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Thermal Characterization of Typha-Lime-Starch Thermal Insulation Panels

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Abstract

This study deals with the thermal characterization of thermal insulation panels made from typha, lime and starch. The objective is to assess how the progressive substitution of part of the lime by starch affects the thermal properties of the panels. Six formulations were prepared with a constant typha content of 40%. The starch proportion varies from 0 to 25%, in steps of 5%, replacing part of the lime. Thermal conductivity and thermal effusivity were determined by the asymmetric hot-wire method and the asymmetric hot-plane method, respectively. The results show a progressive decrease in thermal conductivity as the starch proportion increases, from 0.0795 $W \cdot m^{-1} \cdot K^{-1}$ for the starch-free reference sample to 0.0700 $W \cdot m^{-1} \cdot K^{-1}$ for the sample containing 25% starch. At the same time, thermal effusivity decreases from 517.44 to 493.11 $J \cdot m^{-2} \cdot K^{-1} \cdot s^{-1/2}$. Density varies only very slightly, from 0.3733 to 0.3753 $g \cdot cm^{-3}$. The progressive incorporation of starch is therefore associated with a modest improvement in the measured thermal performance.

Keywords

Typha, Lime, Starch, Thermal Insulation Panels, Thermal Conductivity, Thermal Effusivity

1. Introduction

Improving the energy efficiency of buildings requires thermal insulation materials that are accessible, inexpensive to produce, durable and able to limit heat transfer. In this context, typha, a freshwater aquatic plant with low thermal conductivity, has properties that could be exploited for thermal insulation.

Several studies have already demonstrated the potential of typha in construction, particularly in the form of insulating materials or panels. However, choosing

a binder that provides sufficient cohesion while preserving good thermal insulation properties remains a key issue. Lime was chosen as the base binder because of its ability to ensure the cohesion of the material, while wheat starch, a renewable resource with adhesive properties, is progressively introduced to replace part of the lime. This substitution aims to improve the cohesion and mechanical strength of the insulation panels.

This work investigates the effect of this substitution of lime by starch on the thermal properties of panels made from typha, lime and starch. Six samples were produced and studied: the typha content was kept constant at 40 wt%, while the starch proportion was progressively increased from 0% to 25%, replacing part of the lime. Thermal conductivity was determined by the asymmetric hot-wire method and thermal effusivity by the asymmetric hot-plane method.

2. Material and Method

2.1. Typha

2.1.1. Description

Typha australis (or *Typha domingensis*), known in French as massette or quenouille and in English as cattail, bulrush or reedmace, is an aquatic plant of the Typhaceae family found in tropical, subtropical and Mediterranean wetlands and aquatic environments [1]. *Typha australis* belongs to the spermatophytes (monocotyledonous angiosperms, commelinid clade), to the order Poales and to the family Typhaceae [2]. Typha generally grows along rivers, backwaters, lakes and canals, in water no deeper than 1.5 m. It is a perennial plant that can reach 3.5 m or even 4 m in height [1].

Typha produces seeds at maturity. The inflorescence is a spike 15 to 20 cm long, brown when mature. Inside the spike, the flowers are very numerous and tightly packed. Flowering peaks from April to June, *i.e.* when the days are longer and warmer. *Typha australis* is a herbaceous monocotyledon with a fibrous rhizomatous root system (**Figure 1**). Each lateral rhizome can produce one or more stems, which leads to very rapid spread of typha when conditions are favourable. Typha can survive relatively short periods (4 to 6 days) in an anaerobic environment [1]. **Figure 2** is an example of a typha plant.



Figure 1. Typha rhizomes.



Figure 2. Typha plants.

2.1.2. Physicochemical Properties of Typha

Microstructural analysis shows that typha leaves consist of distinct sections with porous walls, finely subdivided into smaller zones filled with a finely porous material (aerenchyma). For the same loading level, the geometry of the voids has a significant influence: the larger the voids between the fibres of the sample, the higher the heat transfer coefficient [3]. The thermal conductivity of typha depends on its density: it is 0.04 $W \cdot m^{-1} \cdot K^{-1}$ for a density of 58 $kg \cdot m^{-3}$ [3].

Plant fibres such as typha are natural composite materials. Apart from cotton, most plant fibres are composed of cellulose, hemicellulose, lignin, waxes and some water-soluble compounds, cellulose, hemicellulose and lignin being the main constituents [4]. The chemical characteristics of typha mainly indicate the plant's suitability and potential uses [1]. Typha tolerates salinity below 2% [2].

