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Pablo Lopez Hurtado, Antoine Rouilly, Virginie Vandebossche Maréchal,
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A review on the properties of cellulose fibre insulation

Pablo Lopez Hurtado ^{a, b, d, *}, Antoine Rouilly ^{a, b}, Virginie Vandebossche ^{a, b},
Christine Raynaud ^{a, c}

^a University of Toulouse INP-ENSIACET, LCA (Laboratoire de Chimie Agro-industrielle), 31030, Toulouse, France

^b INRA, UMR 1010 CAI, 31030, Toulouse, France

^c CATAR-CRITT Agroressources, 31077, Toulouse, France

^d Greenbuilding, 75001, Paris, France

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ABSTRACT

The building sector is constantly innovating in its use of materials with regards to sustainability. There is a need to use cost effective, environmentally friendly materials and technologies which lessen the impact of a construction in terms of its use of non renewable resources and energy consumption. Cellulose fibre insulation is an eco friendly thermal insulation material made from recycled paper fibres. It offers good thermal properties and has a low embodied energy. However due to lack of expertise in its application and properties, cellulose insulation is not widely used in comparison to more traditional insulation materials. The present paper reviews the available research on cellulose fibre insulation, its manufacture, installation, and performance. The paper focuses the physical properties of cellulose insulation, the environmental factors that affect these properties, and possible means of future innovation.

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* Corresponding author. Present adress: Laboratoire de chimie agroindustrielle, ENSIACET, 4 Allée Emile Monso, 31030, Toulouse, France.

E-mail address: pablo.lopezhurtado@ensiacet.fr (P. Lopez Hurtado).

Table 1

Embodied energy per kg of different insulation materials, data from Ref. [18].

| Insulation material | Embodied energy (MJ/kg) |
|------------------------|-------------------------|
| General Insulation | 45 |
| Cellular Glass | 27 |
| Cellulose | 0.94 3.3 |
| Cork | 4 |
| Fibreglass (Glasswool) | 28 |
| Flax (Insulation) | 39.5 |
| Mineral wool | 16.6 |
| Paper wool | 20.17 |
| Rockwool | 16.8 |
| Woodwool (loose) | 10.8 |
| Woodwool (Board) | 20 |
| Wool (Recycled) | 20.9 |

1. Introduction

Energy efficiency in buildings is an important factor in contributing to the reduction of greenhouse gas emissions. The building and construction sector accounts for 30%–40% of world wide energy consumption [47], with a large part belonging to the need to heat and cool buildings. It is with that in mind that many countries are looking to improve the energy efficiency of buildings with better insulation materials and technologies applied to the building envelope, with directives such as the European directive 2010/31/EU which states that new constructions in 2020 will have to consume 'nearly zero energy' [14].

The main role of thermal insulation materials in a building envelope are to prevent heat loss and provide thermal comfort for a building's interior. The factor that characterizes an insulation material's effectiveness is its thermal conductivity λ (measured in W/mK). The lower a material's thermal conductivity, the more effective it is as an insulator, thus requiring a thinner layer to provide the same interior temperature. Traditional insulation materials include glass fibre, stone wool, expanded polystyrene, and polyurethane foam. While these materials are efficient in maintaining thermal comfort to a buildings interior, they are made with non renewable resources and have a high embodied energy. Consequently, there is an increasing interest for alternative insulating materials that come from renewable or recycled fibres. Natural fibres such as jute, flax and hemp have shown to be suitable alternatives to mineral insulation and are the subject of numerous research projects [23].

One such material is cellulose fibre insulation (CFI). Comprising mostly of recycled paper fibres, cellulose is increasing in popularity due to its eco friendly nature and favourable thermal and acoustic properties. Even amongst other insulation materials CFI presents some of the lowest embodied energy per kg of material, as is shown in Table 1 [18]. Despite growing interest, Cellulose and other natural insulation materials still only represent a low percentage of total European market share [29]. This is partly due to the fact that cellulosic fibres, while having favourable thermal properties, still have some disadvantages compared to traditional fibres. Some factors such as its high hygroscopicity, potential for combustibility and for fungal growth can limit CFI from having a more widespread usage in construction and renovation projects. Proper knowledge of these limits, their causes and their effect on the properties of the insulation material are necessary to ensure that sustainable

materials such as CFI become more common in the building sector and thus help contribute to the reduction of the environmental impact of construction and renovation projects.

The aim of this paper is to review the available information regarding cellulose fibre insulation (CFI). First the general context on CFI is given, including its background and main methods of fabrication and installation are presented. The available research on the properties of CFI is exposed, as well the different conditions that affect these properties. Finally the paper comments on possibilities for future investigation on the material and improvements of its properties.

