibrated in a climatic chamber (60% RH, 25 °C) for three weeks before any analyses. A first fiberboard was used to assess the mechanical properties for bending, and a second one for measuring the heat insulation properties.

An insulation block from milled straw was also produced using the following conditions: a mixture made of 250 g milled straw, 44.1 g starch-based binder (i.e. 15% in proportion to the sum of the masses of straw and binder), and 500 g water, 87 kPa applied pressure, 30 sec molding time, and 80 °C drying temperature.

2.7 Mechanical properties for bending

Measurement of the flexural properties of the test specimens according to French standard NF EN 310 was undertaken using an Instron 33R4204 (USA) universal testing machine fitted with a 500 N load cell. Properties covered the flexural strength at break (σ_f) and the elastic modulus (E_f). Insulation blocks were equilibrated for three weeks in a climatic chamber (60% RH, 25 °C), and then 30 mm wide test specimens were cut and their thickness measured at three points and their length at two points, with a 0.01 mm resolution electronic digital sliding caliper. Thickness (t) and length (l) mean values were recorded to calculate the specimen volume, and they were all weighed to calculate mean apparent density (d). The test speed was 2 mm/min with 80 mm grip separation. All determinations were carried out four times.

2.8 Heat insulation properties

A Neotim FP2C (France) thermal conductivimeter with a hot wire was used to measure the thermal conductivity of bulk materials and insulation blocks at 25 °C. According to the technical specifications provided by the manufacturer, the accuracy on thermal conductivity is of 5%. The hot wire method is a transient technique in which an increase of the material temperature is measured. A linear wire, assumed to be of infinite length and negligible diameter, generates heat under the influence of an electric current. Here, the wire and the associated thermocouple were included in a Kapton probe placed between two samples of the material. Then, solving the heat conduction equation in cylindrical coordinate, assuming a semi-infinite material, the thermal conductivity (λ) can be determined. The associated thermal resistance (R) was calculated for a 5 cm thickness of bulk material or insulation block. All samples were equilibrated in a climatic chamber (60% RH, 25 °C) for three weeks before being tested. All determinations were carried out three times.

3 RESULTS AND DISCUSSION

3.1 Coriander straw characterization

In this study, coriander straw was used as the main raw material, which is the lignocellulosic material consisting of the vegetative stalk parts of the coriander plant. It thus represents the crop residue after the coriander fruits have been harvested. The chemical composition of coriander straw used in this study revealed that it was rich in cellulose (52.5±0.1% of its dry matter) and hemicelluloses (21.2±0.5%), and contained a relatively low amount of lignins (9.8±0.2%). Most nonwoody, lignocellulosic materials show cellulose and lignin contents of 30-45% and 10-25%, respectively [Uitterhaegen 2017]. With a similar composition to jute fiber and wheat straw, and owing to its high cellulose content, which provides reinforcement for fiberboards [Uitterhaegen 2017] and natural capacity for thermal insulation [Saiah 2010], coriander straw shows potential as a raw material to produce cohesive insulation blocks. The complementary chemicals inside coriander straw were hot-water extractives (10.4±0.1%), minerals (4.2±0.2%), proteins (3.7±0.1%), and lipids (0.8±0.1%).

Tab. 1: Molding conditions used for the manufacture of the eighteen insulation blocks.

Insulation block	Raw material	Binder content (%)	Raw material mass	Raw material (g)	Binder (g)	Binder solution (g)
AX1	A	10	Minimal	150	15.0	200.0
AX2	A	10	+33%	200	20.0	266.7
AX3	A	10	+66%	250	25.0	333.3
AY1	A	15	Minimal	150	22.5	200.0
AY2	A	15	+33%	200	30.0	266.7
AY3	A	15	+66%	250	37.5	333.3
AZ1	A	20	Minimal	150	30.0	200.0
AZ2	A	20	+33%	200	40.0	266.7
AZ3	A	20	+66%	250	50.0	333.3
BX1	B	10	Minimal	210	21.0	280.0
BX2	B	10	+33%	280	28.0	373.3
BX3	B	10	+66%	350	35.0	466.7
BY1	B	15	Minimal	210	31.5	280.0
BY2	B	15	+33%	280	42.0	373.3
BY3	B	15	+66%	350	52.5	466.7
BZ1	B	20	Minimal	210	42.0	280.0
BZ2	B	20	+33%	280	56.0	373.3
BZ3	B	20	+66%	350	70.0	466.7

Tab. 2: Particle size distribution of extrusion-refined materials and milled coriander straw.