2.1.3. Impacts of Typha

The negative impacts of typha explain why many researchers, government programmes and non-governmental organisations are interested in the plant and its properties, with a view to taking advantage of its rapid proliferation. The Diama dam, which now prevents saltwater intrusion, has created favourable conditions for the expansion of typha [1]. Typha proliferates in cultivated plots and invades irrigation and drainage canals, which disrupts the proper functioning of hydraulic infrastructure. Water flows are slowed, water levels are raised and the risk of flooding during high-water periods (rainy season) has increased.

The spread of typha can obstruct canoe navigation and fishing by considerably reducing the open water surface [2]. Typha also provides a favourable habitat for granivorous bird populations [5].

One of the most worrying negative environmental effects of Typha domingensis reported in the literature is the loss of biodiversity. Dense, extensive typha stands can have a major impact on the overall water balance because of considerable evapotranspiration losses. This may have ecological consequences for the region, but should also be considered from a socio-economic standpoint in the overall management of water resources [6].

However, typha does not only have negative effects on the environment. It is

remarkably tolerant to heavy metals such as nickel, lead, zinc and cadmium, and is therefore used to restore polluted wetlands. It may also absorb part of the mineral elements (nitrogen, phosphorus) discharged with drainage water, thus helping to purify it. This may seem paradoxical, since typha stands are locally known to promote eutrophication, owing to the slowing of water flow, but probably also to the growth of associated algae or other aquatic species such as Ceratophyllum, which consume the oxygen in the water [6].

2.1.4. Uses of Typha

Control and valorisation are two complementary actions serving the same objective: managing the invasion of *Typha australis* [2]. Since the 1990s, faced with the uncontrolled spread of typha in the Senegal River delta, many companies from various sectors have explored typha processing and the feasibility of productive investments. Among these initiatives, only small-scale experiments have actually materialised, notably in fuels, construction and handicrafts [6], as well as in other fields:

Biomass potential: over a distance of 40 km along the Senegal River, the useful dry biomass amounts to at least 200,000 tonnes [2];

Local handicrafts: nets made from leaf fibres; mattresses, mats, fences and baskets made from the leaves; and typha flakes [3].

Figure 3 below shows some uses of cattail in crafts.

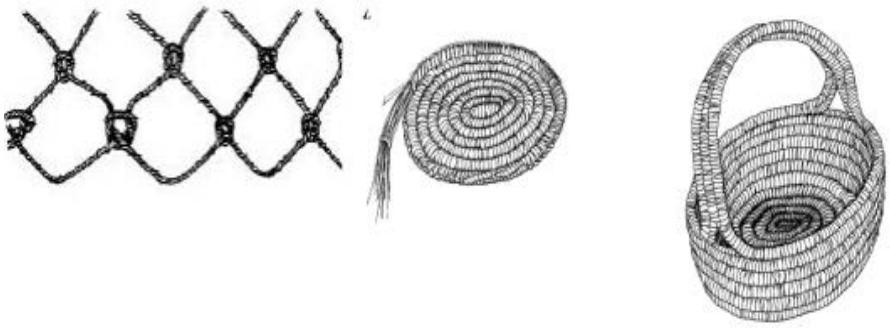

Figure 3. Handicraft objects made from typha.

- Food: the young white-to-green shoots were eaten raw or boiled by Aboriginal populations in south-western Australia. The roasted rhizomes were their staple food [3];
- Medicine: for some populations, *Typha* sp. has many therapeutic properties. For example, according to Hartwell (1967), cited in Duke (1983), the roots of *Typha angustifolia* were used as a remedy for tumours in Chile and Argentina [2].
- Industry: cellulose extracted from the leaves was used to make paper (Romania, 1920), and the leaves provided textile fibres (9 to 16 t/ha, compared with 1 t/ha for cotton). A process for spinning seed fibres (1 to 1.5 cm long) was patented in Germany in 1941. In the United States, some 1000 t of seed fibres were used as stuffing in life jackets. In France, a process was developed in 1948 to produce

ethyl alcohol from chopped leaves; the residue can be used to produce fertiliser and cellulose. In the United States, around 1945, the seeds were used to make an edible oil and as a raw material for varnish. The rhizomes were used to produce flour and pure starch, the latter also serving to produce ethyl alcohol [3];

- Energy: typha has an attractive calorific value, about one third of that of fuel oil. In other words, a yield of 22 t DM/ha/year is equivalent to 8000 litres of fuel oil. Typha could be a significant renewable energy source for households in the form of briquettes similar to charcoal briquettes [2];
- Construction: typha can be used in construction on its own or combined with other materials such as clay. Typha straw could thus easily be valorised on a large scale. There is a growing market in Europe that suggests export opportunities for typha-based building materials. Combined with clay, typha can be used to manufacture a wide range of building materials. For example, stems cut to different sizes can be agglomerated with clay to produce cork-like materials; it is also possible to produce materials with improved load-transfer and thermal conductivity characteristics. Recent knowledge indicates that, owing to its particular characteristics, typha can provide a range of building materials comparable to those made from wood (beams, load-bearing elements, boards, insulation panels, etc.). This material is of interest not only for housing but also for prefabricated construction, from interior fittings to doors and furniture. Using a suitable adhesive (for example Sol-Gel, a sodium silicate-based adhesive enhanced by nanotechnology), a non-polluting material is obtained. **Figure 4** shows construction materials made from cattail.