2. A background on CFI

2.1. Composition

Cellulose fibre insulation is mainly composed of ground paper fibres treated with inorganic additives that act as fire retardants and mould growth inhibitors. Its consistency is similar to that of cotton wool. The source material for the cellulose fibres are usually recycled newspaper, coming from either unsold or recovered papers. Newsprint is generally manufactured by mechanical pulp. Recycled newsprint or chemical pulp could also be incorporated. As with most lignocellulosic fibres, newsprint is comprised of a mix of cellulose hemicelluloses and lignin. Unlike chemical pulping, mechanical pulping results in little removal of lignin content. Mineral and organic additives, such as kaolins, china clay or cationic starch are also incorporated into the paper pulp in order to improve such properties as paper opacity, moisture retention, and strength. The inks typically used in the paper are produced from inorganic carbons, with the chromatic inks coming from organic pigments. The average proportions of the main components in newsprint and office paper (chemical pulp) are presented in Table 2 [50].

2.2. Production

As a final product, cellulose insulation can come in two forms: as a prefabricated panel, in which the cellulose fibres are moulded with polyester or a similar binder or, more commonly, the loose fibres are sold in bulk form to be manually applied on attics, ceilings, or walls. The first use of cellulose fibre as an insulation material can be traced back to 1919 in Canada [40], but it was until the 1950s that commercial cellulose insulation products became commercially available in the US, where it was mostly used for attic retrofitting. CFI surged in popularity in the US in the 1970s due to an increased interest in energy performance following the American oil embargo of 1973.

In a typical production process of CFI (see Fig. 1), newspaper arrives in bulk to the manufacturer and is then sorted to remove any foreign objects. Items such as clips and plastics are removed, but also low quality or humid paper is also sorted. The newsprint passes through a feeding conveyor (1) then is torn to smaller pieces that are between 2 and 4 cm in diameter in a shredder (2). The fibres then pass through a cyclone separator (3) in order to remove any remaining staples or other metallic elements. The fines from the shredded paper are blown through a filtering unit (4). The material then goes through a fiberizer (5) which uses high

Table 2

Average component proportions of newsprint and office paper, [50].

| | Cellulose % | Hemicellulose % | Lignin % | Extractives % | Proteins % | Ash % |
|--------------|-------------|-----------------|----------|---------------|------------|-------|
| Office paper | 67.4 | 13 | 0.93 | 0.7 | 0.31 | 11.6 |
| Newsprint | 48.3 | 18.1 | 22.1 | 1.6 | 0.44 | 2 |

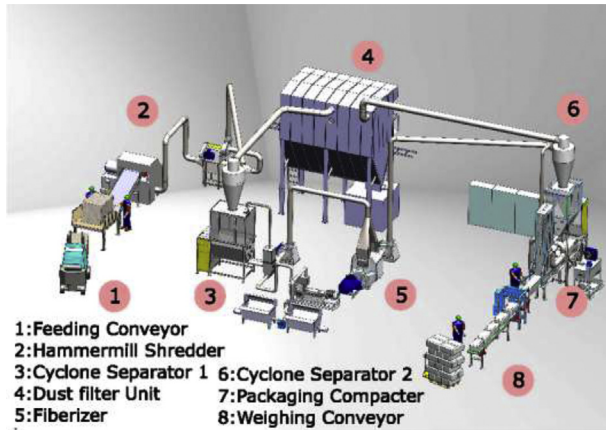


Fig. 1. Example of a typical manufacturing process of CFI, adapted with permission from Ref. [24].

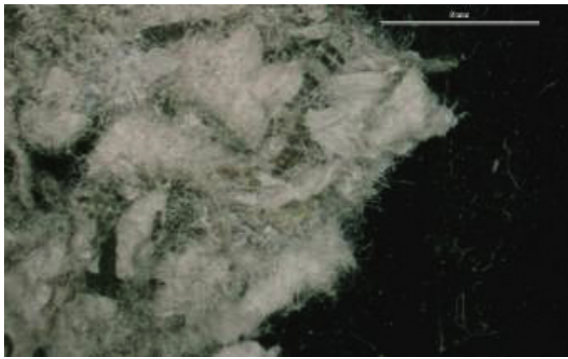


Fig. 2. Microscopic scan of cellulose fibres, 10X magnification.

pressured air to reduce the paper into low density cotton like flakes, as shown in Fig. 2. It is in this stage that the powdered additives are dispersed and mixed with the fibres. The additives used are typically a mix of borax and boric acid, with a dose of around 15%–20% of the mass of cellulose fibres. A second cyclone separator (6) then removes the fines created from the fiberizer. In the final stage of the process, the fibres are filled in bags and then mechanically compacted (7) into 3 times its normal density (around 130 kg/m^3), in order to reduce transport costs. The bags are then weighed (8) and bundled into pallets and transported to supplier or directly to construction sites.

