The properties of cellulose insulation applied via the wet spray process

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ABSTRACT

Cellulose fibre insulation is a sustainable thermal insulation material made out of recycled paper. It can be installed in open walled cavities using the wet spray method. The isotherm of loose cellulose insulation fibres was determined using dynamic vapour sorption to study their relationship with water. The types of water within the fibres, known as bound and unbound water was studied via a differential scanning calorimetry method. Wet spray cellulose samples were produced with varying water content and subjected to compression, and thermal conductivity testing. Results showed that density, modulus of elasticity, and thermal conductivity all increased with water dosage. The increase in these properties was higher when the material was sprayed with water than when it was dry compacted. These are factors which need to be considered for when applying wet spray cellulose fibre insulation, in order to ensure the properties of the material are consistent.

1. Introduction

Insulation materials are an essential part of a building envelope. They assure that the inside temperature of a room is maintained at a certain level and reduce the use of heating and cooling, which have a high energy demand. Currently the majority of traditional insulation materials, such as polystyrene, glass wool, and mineral wool are made from non renewable minerals or polymers, and have a high embodied energy and global warming potential in its production [3,23,28]. An alternative insulation material known as cellulose fibre insulation (CFI), has the benefit of using recycled paper to produce, while having similar performance properties to traditional insulation materials [13]. Being made of hygroscopic fibres, it also has the benefit of acting as a moisture buffer for the control of ambient humidity in a construction [11]. Usually, cellulose insulation is blown dry in closed wall cavities or attics. A more recent method of installing CFI, known as the “wet spray” method, has the advantages of ensuring a proper distribution and filling of the material in a wall cavity, while preventing sagging through the use of pulverized water [7]. With this technique, as the fibres are blown through the material hose, a jet of pulverized water is sprayed simultaneously into an open wall cavity with the fibres. The water makes the fibres adhere to the cavity, in order to prevent sagging and to ensure a homogeneous distribution of the fibres. After spraying, the excess material is removed via an electric wall scrubber to ensure a flat surface. The wet spray method also provides a better air tightness for a buildings envelope, preventing the loss of heat caused by air infiltration through voids [14].

The disadvantages associated with this method, however, are mainly due to improper installation of CFI while it is sprayed with water. If too much water is applied, or if it's applied in a high humidity, low temperature climatic conditions, the material could take a long time to dry, imposing a long delay in construction times or worse, promote mould growth within the material or surrounding wood structures. Too much sprayed water could also

Abbreviations: CFI, cellulose fibre insulation; DSC, differential scanning calorimetry; DVS, dynamic vapour sorption; OSB, oriented strand board; RH, relative humidity; (w/w), weight by weight.

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weigh down the material, making the material sag and causing voids in the installed wall cavity. In the work of [22]; the modelled drying of wet spray cellulose varied greatly depending on the month and location it was installed, with cellulose installed in winter months taking several weeks to reach a dry state. Inciden tally, in the same study, wet spray cellulose that was intended to be installed at the minimum recommended water dosage of 40%, turned out to be installed at a dosage of 70%. This shows, albeit anecdotally, that professional installers might have difficulty con trolling the initial water content of wet spray cellulose insulation. High sprayed moisture can also promote fungal development within the material, even when it is treated with borates [9].

Most research on cellulose insulation focuses on the loose fill application [25]. The influence of adsorbed humidity on thermal conductivity on loose fill cellulose fibres has been studied. A linear relation between moisture content and thermal conductivity has been established [16,25,26]. These studies consider only the influ ence of humidity contained within the loose fibres, and not how drying of fibres can influence these properties. It has been shown that once paper fibres dry, their strength increases, porosity de creases, and their moisture retention capacity decreases [10]. These changes in the fibre structure during drying can reduce the mate rial's porosity, thus potentially affecting the thermal conductivity of cellulose insulation, which has yet to be studied.

For loose fill applications, methods have been developed to test the settling of loose fibres in attics [4,5,24]. A model to study me chanical behaviour of loose fill fibres in a closed cavity is detailed in the work done by Refs. [17–20]. This model studies the creep behaviour of loose fibres in a closed wall cavity in order to predict the necessary installed density to prevent settling. The model used friction coefficients with the surface the cellulose fibres are installed on oriented strand board (OSB) closed wall cavities. In the case of cellulose insulation installed through the wet spray method, the fibres form a cohesive structure which adheres directly to the wall cavity. The measurements used on loose fill therefore do not apply to the wet spray application and there has yet to be a defined method to quantify the mechanical performance of materials fabricated with this method. The contribution of water on the mechanical behaviour of these fibres needs to be studied in order to determine a baseline mechanical resistance to ensure that the material will remain rigid and not settle.