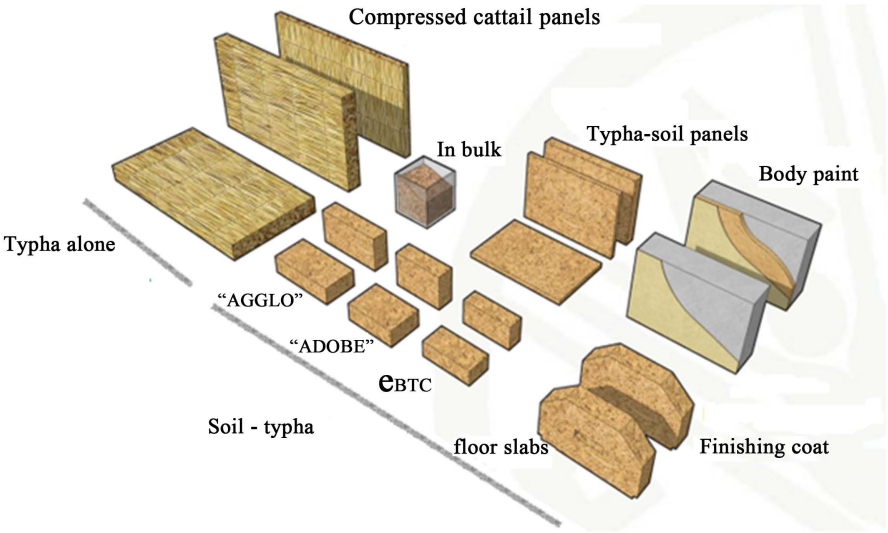

Figure 4. Various typha-based building materials [7].

2.2. Lime

Lime, in its various forms, was one of the first binders used by humankind. The Chinese, Egyptians and Mayans built durable structures with lime-based mortars. In the Middle Ages, lime was very widely used (mixed with crushed tiles or bricks),

and it remained in common use until the middle of the 19th century. At that time, there were thousands of small lime kilns in Algeria, some remains of which still exist [8].

Lime refers to calcium oxide and/or hydroxide, or calcium and magnesium oxide and/or hydroxide, produced by the thermal decomposition (calcination) of naturally occurring calcium carbonate (e.g. limestone, chalk, shells) or naturally occurring calcium magnesium carbonate (e.g. dolomitic limestone, dolomite) [9].

Quicklime: obtained by firing limestone ($CaCO_3$) or dolomitic rocks (a combination of $CaCO_3$ and $MgCO_3$). Calcination releases CO_2 and produces CaO and/or magnesia (MgO) [8].

Slaked lime: obtained from quicklime by slaking, the operation that converts quicklime into slaked lime. Slaking is accompanied by an increase in volume (bulking). It results from a change in molecular structure and the formation of needle-shaped lime hydrate crystals. At the time of use, the lime must be fully hydrated; otherwise, destructive swelling may occur in the structure.

$$CaO + H_2O \rightarrow Ca(OH)_2$$

Slaking is achieved by adding water and can be carried out by several methods: spontaneous slaking, manual sprinkling and the traditional immersion method. These three methods yield powdered lime. Slaking can also be performed by fusion [8].

In terms of setting mechanism, a distinction is made between air lime, which sets only through contact with atmospheric carbon dioxide (CO_2), and hydraulic lime, which sets in the presence of water.

2.3. Starch

Starch granules are synthesised in cellular organelles, the plastids [10]. Starch, considered the second most common renewable polysaccharide after cellulose, is a highly abundant natural carbohydrate polymer. It consists of long chains of glucose units linked by glycosidic bonds, and each macromolecule carries at its end a reducing group (hemiacetal/aldehyde) capable of chemical interaction [11].