2.3. Installation of CFI

There exist two main methods of applying CFI. Depending on the desired properties, CFI can either be installed via the “loose fill” or the “wet spray” method.

In the loose fill method the cellulose fibres are installed with specific pneumatic blowing equipment. The compacted cellulose is fed to the blower which separates the fibres which then pass through the blowing system. The CFI is then delivered via air pressure into closed wall/roof cavities or attics through a hose. When cellulose is installed as “dense pack”, sheets of netting are put in place over wall cavities. The cellulose is then blown into the cavities between studs at a higher density than loose fill, with the netting supporting the fibres. One of the disadvantages of this method is that settling of the material may occur over time, which decreases the insulation's effectiveness, forming voids that cause thermal bridging in a

building envelope [7].

The wet spray technique is mostly used in open wall wood cavities separated by studs. It uses the same blowing equipment as with loose fill CFI, but a separate pump is used to spray water simultaneously as the material is being blown with the cellulose in order to improve the adherence of the fibres. After projection the excess material is removed via a motorized wall scrubber and the excess moist material is reintegrated in the blower. The water/CFI mass ratio used in this process is typically around 40%–60%. Adhesives, either mixed with the water or dispersed within the fibres could also be used [8]. The main disadvantage of this method is that drying times may vary, depending on the thickness and ambient conditions of installation [37]. A variant of the wet spray method is known as “stabilized” cellulose where a smaller dosage of water (less than 20% in mass) is used to prevent dust and settling in horizontal applications.

3. Properties of CFI

3.1. Density and settling

When dealing with loose fibres as an insulating material, it is important to distinguish between the “blown” density and the “design” density of the fibres. The blown density is the declared density after installation in vertical or horizontal applications, and the design density (which takes settling into account) is determined via impact testing and/or cyclic humidity testing. Impact testing consists of subjecting the loose cellulose samples to a series of vibrations. In cyclic humidity tests, the samples are subjected to periodic variations of relative humidity [1]. One of the first studies regarding the settling of CFI was done by [2]. Their study found an average blown density of 34.8 kg/m^3 for horizontal applications. The average loss in thickness from settling was 21.5% wherein 10.5% was from drop impact tests and 11% was from cyclic humidity testing. The design density can be then calculated using by multiplying a factor which takes into account both types of settling:

$$D_d = (100 / (100 - S)) D_i \quad (1)$$

Where D_d is the design density, D_i is the installed density, and S is the sum of both the settling from drop impact tests and cyclic humidity testing.

The previous values give a design density factor of $1.27 D_i$, thus an average design density of 44.4 kg/m^3 for horizontal applications. It was also found that the dosage of fire additives increases density linearly, although the type of additive or mix thereof has little influence on final density. A survey of 38 houses in six Canadian cities [52] found the actual settling density, a year after installation, to be averaged to 11.1%, with a range of 8.3%. The study suggests that the blown density measured in laboratory be first multiplied by a factor of 1.074 to account for differences between lab and building site measurements, and then calculated with Eq. (1) using an average settling of 11.1%.

For horizontal applications the compressibility of loose fill CFI can make its density vary widely. One early study by [3] shows installed density varying between 50 and 90 kg/m^3 . It was recommended to increase density by 10% after filling the wall cavity in order to prevent settling, with a minimum density of 57 kg/m^3 . A series of works by Rasmussen [31–34] have produced an approach which allows to analytically determine the optimal installed density of loose fill CFI that prevents settling in wood frame walls. The method takes into account the dynamic mechanical behaviour of a typical insulated wall cavity that is subjected to a cyclical variation in humidity in order to determine the density required for the fibres to lose volume. The volume stable

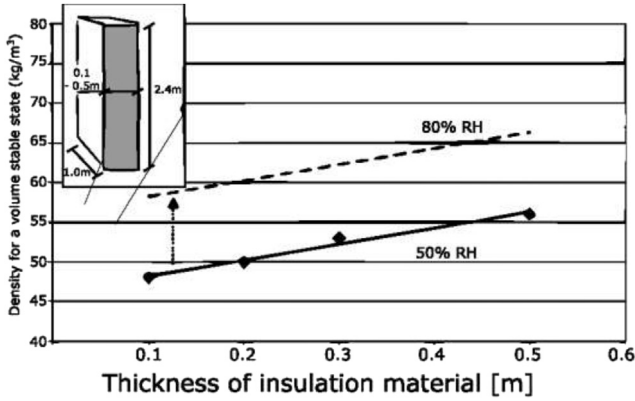


Fig. 3. Calculated minimal density for settling prevention of loose fill CFI in a wall under static humidity conditions (50% and 80% RH), as a function of thickness, top left shows the dimensions of the wall cavity [33].