Isothermal measurements allow the characterisation of mois ture sorption of the material [12]. The water within cellulose fibre walls can be catalogued in three different categories: nonfreezing bound water, freezing bound water, and free or unbound water. Non freezing bound water is the water present in the micropores of the fibre. It corresponds to the water bound to the hydroxyl and carboxylic groups in pores of the fibre. The freezing bound water appears in pores larger than micropores and binds to hemi celluloses. As the freezing bound water dries, this causes the pores of the fibres to close irreversibly. The free or unbound water is the water present in the larger pores and between the lumen in fibres [15,27].

In the present work we analysed the properties cellulose insu lation fibres, and their relation to water sorption. Furthermore, we studied the influence of water dosage on the thermal and me chanical properties of cellulose fibre insulation manufactured through the wet spray method. The interactions of the fibres with water were first considered with dynamic sorption testing and differential scanning calorimetry (DSC). The drying behaviour of projected cellulose insulation samples was then investigated. A method to test the compression resistance of the cellulose fibres was devised to study the influence of initial moisture content on its mechanical properties. The same was done with thermal conduc tivity testing via the guarded hot plate method.

2. Materials and methods

2.1. Preparation of cellulose insulation samples

Cellulose fibres of the brand Univercell Comfort were provided by SOPREMA (Bordeaux, France). The raw materials are pre consumer newsprint paper from several providers from the south of France. In factory, the papers are ground into smaller fragments, which are then turned into loose fibres via a specialized fiberizer. Boric salts are then added as a fire retardant and antifungal agent at the range of 8%–11% (w/w) (weight by weight). The fibres come compacted in a bag in order to optimize transportation costs. Once delivered onsite, the compacted fibres are fed to the blowing ma chine, which first separates them so they can be blown. A separate pump, connected to the blowing hose, pumps water which is then atomized through nozzles at the same time the fibres are blown into the cavity. In order to vary the initial moisture content of the samples, the pumped spray water pressure varied from 6 to 25 bars. The fibres were blown into wooden moulds of dimensions: $300 \times 300 \times 90\ mm^3$ (Fig. 1) for mechanical tests. The moulds were fitted with a removable 2.5 mm rigid cardboard base covered with a coat of vinylic glue. Once the insulation sample was dry, it was carefully unmoulded. Afterwards, another 2.5 mm cardboard was glued to the other side of the sample.

Once the glue dried, the sample was then cut into nine $100 \times 100 \times 90\ mm^3$ pieces via a circular saw. The use of cardboard served two purposes: to ensure that the $100 \times 100\ mm^2$ samples have good contact with the compression plates. This ensured that they were cut evenly without loss of the material. Thermal con ductivity samples were projected on $150 \times 150 \times 50\ mm^3$ moulds with a removable top for unmoulding. Once dry, samples were carefully separated from the moulds using a trowel. All samples were stored in a climatic chamber at 25 °C and 60% relative hu midity (RH). To measure the drying of CFI, the mechanical testing samples were weighed daily in order to measure the evaporated water until equilibrium moisture conditions at 60% RH (a mass variation of less than 1% in 24 h) were reached. The equilibrium moisture content was then determined by taking 3 g of fibres from the ambient dried samples and drying them at 100 °C for 2 h. Using the mass of the samples and the equilibrium moisture content, the initial moisture content as well as the drying of the material at 24 h intervals was determined.