Starch is the main energy source for animal life, and therefore for humans. Starches have always been used in human food, both domestic and industrial. Outside food applications, starch is mainly used in the paper and board industries, although over the past decade there has been strong demand from the chemical and pharmaceutical sectors. The various characteristics of starch give it many applications in sectors such as adhesives and glues (corrugated board manufacturing, etc.), textiles (warp sizing and fabric printing), the chemical industry (fermentation substrate, direct substrate as an excipient, binder, coating agent, active ingredients such as sorbitol, cyclodextrin preparations, etc.), construction (drying regulator, binder, antifreeze, concrete set retarder, etc.), lubricants and agrochemical substrates. Starch comes mainly from maize, followed by potato, wheat and rice [10].

Its abundance and adhesive properties make starch a particularly attractive renewable organic resource for the design of low-carbon binders.

3. Thermal Characterization Methods

As it can be difficult in some cases to obtain two samples with identical composition and water content, asymmetric setups with a single sample were preferred for characterising the materials.

3.1. The Asymmetric Hot Wire Method

This method is mainly used to estimate the thermal conductivity of samples measuring $10 \times 10 \times 3$ cm^3.

The hot wire setup consists of creating a groove in the polystyrene block in order to insert a resistive wire, to which a thermocouple is glued in the centre. The sample to be characterised is placed above the resistive wire, and the assembly is completed by a second polystyrene block positioned above the sample [12] The schematic diagram is shown in **Figure 5**.

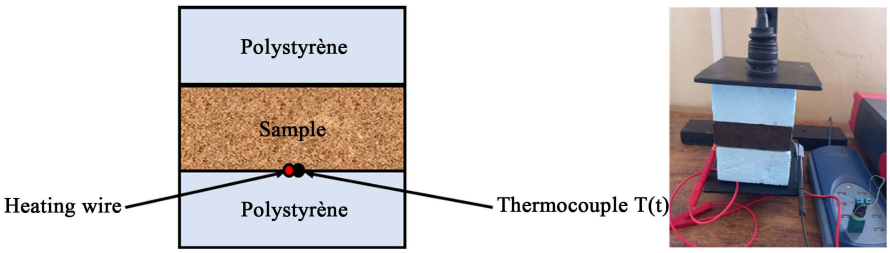

Figure 5. Schematic diagram of the asymmetric hot wire method with a semi-infinite sample [12].

A constant current I is passed through the heating element, and the temperature change is recorded at 0.1 s intervals. The inverse Laplace transform is performed using the Matlab program "invlap" based on De Hoog's algorithm. The Matlab program "leasqr", based on the Levenberg-Marquardt algorithm is used to estimate the conductivity value [13].

3.2. The Asymmetric Hot-Plane Method

The hot plate method is based on using a flat probe, with dimensions matching those of the sample ($10 \times 10 \times 3$ cm^3), placed on a deformable insulator (polystyrene). A thermocouple, made of two thin wires, is attached to the center of the probe on the side that contacts the insulator. The sample to be characterized is then placed on top of the probe, and the setup is completed with a second block of polystyrene, positioned above the sample [14]. The basic diagram of the hot plate method is shown in **Figure 6**.

A constant current is passed through the heating element, and the temperature change is recorded at 0.1s intervals. The thermal effusivity of the sample is estimated using the complete method [16].

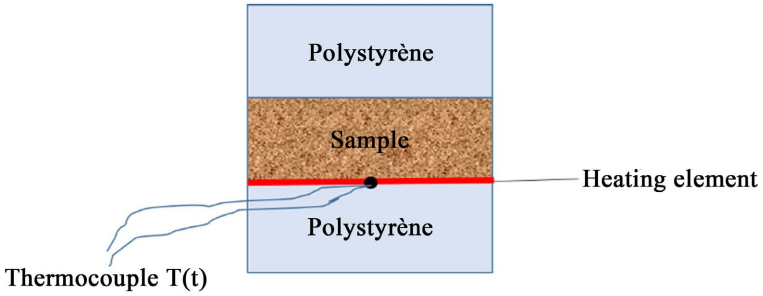

Figure 6. Schematic diagram of the asymmetric hot plate method with a semi-infinite sample [15].

4. Sample Preparation

4.1. The Equipment

During this sampling, the equipment used is made up of:

- A series of sieves with diameters ranging from 80 µm to 2000 mm, allowing for the determination of the particle size class of typha fibers and for sifting the slaked lime.
- A removable wooden mold greased with oil before each casting. The dimensions for each sample are: $10 \times 10 \times 3$ cm^3, which is a volume of 300 cm^3.
- An electronic scale
- An electric mixer
- Gloves and masks as personal protective equipment.

4.2. Preparation of the Raw Materials

4.2.1. Typha

The typha used in this study was harvested at the Technopole of Pikine, Dakar. It was dried and then ground with a plant shredder.