density of CFI was determined through the study of the creep, coefficient of friction, and horizontal stress ratio testing of loose fibres. As an example, the minimum density to prevent settling with CFI a 2.4 m tall, 0.1 m thick and 1 m wide gypsum wall at 25 °C and 50% RH was found to be 48 kg/m³. This value increases linearly with wall thickness and relative humidity (Fig. 3). Dynamic conditions were also tested, where humidity varied from 50% to 80%. In this case a 2.3 m high, 0.198 m thick and 0.495 m wide gypsum board cavity was calculated to require a density of 62.3 kg/m³ to prevent settling. This was later confirmed experimentally with a CFI filled cavity with a density of 62.7 kg/m³ where settling was not observed.

For wet spray applications, the dry density of CFI has been shown to increase linearly with installed moisture content, ranging from 39.6 with 40% moisture content to 71.3 kg/m³ with 100% moisture content [37]. If installed properly, wet spray cellulose does not settle. For stabilized cellulose, an initial moist density of around 45 kg/m³ gets reduced to around 38 kg/m³ after drying. Settling with the stabilized cellulose method in attics was found to be reduced to around 5% [16].

3.2. Thermal properties

Although the typical value for CFI's thermal conductivity is around 0.040 W/mK, its properties and performance can vary slightly depending on manufacturing and method of installation. The work of Ref. [22] has shown that a difference in the source newsprint quality can affect thermal performance. In their study, CFI samples coming from US and Korea were measured through heat flow meters, in accordance with ASTM C 518. By comparing CFI from both countries, the study found that the Korean fibres that are shorter due to having gone through more recycling processes show a higher value for thermal conductivity, and therefore lower insulating performance than CFI fibres from the US.

Since cellulose fibres are naturally hygroscopic, moisture absorption can also affect thermal conductivity values. Tye and Spinney [46] studied loose fill CFI installed in ceiling and wall constructions subjected to cyclic thermal and moisture gradients. Thermal conductivity measurements were made on installed samples using the standard ASTM C236 guarded hot box method with a mean temperature of 15 °C and a temperature difference of approximately 10 °C. It was found that thermal conductivity increased by 15% for a moisture gain of 10%. Nicolajsen [28] found that under the hygroscopic range (RH < 90%) the change in thermal transmittance of loose fill cellulose insulation within a wall cavity

was not significant (1%–3% increase). The study was done on facade elements with 285 mm loose fill CFI equipped with heat flow meters and moisture measuring dowels. Heat flow measurements were made according to the DS 418 standard. Sandberg [38] developed three approaches to determine thermal conductivity as a function of water absorption using moisture content profiles of cellulose insulation. Measurements were made on 164 mm thick loose fill CFI samples on 600 mm × 600 mm frames, following the ISO 8301 and ISO DIS10 051 standards. Computer simulations used the following relation with regards to the thermal conductivity of cellulose:

$$\lambda = 0.037 + 0.0002' w(W/mK). \quad (2)$$

Where w is the mass of water per unit volume of cellulose kg/m³. The calculated results were in agreement with sample measurements.

Talukdar et al. [44] determined a polynomial function to describe the relation between moisture and thermal conductivity by curve fitting values measured by a heat flow meter apparatus according to ASTM standard C518 on cellulose at different relative humidity conditions. Measurement temperatures were at 10 °C and 350C, with an average temperature of 22.5 °C

$$\lambda_{\text{eff}} = (a + b\phi + c\phi^{1.5} + d \exp(-\phi)) \quad (3)$$

where $a = 0.092482655$, $b = 0.15480621$, $c = 0.066517733$ and $d = 0.1296168$.