2.2. Dynamic vapour sorption

Sorption isotherms were made by dynamic vapour sorption (DVS) apparatus DVSAdvantage from Surface Measurement Sys tems Ltd (London, United Kingdom). The apparatus measures the uptake and loss of vapour gravimetrically via a microbalance. The partial vapour pressure around the sample is increased by mixing dry and water saturated air to specific relative humidity values. Loose fibre samples were placed into an aluminum sample holder connected to a microbalance. The samples were then subjected to a series of relative humidity variations from 5% to 95%, with 10% in tervals, at a constant temperature of 25 °C. The variations in mass due to moisture adsorption and subsequent desorption were then plotted against relative humidity. In order to have an approxima tion of the isotherm, the Oswin model is recommended for porous building materials [12], where it is more precise at high relative humidity values. The relation is as follows:

$$X_e \quad b_0 \exp\left(\frac{b_1}{T}\right)\left(\frac{a_w}{1 \quad a_w}\right) \tag{1}$$

Where X_e is the calculated moisture content (% w/w), a_w the

Fig. 1. 300 × 300 × 90 mm^3 sprayed samples.

relative humidity (%), T is the ambient temperature (°C), and b_0, b_1, b_2 are coefficients dependent on the material. These coefficients were determined by minimizing the standard deviation between the calculated values and the average between the measured sorption and desorption values.

2.3. Bound water determination with dynamic scanning calorimetry

The bound and unbound water contents were determined according to the method described in Ref. [27]. The method uses differential scanning calorimetry (DSC) to freeze the wetted fibres and measure the melting enthalpy as the frozen fibres reach 0 °C. In these melting curves two peaks can be observed: one corresponds to the frozen bound water and the other to free water. The remaining water is considered to be the non freezing bound water. 50 g of untreated Univercell loose fibre samples were moistened at around 250% moisture content then left to dry at 50% RH and 25 °C. Around 5 mg of fibres were then placed in an aluminium crucible and sealed. DSC measurements were made from 30 °C to 15 °C. As the fibres dried, samples were placed in the DSC apparatus and the melting enthalpies were measured from decreasing moisture content. This was repeated daily as the material dried to have samples with decreasing moisture content. The melting peaks were then integrated to determine bound and free water content as a function of total water. The melting enthalpy for the type of water was divided by the known melting enthalpy for water, 334 J/g, to give proportions of each type, with the remaining water attributed to nonfrozen bound water. The amount of water in a melting peak was calculated according to:

$$X_{water}\ (\%) \quad \frac{\Delta H_{peak}}{H_f \cdot m_{dry}} \tag{2}$$

where: ΔH_{peak} (J) is the energy transferred according to the peak melting peak, H_f the specific heat of fusion of water (334 J/g at 20 °C) and m_{dry} is the mass of solids (g). The quantities of bound frozen, bound unfrozen, and free water was plotted as a function of total moisture content in the fibres.

2.4. Compression testing

Compression tests, adapted from the standard NF EN 826 [1], on the cut 100 × 100 × 90 mm^3 samples were made by means of an H5KT universal testing machine from Tinius Olsen (Surrey, England) equipped with either 100 N or 500 N sensors, depending on the material's resistance. Steel 100 × 100 mm^2 compression plates ensured direct contact with the samples (Fig. 2). Compression was done at a speed of 10 mm/min. A pre charge of 1 N was applied to ensure direct contact with the sample. Due to the fact that the material is highly compressible, no fracture or rupture was detected so instead the measured stress at 5% and 10% strain was logged for each sample. Compression tests stopped once 20% strain was reached. Since each sample had slight variations in dimensions of the order of ±2 mm, they were measured in order to accurately calculate their respective stress and strain. Each value represents the average of the nine samples.

2.5. Thermal conductivity

Thermal conductivity measurements were done according to the standard NF EN 12667 [2]. Samples of 150 × 150 × 50 mm^3 were placed in a λ Meter EP500e guarded hot plate apparatus from Lambda Messtechnik (Dresden, Germany). The method consists of placing the sample between heating and cooling plates. A constant heat flow is then applied through the specimen thickness. Thermal conductivity can then be determined by the heat flow, the mean temperature difference between both sides of the sample and its surface. Foam insulation was used around the samples to ensure the contact plates measured only the 150 × 150 mm^2 surface of samples. The contact plates were configured to be applied at a pressure of 50 Pa to ensure direct contact with the samples without compacting them. Measurements were made at 10 and 25 °C average temperature with a temperature difference of 10 °C between plates. Steady state was assumed to be reached when the value of thermal conductivity varied less than 1% in 60 min. Each measurement at 25 °C was done twice to ensure repeatability.