The ground material was then sieved to determine the particle size class of the typha particles. The results show that the particles pass through the 2000 µm (2 mm) sieve and are retained by the 250 µm sieve. The corresponding particle size class is therefore 250 µm < d < 2000 µm.

Figure 7 shows an image of crushed typha.



Figure 7. Ground typha.

4.2.2. Lime

The lime used is commercially available quicklime. It was slaked by sprinkling. After cooling, it was sieved to obtain a powder with a uniform particle size.

An image of quicklime and slaked lime in powder form is shown in Figure 8 and Figure 9, respectively.



Figure 8. Commercial quicklime.

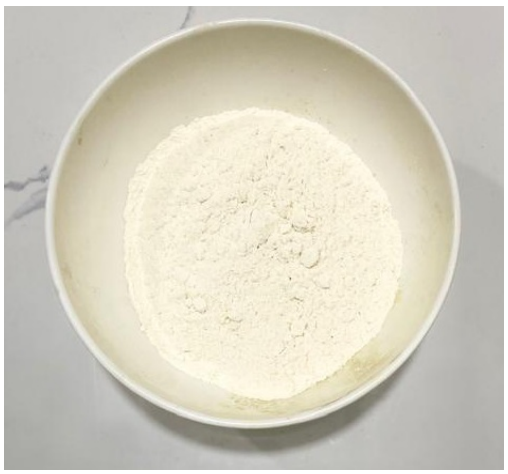

Figure 9. Powdered slaked lime.

5. Preliminary Tests

In general, low density favours the thermal insulation properties of porous materials. Experimental optimisation of the formulation by successive trials made it possible to determine the smallest quantities of each constituent needed to produce a 300 cm^3 sample.

- Typha content: the smallest mass of typha that, mixed with water, fills the target volume without using a mechanical press was determined by successive trials. This led to a typha mass of 42.5 g, *i.e.* a bulk density of 0.14 $g{\cdot}cm^{-3}$.
- Lime content: lime is the base binder of the panels. Successive trials were carried out to find the minimum mass of lime giving a sample cohesive and stable

enough to be handled and subjected to thermal characterization. Although a small amount of lime favours thermal insulation, enough must be used to prevent the samples from crumbling or disintegrating after drying. The selected quantity is 65 g of lime for 42.5 g of typha, *i.e.* 60% of the dry mass of the constituents; it represents a compromise between the minimum cohesion needed to handle the sample and the search for low density.

- Water content: the amount of water is a very important parameter of the formulation. Too little water makes the mixture difficult to homogenise, leading to poor cohesion and dry zones before moulding. Conversely, excess water causes significant shrinkage during drying, leading to slumping or deformation that compromises the dimensions of the sample. The amount of water selected experimentally to limit these two effects is 300 g, *i.e.* 2.8 times the total dry mass of typha and binder.
- Starch: wheat starch is absent from the reference sample, which consists only of typha and lime. It is progressively introduced to replace part of the lime, in steps of 5% from one sample to the next, while the typha mass is kept constant. The preliminary tests revealed early mould growth, even before demoulding, when the starch content reached 30% of the dry mass. To avoid this, the starch content was limited to 25% in the samples studied.
- Drying time: the drying time for the samples is at least 4 days:

- 1 day in the shade to limit surface drying and the early appearance of cracks;
- followed by one day in the sun with partial demolding, which involves removing the side walls of the mold;
- and finally, two days in the sun to have samples ready to be fully demolded.

6. Manufacturing Protocol

The samples were made following the following protocol:

- Well lubricate the mold with oil to facilitate demolding.
- After proper treatment and preparation, weigh dry inputs (typha, lime and starch) and measure the amount of water to be used.
- Mix and knead dry inputs well.
- Starch is added in its raw state without gelatinization. It is a component of the dry input mixture.
- Add the water gradually while continuing to knead until you obtain a homogeneous mixture.
- Move on to molding.
- The unmolding will be done after 4 days as described in the foreplay section

7. Sample Composition

Table 1 shows the composition of the samples studied.

Figures 10-13 show respectively the molding of the samples, the crumbling and sagging of a sample, the early appearance of mold, and the disintegration of a sample containing a small amount of lime.

Table 1. Composition of the samples studied.