The only research that studied changes in thermal conductivity past the hygroscopic range was done by Vėjelis et al. [48]. Their study determined moisture content of CFI in one and two floor buildings with masonry walls with different thickness of insulation throughout various moisture periods measurements. A qualitative method was used to determine the influence of moisture on variations in thermal conductivity. An increase in 1% of moisture content can lead to an average increase of 1.2%–1.5% in λ values for loose fill CFI. Even when high moisture content was reached, thermal conductivity increased from 1.6 to 2.0 for 1% of moisture content (Fig. 4). These changes in values of λ are similar to those mentioned previously by Refs. [28] and [44] in the hygroscopic range. Generally for the hygroscopic range, the increase in thermal conductivity could be considered negligible. It is only when capillary moisture begins (RH > 90%) where the insulating properties would be ineffective. Such cases could arrive due to rain infiltration, leaking pipes, or improperly installed wet spray cellulose.

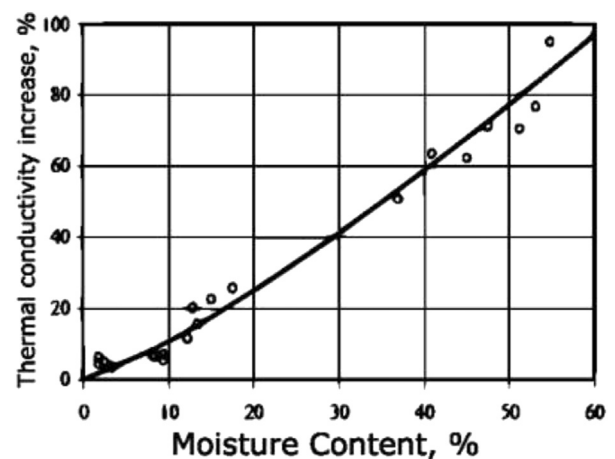


Fig. 4. Increase in thermal conductivity with moisture content of cellulose fibre insulation [48].

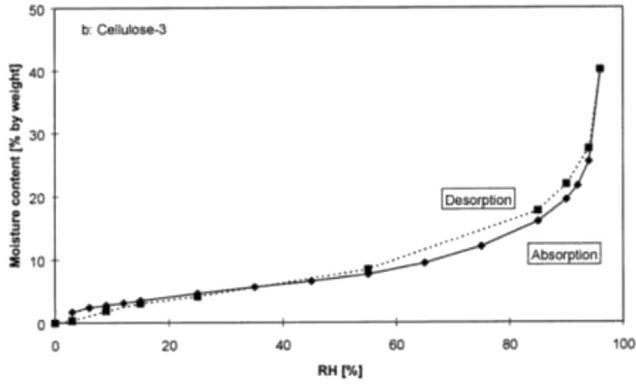


Fig. 5. Sorption-desorption isotherm of treated cellulose insulation.

3.3. Moisture properties

The behaviour of a building material with moisture can be determined by a series of intrinsic parameters. The sorption isotherm of a material can determine amount of water absorbed under different values of relative humidity. This series of values is usually measured through continuous weighing of a cellulose insulation sample subjected a series of changes in humidity via saturated salt solutions.

Sorption and desorption isotherms were determined experimentally by Hansen et al. [19] (Fig. 5). The isotherms are measured at $20.0\text{ }^{\circ}\text{C} \pm 0.5\text{ }^{\circ}\text{C}$ in a test chamber as described in EN ISO 12571, a magnesium perchlorate solution was used as a desiccant. The difference between sorption and desorption values (hysteresis) was negligible. Untreated CFI had a slightly lower sorption curve than treated CFI, suggesting that the mineral additives contribute to the adsorption of ambient humidity. A similar sorption curve was found by Talukdar et al. [44].

Moisture diffusivity, is a property that is used in simulations to determine the moisture concentration profile of a material. It is defined by the moisture transport equation:

$$J_m = -\rho \cdot D \cdot \text{grad } u \quad (4)$$

With J_m moisture flux [(kg/m²s)], ρ the dry density of the material [(kg/m³)], and u the moisture content [(kg/kg)]. This parameter was determined by Marchand and Kumaran [25]. Samples of blown CFI were subjected to moisture intake and then continuously scanned via gamma ray attenuation. These scans provided the moisture content profiles within the material as a function of time. Through Boltzmann transformation of these profiles, the moisture diffusivity D was determined as a function of moisture content within the cellulose. The value of D varied exponentially from $5 \times 10^{-8}\text{ m}^2/\text{s}$ to $1.2 \times 10^{-7}\text{ m}^2/\text{s}$ for moisture contents of approximately 10%–175%.

The water vapour permeability is the rate in which vapour water is transported materials. This characteristic defines the “breathability” of a material. Hansen et al. [19] determined the value of vapour permeability of CFI from cup measurements at 23 °C varying from 50% to 94% RH according to prEN ISO 12572: $177 \pm 29 \times 10^{-12}\text{ kg}/(\text{Pa}\cdot\text{m}\cdot\text{s})$. An increase in density (from 40 to 65 kg/m³) greatly reduced the permeability, while the removal of mineral additives had less of an impact. The values are similar to those found in Refs. [26,30], and [21]. Talukdar et al. [44] established the water vapour permeability of CFI as a function of relative humidity using ASTM Standard E96/E96M 05.