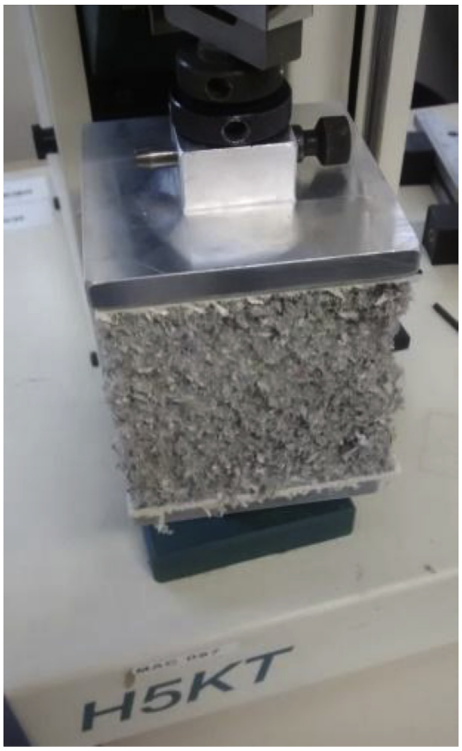

Fig. 2. Compression tests.

3. Results and discussion

3.1. Sorption isotherms

The Oswin model shows good relation with the values deter mined experimentally (Fig. 3). The moisture content at saturation can be estimated when RH values approach the saturation point of 100%. At a RH tending towards 100% the Oswin model gives a value of 774% moisture content, showing that, past the hygroscopic range, cellulose can absorb high quantities of water via capillary con duction. For cellulose insulation drying, this would mean that the range of minimum applied water dosage of 40%–60% corresponds to water past the hygroscopic range and within the capillaries. In practice, capillary water tends to dry faster than absorbed water within the pores although below the threshold of 20–15% moisture content, the cellulose insulation is already considered dry. As was presented in previous works [6,21], this high hygroscopisity is also considered favourable for building envelope materials, as it makes the material "breathable" and thus lower ambient humidity in a room to a comfortable level, or conversely increase it when it is too dry.

3.2. Bound water determination with differential scanning calorimetry (DSC)

Fig. 4 shows the distribution of the bound and free water in cellulose insulation fibres as a function of total moisture.

The shape of the DSC curves are similar to those found in the work of [27]. The figure shows how for low moisture contents, only non freezing bound water is present, then as moisture content increases, other types of water start to appear: at around 14% for freezing bound water and 27% for free water. The values of both freezing and non freezing bound water increase gradually until the micropores are saturated. It is at this point, at around 108% mois ture content, in which free water fills the bigger pores and the voids between fibres. Past this point only the amount of free water in creases. For the recommended dosages of cellulose insulation of 40–60% moisture content, mostly bound water is present, with smaller proportions of free water, which increases as total moisture content increases. Once the fibres are sprayed, the bound water

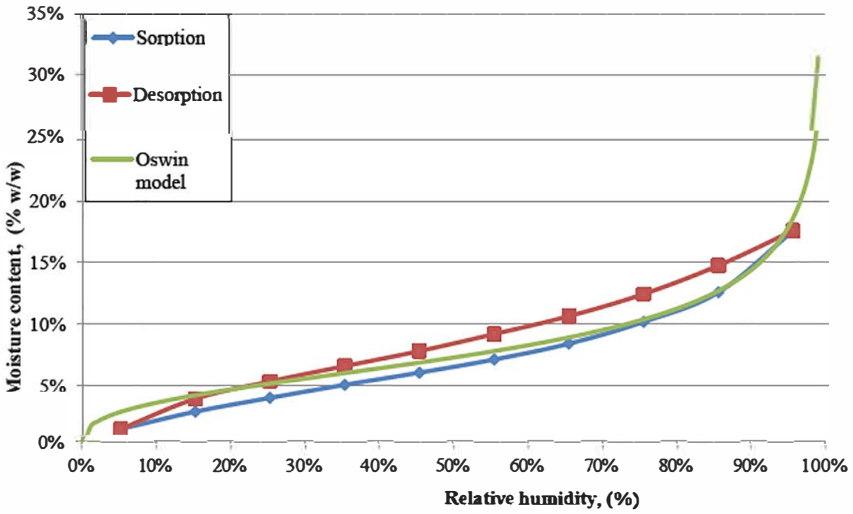

Fig. 3. Dynamic vapour sorption of CFI, with Oswin model approximation.