Composition of the samples for thermal characterization/volume of each sample: 300 cm^3										
Sample	Typha		Lime		Starch		Water	Dry mass of constituents (g)	Mass after drying (g)	Density (g/cm^3)
	Mass (g)	wt%	Mass (g)	wt%	Mass (g)	wt%	Mass (g)			
E1	42.5	40%	65	60%	0	0%	300	107.3	112	0.3733
E2	42.5	40%	59	55%	5	5%	300	106.9	112.2	0.3740
E3	42.5	40%	54	50%	11	10%	300	107.3	112.3	0.3743
E4	42.5	40%	49	45%	16	15%	300	107.3	112.3	0.3743
E5	42.5	40%	43	40%	22	20%	300	107.3	112.4	0.3747
E6	42.5	40%	38	35%	27	25%	300	107.3	112.6	0.3753

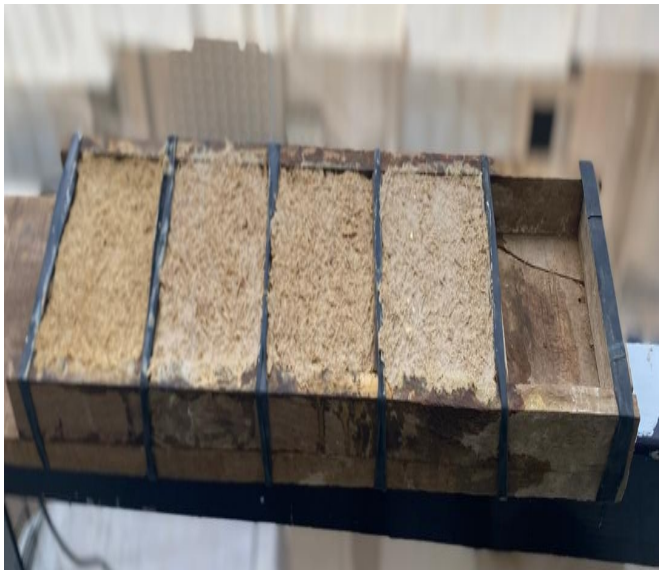

Figure 10. Molding of the samples.



Figure 11. Crumbling and slumping of a sample.

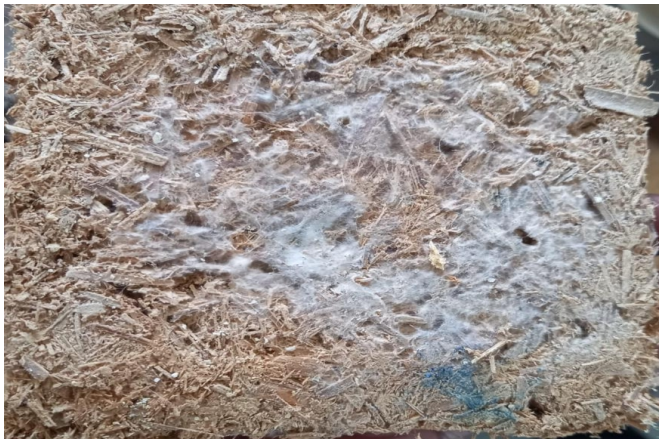

Figure 12. Early appearance of mold.

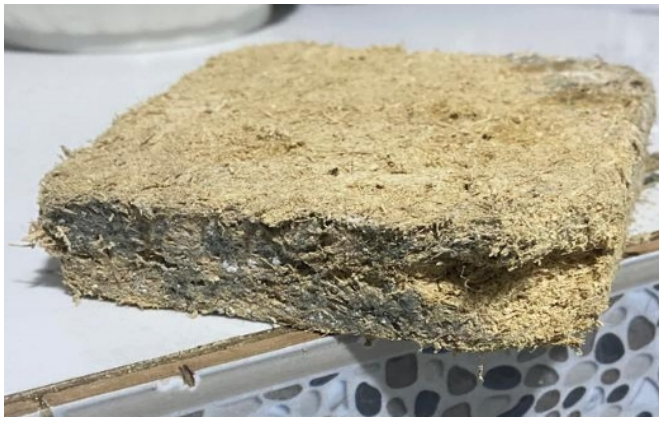

Figure 13. Disintegration of a sample with insufficient lime.

8. Measurements Results

The measurement results of the thermal conductivities and thermal effusivities of our samples are gathered in Table 2.

Table 2. Summary of thermal conductivity and effusivity values.

Sample	Typha		Lime		Starch		Density ($g \cdot cm^{-3}$)	Thermal conductivity λ ($W \cdot m^{-1} \cdot K^{-1}$)	Thermal effusivity E ($J \cdot m^{-2} \cdot K^{-1} \cdot s^{-1/2}$)
	Mass (g)	wt%	Mass (g)	wt%	Mass (g)	wt%			
E1	42.5	40%	65	60%	0	0%	0.3733	0.0795	517.44
E2	42.5	40%	59	55%	5	5%	0.3740	0.0769	510.32
E3	42.5	40%	54	50%	11	10%	0.3743	0.0743	504.32
E4	42.5	40%	49	45%	16	15%	0.3743	0.0714	498.03
E5	42.5	40%	43	40%	22	20%	0.3747	0.0703	495.33
E6	42.5	40%	38	35%	27	25%	0.3753	0.0700	493.11

Figure 14 shows an example of the experimental, theoretical thermograms, and

residuals obtained during the estimation of the thermal conductivity of sample E4, using the quadrupole model.