A parameter that is frequently cited by manufacturers is the moisture buffering value (MBV) which is the ability of the materials

within the room to moderate variations in the relative humidity. Cerolini et al. [6] calculated the MBV of CFI by exposing 69.6 g of CFI to daily cyclic exposure of high (75%) and low (33%) relative humidity levels for 8 h and 16 h. The moisture buffering value of CFI was found to be around 3.06 [g/m²·%RH], which can be classified as an “excellent” moisture buffer according to the scale established by Rode et al. [36].

The highly hygroscopic nature of cellulose insulation can be detrimental to CFI’s performance, as was shown with the two previous sections. However having a hygroscopic material in a building envelope could theoretically be beneficial when it comes to regulating humidity conditions inside a building, especially if a vapour retarder is not integrated in the building envelope. Rode [35] modelled the performance of a CFI wall under isothermal and nonisothermal conditions in Nordic climate. In the case where no moisture barrier or plasterboard was applied a small improvement in interior relative humidity was found for winter months. However, external humidity conditions caused moisture accumulation within the CFI to reach levels over 90% RH, which could potentially promote mould growth. Hagentoft and Harderup [17] used hygrothermal 1D models to calculate moisture uptake of a typical wall with a brick façade and thermal loose fill CFI insulation exposed to Swedish climate. The study found that in when vapour retarder is not used, moisture accumulation can reach critical levels and possibly cause mould growth in the wooden elements of the wall. In the work of [49], moisture transport within CFI was measured experimentally in order to model its behaviour under massive condensation and sub zero temperatures that create ice formation. Their studies found that ice formation had little influence on the water vapour permeability of the material, yet the material continued to accumulate moisture and did not reach a steady state within the testing period of 100 h.

Using a full scale testing chamber subjected to moisture load, Mortensen et al. [26] found that CFI can reduce interior relative humidity peaks by up to one half, but as with the previous studies, this moisture reduction becomes negligible once the surface layers of the composite wall are covered in plasterboard.

For wet spray cellulose, drying is an important factor to consider during installation. The water from the sprayed fibres could be transmitted to wood frames cavities which could cause warping or mould growth. A study by the Canada Mortgage and Housing Corporation [10] found that the cellulose increased plywood sheathing moisture content to 24% 30 days after installation, which then reduced to 15% after 260 days. The critical moisture content in which wood starts to develop fungi is around 30% so the moisture

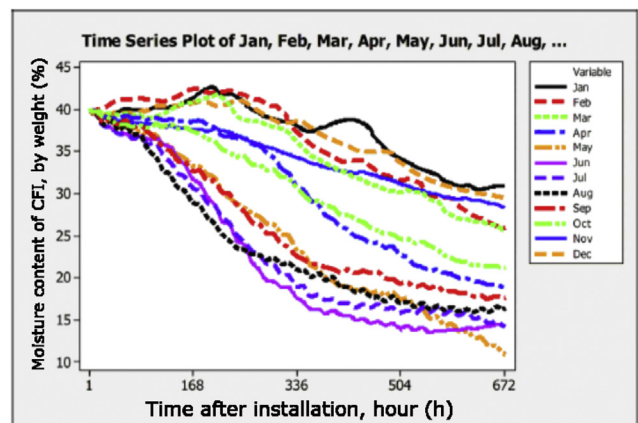


Fig. 6. Calculated evolution of average moisture content in exterior facing half of wet spray CFI with varying months of installation in Detroit Michigan [37].

values were acceptable. Salonvaara et al. [37] studied drying of wet spray CFI with a hygrothermal model that takes into account the period of installation. The study compared drying in a region with warm dry climate vs. a region with cold humid climate. It was found that for winter months the wet spray CFI would take many weeks to dry and in some cases not dry at all, especially in colder region. For example Fig. 6 shows that, during the winter months of November, December, and January (solid blue, dashed orange, and solid black lines in the graph, respectively) moisture content decreased by only 10% in a month. The wet spray method is therefore preferred to be applied in warmer drier climates.

3.4. Air infiltration

Openings in a building's envelope can cause air leakage which can have an impact on energy loads in buildings. The most cited study by manufacturers regarding air infiltration with CFI was done by Boonyakarn et al. [5]. The study found that the installation of CFI (wet spray in walls and loose fill in attics) reduced the air change rate from 87.5 to 29.4 ACH (Air changes per hour) with 50 Pa blower door testing. CFI was found to improve air tightness 36% better than fibreglass.