Material	Fiber length (µm)	Fiber diameter (µm)	Aspect ratio	Fines (%)
A	547±21	20.6±0.3	26.5±1.0	56.3±3.3
A*	381±9	21.7±0.0	17.6±0.5	62.3±16.0
B	485±3	21.2±0.1	22.9±0.2	40.8±0.2
Milled straw	3541±1357	838±335	4.5±1.7	Negligible

Tab. 3: Apparent and tapped densities, and heat insulation properties of bulk materials.

Material	Apparent density (kg/m^3)	Tapped density (kg/m^3)	λ (mW/(m.K))	R ((m^2.K)/W)
A	44.8±0.5	60.6±0.3	47.3±2.3	1.058±0.050
A*	59.4±0.3	79.8±0.2	49.3±1.5	1.014±0.031
B	81.8±1.2	109.9±1.6	52.5±4.9	0.957±0.090
Milled straw	95.3±4.2	115.1±2.7	51.0±3.0	0.982±0.057

3.2 Mechanical pretreatments of coriander straw

Before producing insulation blocks, two different mechanical pretreatments were investigated for coriander straw, i.e. crushing using a hammer mill fitted with a 7.5 mm sieve on the one hand, and extrusion-refining using water (1.0 and 0.4 L/S ratios) or an aqueous solution of borax (1.0 L/S ratio) on the other hand. This resulted in important differences in terms of morphological characteristics (Tab. 2) and fiber densities (Tab. 3). When comparing the grinding process using a hammer mill with twin-screw extrusion, it is clear that the extrusion pre-treatment resulted in a substantial improvement of the coriander fiber morphology, illustrated by a strong increase in the fiber aspect ratio, from 4.5 to 17.6-26.5. Thus, the twin-screw extrusion pre-treatment contributed to improved fiber fibrillation and destructurization, resulting in a more expanded, fluffy appearance of the extrusion-refined straw but also in the generation of fines (41-62%). Logically, a reduction in the density characteristics of the fiber material was observed with the extrusion treatment: 45-82 kg/m^3 apparent density instead of 95 kg/m^3 for milled straw, and 61-110 kg/m^3 tapped density instead of 115 kg/m^3.

When considering the varying L/S ratio applied during the extrusion process, representing different treatment severities, it can be seen from Tab. 2 and Tab. 3 that a reduction of the L/S ratio from 1.0 (A extrusion-refined material) to 0.4 (B extrusion-refined material) resulted in a slightly decreased fiber aspect ratio (from 26.5 to 22.9), and increased apparent density (from 45 to 82 kg/m^3). This was mainly attributed to the reduction in fiber length (from 547 to 485 µm) due to the increased severity of the treatment with a lower L/S ratio.

The same tendency was also evidenced at 1.0 L/S ratio when using an aqueous solution of borax (A* extrusion-refined material) instead of water (A extrusion-refined material): 17.6 aspect ratio and 59 kg/m^3 apparent density. However, for future heat insulation applications, the use of borax during the twin-screw extrusion refining treatment allowed fire-proofing of straw.

3.3 Heat insulation properties of bulk materials

Looking at the heat insulation properties of bulk materials (47.3-52.5 mW/(m.K) thermal conductivity, corresponding to a thermal resistance varying from 1.06 to 0.96 (m^2.K)/W for a 5 cm thickness) (Tab. 3), they could be considered as viable solutions for building insulation when used as loose fill in the attics of houses. And, because the A extrusion-refined straw was the least dense bulk material, it logically revealed the most promising heat insulation properties (47.3 mW/(m.K) thermal conductivity).

The use of an aqueous solution of borax (A*) instead of only water (A) resulted in a very slight increase in thermal conductivity (49.3 mW/(m.K)), giving the opportunity of applying fire treatment in anticipation of future commercial applications.

3.4 Bending and heat insulation properties of insulation blocks

Eighteen insulation blocks were manufactured through compression molding using different molding conditions (Tab. 1). Conditions included the extrusion-refined material (A or B), the starch-based binder content (10-20%) and the raw material mass (minimal, +33% or +66%). Compression molding was conducted at room temperature, generating blocks with consistently 5 cm thickness.

No problem was observed for the binder dissolution in distilled water. In the same way, manual mixing of the binder solution with extrusion-refined materials was effective for all molding conditions tested. The eighteen insulation blocks were carefully removed from the aluminum mold immediately after compression molding. They were then dried at 60 °C using a ventilated oven to eliminate the water added for binder dissolution. Depending on the molding condition used, the drying duration varied from 38 to 72 h.