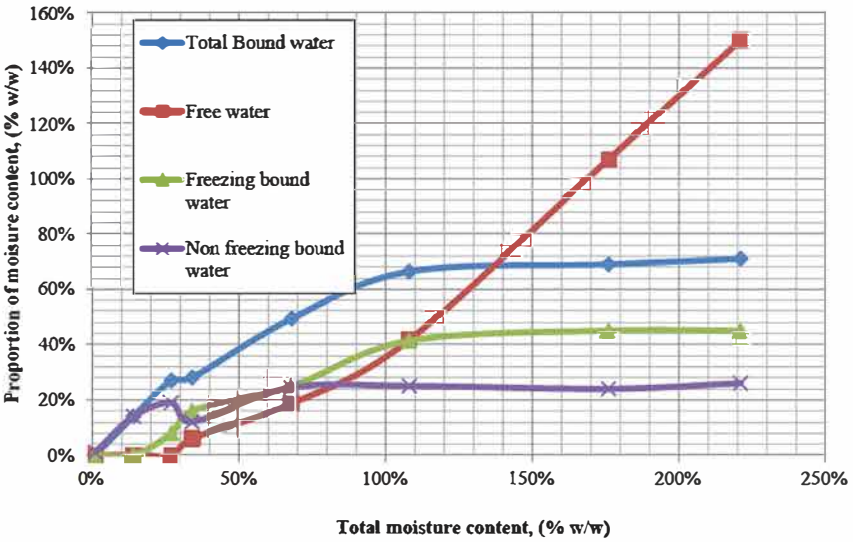

Fig. 4. Frozen and unfrozen bound water, free water and total bound water as a function of total water content for CFI.

strengthens and closes the pores within the fibres while the free water reinforces the link between fibres and microfibrils. This only applies once the water is fully absorbed within the fibres, as during spraying the bound water in the surface of the fibres gradually penetrate into smaller pores. The presence of freezing bound water in this dosage range means that as the fibres dry, the size of pores diminishes and this change in pore size could affect the thermal conductivity of the material. As the fibres dry, the free water is the first to diffuse within the material and evaporate since it is more present in the surface of fibres. For the equilibrium moisture ranging from 8% to 11% at 60% humidity after drying, only non freezing bound water, is found in the material.

3.3. Drying of cellulose samples

The drying curves of projected 300 × 300 × 90 mm^3 samples with varying water pressure are shown in Fig. 5. All samples show an initial linear constant drying rate, which corresponds to the removal of free water, and around 25% moisture content, the drying rate slowed down until the material reaches equilibrium moisture content. This point is close to the region in which only bound water is present in the fibres, as was shown in Fig. 4, which indicates that below 25% mainly bound water is present, which is harder to remove from the fibres, hence the slower drying rate.

Evidently, an increase in water dosage increased the time for the material to reach an equilibrium dry state. In practice, installers of cellulose fibre insulation consider that when the material reaches around 20% moisture content, it is considered dry enough to allow the installation of a vapour barrier and drywall. For example, a water dosage of 70% can increase the time to reach 20% moisture to 58 h versus the 19 h needed when the minimum recommended dosage of 40% is applied, over three times the standard drying time. It is worth noting that this applies only to 90 mm thick insulation at the constant conditions of 25 °C at 60% RH. In reality, the drying rates vary depending on thickness and ambient conditions. The thicker the specimen, the colder and more humid drying conditions are, the longer the drying times, which sometimes cause unac ceptable delays in a construction project. This drying behaviour could eventually be compared with numerical hygrothermal sim ulations, such as was done by Ref. [22].

3.4. Changes in density

As shown on Fig. 6, the final density of the material depends on

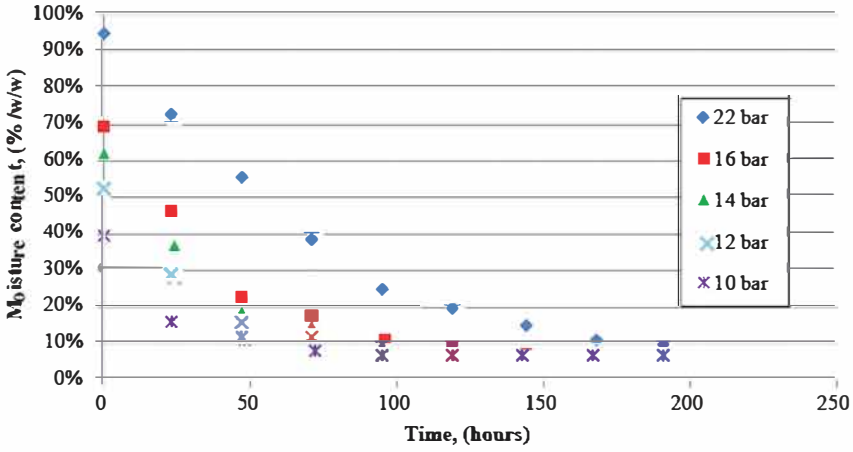

Fig. 5. Drying of CFI samples, with varying installed water pressure.