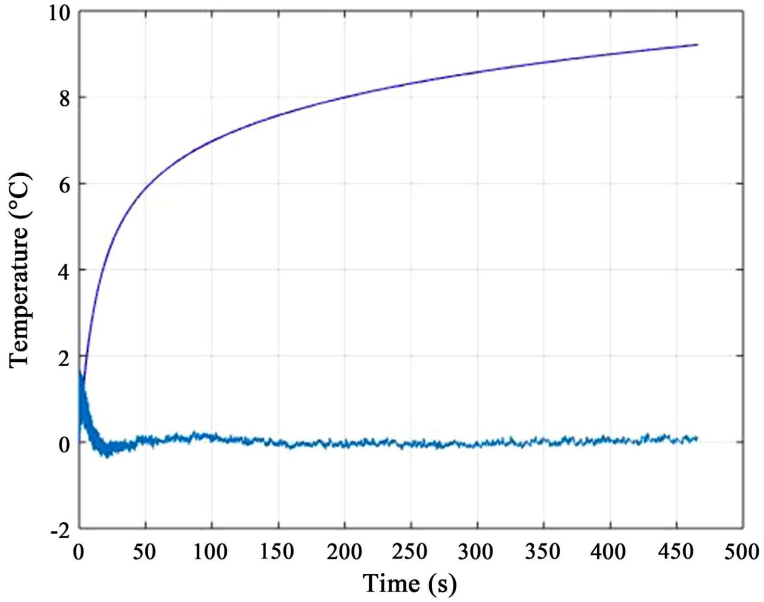

Figure 14. Model curve, experimental curve, and residuals obtained during an asymmetric hot-wire experiment with sample E4.

In this figure, the residuals remained centered and flat between 50 and 450s. So, the criterion of minimizing the squared deviations between the model curves and the experimental points is validated. The estimated conductivity values of our materials from the full model are therefore indeed valid.

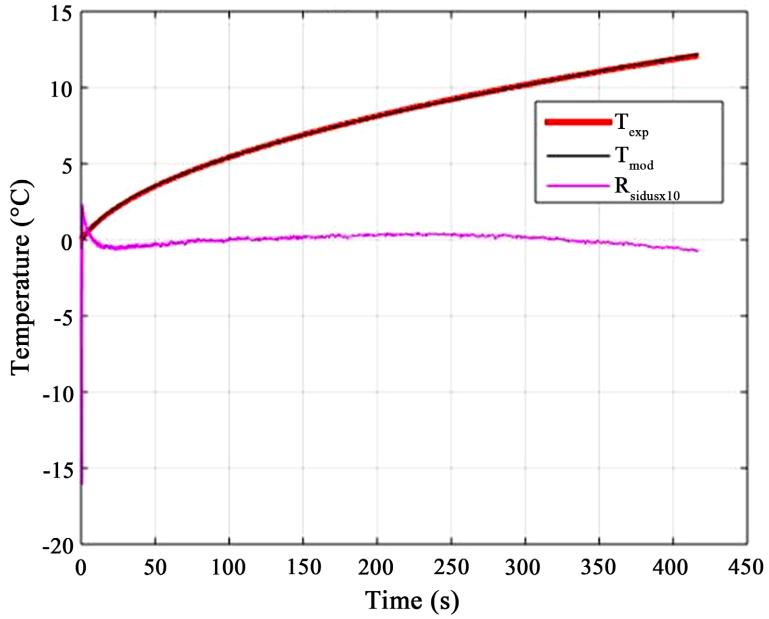

Figure 15. Model curve, experimental curve, and residuals obtained during an asymmetrical hot plate experiment with E4.

The model curves, experimental data, and residuals obtained by estimating the thermal effusivity of sample E4, using an asymmetric hot plate model from the Matlab program, are shown in Figure 15.

We notice that the model and experimental curves match very well up to 350 s. This shows the validity of the 1D model at the center of the sample. This finding is confirmed by observing that the residuals remain flat for 350 s. So, the thermal effusivity value is well estimated using the full model between 50 and 350 s.

Figure 16 and Figure 17 show, respectively, how thermal conductivity and thermal effusivity change depending on the starch content.