All insulation blocks produced were cohesive mixtures of the extrusion-refined straw and the starch-based binder, the latter ensuring material cohesion and the lignocellulosic fibers acting as reinforcement. Conditioning in the climatic chamber was conducted immediately after production in order to assess the mechanical and heat insulation properties of insulation blocks from equilibrated materials. The moisture content of equilibrated blocks was 8-10%.

The density of the equilibrated insulation blocks was greatly affected by the molding conditions, varying from 127 to 292 kg/m^3. The B extrusion-refined straw consisting of smaller solid particles generated denser boards. In the same way, an increase in the board density was also observed when using more binder or more total raw material.

The bending properties of insulation blocks were also clearly influenced by the molding conditions, and could be correlated to their densities (Fig. 1 for flexural strength at break and Fig. 2 for elastic modulus). Indeed, the higher the insulation block density, the higher its mechanical properties. The effect of formulations on the bending properties can be also clearly underlined. For example, the AX formulations (extrusion-refined material with longer fibers plus low binder content) revealed the highest values regarding the flexural strength at break and the elastic modulus when the insulation block density was under 200 kg/m^3. On the contrary, the BZ formulations (extrusion-refined material with shorter fibers plus high binder content) gave the lowest curve of bending properties versus density.

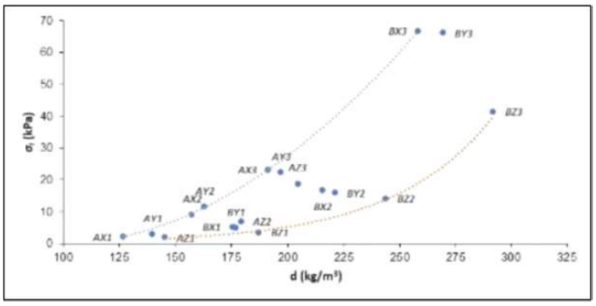

Fig. 1: Flexural strength at break of the eighteen insulation blocks, as a function of their density.

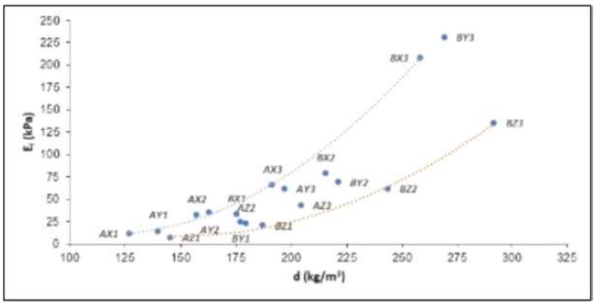

Fig. 2: Elastic modulus of the eighteen insulation blocks, as a function of their density.

Similarly, the thermal conductivity of insulation blocks depended on the molding conditions, its increase being observed progressively with increasing density (Fig. 3). In parallel, the thermal resistance was reduced (Tab. 4).

In conclusion, the insulation blocks that revealed interesting properties for both thermal insulation and mechanical behavior were obtained from the A extrusion-refined material (consisting of longer fibers) and an intermediate starch-based binder content (15%). The AY2 insulation block (163 kg/m^3 density) presented a good compromise between insulation performance (62.3 mW/(m.K) thermal conductivity, corresponding to a 0.80 (m^2.K)/W thermal resistance for a 5 cm thickness) and mechanical properties (11.4 kPa flexural strength at break and 34.4 kPa elastic modulus), the latter being sufficient for both handling and cutting.

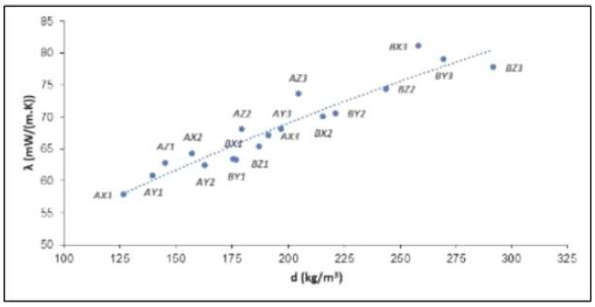

Fig. 3: Thermal conductivity at 25 °C of the eighteen insulation blocks, as a function of their density.