A study by the North American Insulation Manufacturers Association (NAHB [27] found that, via testing in wood framed walls, wet spray cellulose had reduced the air infiltration of a structure from 10.5 to 2.2 m³/h (converted from cubic feet per minute) while fibreglass batts only reduced it to 6.1 m³/h. The difference in air infiltration between types of insulation is negligible once a weather barrier was applied.

3.5. Fire properties

The high flammability of cellulosic fibres requires them to be treated before installation in order to achieve acceptable levels of combustion and smouldering resistance. In a typical CFI material, borate salts are added to prevent combustion and boric acid is added to prevent smouldering [42]. Other additives include aluminium sulphate, aluminium trihydrate, ammonium phosphate, and ammonium sulphate. Day and Wiles, [13] studied the influence of the proportions of these additives on flame spread and smouldering resistance. The minimum boric acid required to prevent smouldering as a function of borax dosage was established:

$$\text{boric acid required} = 11.6 + 0.185 \times (\text{borax used}). \quad (5)$$

Day et al. [11] found that the optimal borax/boric acid ratio of 1/

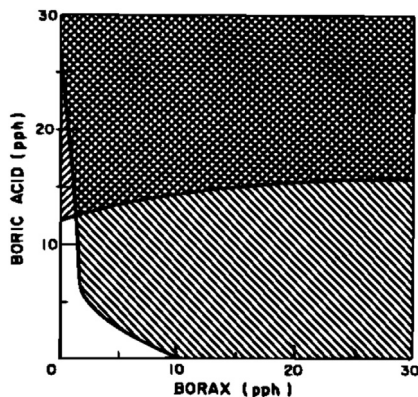


Fig. 7. Proportions (parts per hundred) of borax and boric acid in order to achieve smoulder retardancy (///diagonal) and flame retardancy (\\ diagonal) [12].

8 with a dosage 16% is necessary to prevent both flaming and smouldering combustion (Fig. 7).

A three component formulation using borax, boric acid, and aluminium sulphate was also studied. Varying dosage from 12% 18% and 24% increases the possible proportions of these constituents which allow both smouldering and combustion resistance to be obtained. In another study (1981), they studied the effect of wetting on additives. They establish that wetting and drying of the CFI caused a higher concentration of both borax and boric acid to appear on the surface of the material. This migration did not affect smouldering resistance and would actually be favourable for flame combustion resistance. Sprague [41] studied the consistency of formulations and found variability in the distribution of test results. Samples were found to attain class I or II flame resistance with a variable distribution. As additive dosage increased, this variability was reduced. Some of the variability was due to inconsistency in the testing method itself.

3.6. Fungal development

It is widely known that wet lignocellulosic materials can allow mould growth. In the case of CFI, the added additives can serve a dual purpose of preventing mould growth as well as fire propagation. In the work of [20]; it was found that the boron included in the cellulose was found to have a sporocidal effect on five of the most common types of fungal spores, even when subjected to a high concentration of fungi. For untreated fibres exposed to fungal samples, moisture content and relative humidity was found to have an influence on the fungal growth rate of cellulose insulation. As the CFI samples dried, the rate of mould growth decreased.

There exist however, case studies where mould growth has been found to be produced in houses insulated with CFI. Godish and Godish [15] studied four wet spray CFI insulated houses where mould was prevalent. While the conditions in which the wet spray CFI was applied were not detailed, (i.e. high water dosage), it was found that two of the houses developed fungi due to rewetting of the fibres because of water infiltration. Numerous hydrophilic xerophilic and toxigenic species of fungus were found both within the CFI material and in airborne samples. While this mould exposure poses a risk to building occupants, properly applied wet spray CFI will not present these problems.

3.7. Life cycle analysis

As mentioned before, CFI has a low embodied energy compared to traditional mineral and natural insulation materials. A comparative analysis of three impact categories of the life cycle analysis (LCA) of common insulation materials was featured in Zabalza Bribián et al. [51] (see Table 3). It is worth noting that the functional unit is 1 kg of material. Since the materials have different densities and thermal conductivities, a more proper functional unit would be the necessary amount of material to provide a specific value of thermal resistance.