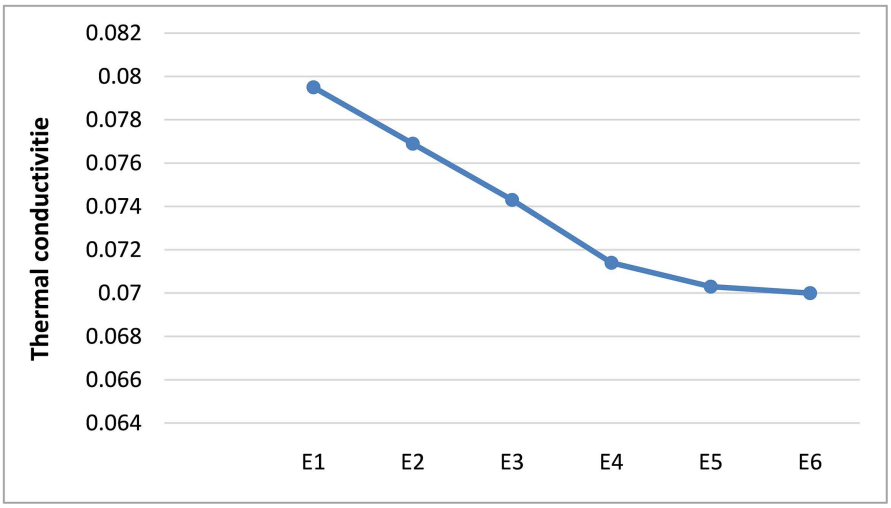

Figure 16. Thermal conductivity as a function of starch content.

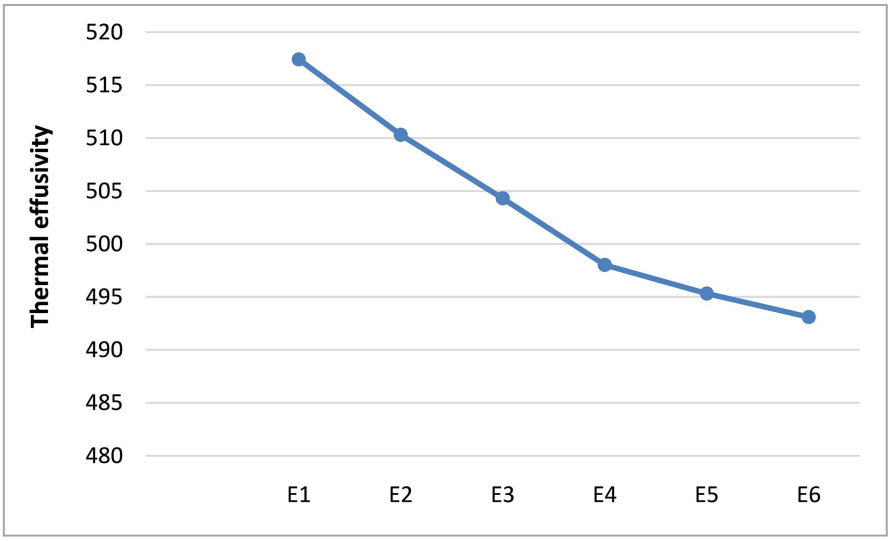

Figure 17. Thermal effusivity as a function of starch content.

9. Analysis and Discussion of the Results

Increasing the starch content from 0 to 25% leads to a progressive decrease in thermal conductivity, from 0.0795 to 0.0700 $W \cdot m^{-1} \cdot K^{-1}$, *i.e.* a reduction of 11.9%

compared with the reference sample. This decrease could be related to a change in the internal structure of the material (porosity, distribution of the binder around the particles) or to the fact that starch has a lower thermal conductivity than lime.

Although the density remains practically constant (from 0.3733 to 0.3753 $g \cdot cm^{-3}$), the thermal effusivity decreases from 517.44 to 493.11 $J \cdot m^{-2} \cdot K^{-1} \cdot s^{-1/2}$, *i.e.* a reduction of 4.7%. These trends show that incorporating starch is beneficial to the thermal insulation properties of typha-lime panels, even though the reductions in thermal conductivity and effusivity remain moderate.

10. Conclusions

This study assessed the thermal performance of typha-based insulation panels in which lime was progressively replaced by starch. The preliminary tests guided the formulation of panels combining typha with lime and starch. The results show low and relatively similar thermal conductivities for the different formulations, ranging from 0.0795 to 0.0700 $W \cdot m^{-1} \cdot K^{-1}$.

Under the conditions studied, partial substitution of lime by starch (up to 25%) leads to a moderate decrease in thermal conductivity (−11.9%) and thermal effusivity (−4.7%), without any notable change in density. Starch thus appears to be a co-binder compatible with the thermal insulation objective; investigating its effects on mechanical properties and durability (mould resistance) is a natural extension of this work.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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