An insulation block was also successfully produced through compression molding using milled straw (Fig. 4). Molded under 87 kPa applied pressure and from a mixture made of 250 g milled straw and 44.1 g starch-based binder (i.e. 15% in proportion to the sum of the masses of straw and binder, or 17.6% in proportion to the only straw mass), this nineteenth insulation block was thinner (3.5 cm thickness instead of 5 cm for blocks made from extrusion-refined straws). It revealed a 155 kg/m^3 density and a 55.6 mW/(m.K) thermal conductivity, corresponding to a 0.90 (m^2.K)/W thermal resistance for a 5 cm thickness. Thus, it was slightly better thermal insulator in comparison to the AY2 block made from the A extrusion-refined material. In addition, its bending properties were far superior, i.e. 64.5±2.9 kPa for flexural strength at break and 2.1±0.4 MPa for elastic modulus. Because fiber bundles inside milled straw were much bigger than inside extrusion-refined materials, this contributed to a reduced surface area per unit weight of crushed material. Thus, the binder added in that case at an amount of 17.6% (in proportion to straw mass) surely allowed complete wetting of the fibers, resulting in an improved cohesion. As for the AY2 material, this optimal block from milled straw could also be used for the thermal insulation of buildings, including the filling of walls, interior partitions, etc.

Fig. 4: Photograph of raw straw, milled straw and insulation block from the latter (from left to right).

For future work, the resistance of these building insulation materials to fire, rodents, pests, and fungi should be investigated to ensure the preservation of their properties of use over time. An improvement in their water resistance will also need to be considered.

Tab. 4: Density, heat insulation and bending properties of insulation blocks.

Insulation block	d (kg/m^3)	λ (mW/(m.K))	R ((m^2.K)/W)	σ_f (kPa)	E_f (kPa)
AX1	126.9±1.0	57.8±2.2	0.866±0.034	2.1±0.5	11.2±1.8
AX2	157.3±1.5	64.3±1.0	0.778±0.012	9.0±2.5	31.9±5.2
AX3	191.3±2.3	67.0±1.8	0.746±0.020	23.1±3.8	65.1±8.2
AY1	139.7±0.9	60.8±1.0	0.823±0.013	2.8±0.2	13.7±0.6
AY2	163.0±0.4	62.3±1.3	0.802±0.017	11.4±2.3	34.4±2.6
AY3	197.0±1.2	68.0±1.4	0.735±0.015	22.2±0.9	61.1±3.3
AZ1	145.5±2.8	62.8±0.5	0.797±0.006	1.7±0.3	7.0±0.7
AZ2	179.6±2.7	68.0±2.3	0.735±0.025	6.9±0.8	22.2±3.1
AZ3	204.5±1.2	73.5±1.9	0.680±0.018	18.7±1.2	42.7±1.9
BX1	175.5±1.2	63.3±1.4	0.789±0.017	5.1±0.3	32.6±4.7
BX2	215.5±4.5	70.0±1.7	0.714±0.017	16.7±1.0	78.4±3.0
BX3	258.2±2.5	81.0±2.2	0.617±0.017	66.6±7.2	208.1±27.9
BY1	177.1±4.5	63.3±2.6	0.791±0.032	4.8±0.2	24.3±1.4
BY2	221.2±1.7	70.5±1.0	0.709±0.010	15.8±0.3	68.8±2.4
BY3	269.4±6.3	79.0±4.7	0.633±0.038	66.0±1.6	230.7±8.0
BZ1	187.2±3.7	65.3±1.5	0.766±0.018	3.4±0.5	20.3±1.9
BZ2	243.6±0.7	74.3±1.2	0.673±0.011	13.9±1.8	61.3±6.4
BZ3	291.8±1.6	77.7±0.6	0.644±0.005	41.2±4.6	135.2±7.9

4 CONCLUSION

New thermal insulation blocks were manufactured from coriander straw. All materials were cohesive mixtures of a starch-based binder and fibers from straw. The binder contributed to the board cohesion, and entanglement of the fibers acted as reinforcement. The operating conditions (i.e. straw mechanical pretreatment, binder content, and straw mass) had an important influence on board density, and on mechanical and heat insulation properties, the density varying from 127 to 292 kg/m^3. The heat insulation properties improved with decreasing density. From the A extrusion-refined straw, a board containing 15% starch-based binder (163 kg/m^3 density) was a good compromise between mechanical and heat insulation properties (62 mW/(m.K) thermal conductivity). The latter were even better when starting from milled straw (7.5 mm sieve): 155 kg/m^3 density, and only 56 mW/(m.K) thermal conductivity. Placed in walls and ceilings, such insulation blocks could be used as thermal insulation in the construction industry. The heat insulation capacity of the bulk materials was even better, especially for the A extrusion-refined straw (47 mW/(m.K) thermal conductivity), thus allowing their use as loose fill in attic spaces for the thermal insulation of houses.

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