A more in depth LCA comparison was done by Schmidt et al. [39], who studied the cradle to grave assessment of stone wool, flax, and CFI, in compliance with the LCA standard ISO 14040. In this case the functional unit was the amount of material necessary to provide a thermal resistance of 1 m²K/W so 1.280 kg of material in the case of loose fill CFI. The study takes into account the production of newsprint, the manufacture of CFI, the incorporation of its additives, its installation, use and disposal for the calculation of its inventory. sensitivity analysis of the end of life stage was studied. For loose fill solutions, manufacturers state that CFI can be recycled if no contaminants are present [4], or incinerated to provide energy in a waste incineration plant. The study analyses the impact of

Table 3
Comparative life cycle analysis of common building materials [51].

| | Building product density (kg/m ³) | Thermal conductivity (W/mK) | Primary energy demand (MJ-Eq/kg) | Global warming potential (kg CO ₂ Eq/kg) | Water demand (l/kg) |
|-------------------------|---|-----------------------------|----------------------------------|---|---------------------|
| EPS foam slab | 30 | 0.0375 | 105.486 | 7.336 | 192.729 |
| Rock wool | 60 | 0.04 | 26.393 | 1.511 | 32.384 |
| Polyurethane rigid foam | 30 | 0.032 | 103.782 | 6.788 | 350.982 |
| Cork slab | 150 | 0.049 | 51.517 | 0.807 | 30.337 |
| Cellulose fibre | 50 | 0.04 | 10.487 | 1.831 | 20.789 |
| Wood wool | 180 | 0.07 | 20.267 | 0.124 | 2.763 |

partial recycling incineration or landfilling of the material. The highest impact was caused by partial landfilling of the CFI, which nearly tripled the global warming impact factor, due to the amount of methane released by the material. Recycling vs incineration had less of an impact. Interestingly, in this study CFI showed a higher total energy consumption than stone wool (for the same functional unit), which contradicts the studies previously shown. One reason for this could be strategy involved in the consideration of the impact of the manufacture of newsprint. In this study, newsprint production represented over 90% of overall energy consumption in the LCA of CFI. This highlights the importance of the initial hypotheses when analysing the life cycle of a recycled material such as CFI.

Life cycle assessment is a useful tool in material selection for construction projects. Takano et al. [43] studied the impact of building material selection on the environmental characteristics of a construction in Finland. It was found that the change from rock wool to CFI as an insulator could reduce greenhouse gas emissions and embodied energy of the building envelope by 15%. Similarly [45] studied the influence of different insulation materials on primary energy and CO₂ emission of a residential multi storey building using the criteria of BBR 2012 and Passivhaus 2012 energy efficiency standards. It was found that the replacement of stone wool by CFI on most parts of the building envelope resulted in global energy reduction of 6%–7% and a decrease in CO₂ emissions from material production of 6%–8%, depending on the standard chosen (BBR 2012 or Passivhaus). This is an interesting factor to consider when dealing with the refurbishment of buildings, where not only the replacement of old mineral insulation with CFI will improve thermal properties of a refurbished building, but also reduce its ecological impact.

4. Conclusions

As has been shown by the available literature, CFI is an innovative eco friendly insulation material that presents similar characteristics in terms of thermal comfort and performance to its non renewable counterparts. Nevertheless the material presents some disadvantages compared to less eco friendly insulation materials and has shown the need for more optimization and development. Further research needs to focus on studying and resolving the issues with the material's properties and performance.

First of all there needs to be a better understanding of the source material. While the available research has been shown on the performance of CFI after installation, more work needs to be done on the manufacture and installation methods in order to further optimize the material. Studying this can be difficult due to the fact that CFI manufacturers have many suppliers for newsprint, each of whom may use different compositions of paper and methods of manufacture. Nevertheless, knowing the properties of the source newsprint in terms of paper quality, composition, fibre morphology, and their influence on CFI insulation quality will help

reduce variability in the performance of CFI. Only the work of [22] has compared cellulose insulation from two different sources (Korean and US CFI), but the differences between the quality of these two are not well detailed.

For loose fill CFI, novel methods need to be developed to reduce settling, especially in horizontal applications. How material separation and blowing speed during installation can affect these factors has yet to be analyzed. The stabilized approach needs to be further developed to study the influence of water on dust exposure, density and settling. This also applies to the wet spray method, where the role of water dosage on the final properties of cellulose should be investigated.

Finally changes in the formulation of CFI could be envisioned. Other, more environmentally friendly additives with antifungal or fire retardant properties could replace some or all of the mineral additives used currently. The incorporation of adhesives and tackifiers in the wet spray method has been known to be used by some manufacturers of CFI [9] but their effect on the fibres and the performance of CFI has not yet been quantified.

It is through these innovations that cellulose fibre based insulations can become more prevalent and contribute to more eco friendly construction projects.

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