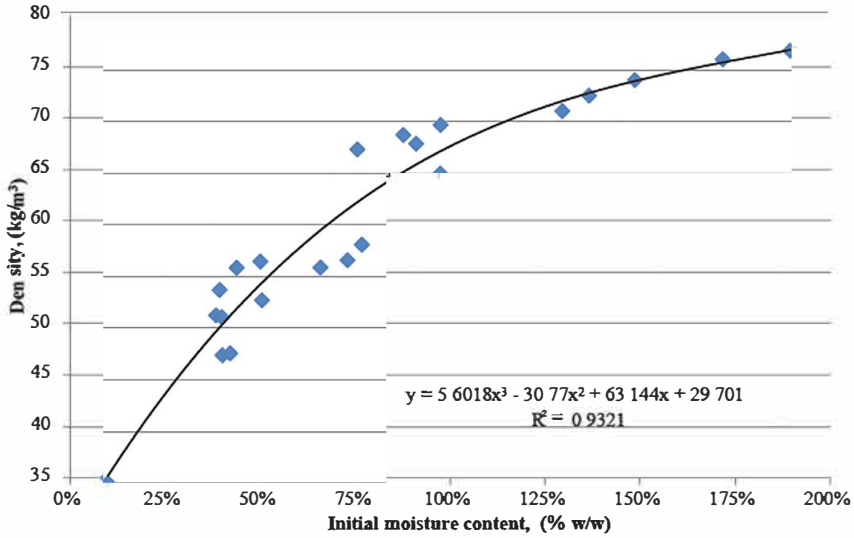

Fig. 6. Influence of installed moisture on final density at equilibrium of CFI samples, with polynomial regression line.

the installed moisture content. The values shown are slightly higher than those found by Ref. [22]. The first point in the series corresponds to the initial moisture content and density before spraying (blown density). At the minimum moisture content of around 40%, density varies from 47 to 53 kg/m^3. The results show a semi linear increase of density with initial moisture content up to 77% moisture. Past this point the density increase is at a much slower rate. When cross referencing this inflection point with Fig. 4, one could observe that at the 77% moisture point almost all of the bound water has been absorbed within the fibres, while free water content continues to increase. The changes in density has two probable sources: the increased pressure from the pulverised wa ter, which causes compaction of the material as it is projected, and the strengthening and hardening of fibres as they dry. It could be feasible that the free water within the fibres contribute less to the increase in density than the bound water. As it has been shown with other natural building materials [8], these variations in den sity can also cause changes in the thermal and mechanical prop erties of the material, as will be shown in the following sections. It is therefore necessary not only to observe the influence of the sprayed moisture content on the mechanical and thermal proper ties, but to differentiate it from the influence of the increase in density induced by sprayed water. This further emphasises the need to control of water dosage since as the density increases, more of the material is used to insulate the same volume, which subse quently has the double penalty of increasing costs of installing the insulation, as well as making it a less efficient insulator through the increase in thermal conductivity.

3.5. Compression tests

Figs. 7 and 8 show the relation between the moisture content and the calculated elasticity modulus E and measured stresses at 5% and 10% deformation, respectively. The lightweight material shows a quasi linear elastic behaviour with no rupture at strains up to 20%. At higher deformation levels, the material starts to consoli date. At this point, the slope of the stress strain curve increases. As was expected, the material showed an increase in its mechanical resistance with increasing moisture content.

While all the values showed a good linear relation with moisture content, the best indicator seems to be the stress measured at 10% strain $\sigma_{10\%}$. This could be due to the fact that as the material is compacted, the heterogeneous voids within it are filled with fibres, giving a more linear and constant reading of the applied stress at higher deformation.

Below 40% sprayed moisture, the CFI samples could either not be sprayed or crumble under their own weight. In order to define a « minimum resistance » of wet spray cellulose insulation to ensure that the material will not sag or tear once projected, the measured values of the modulus of elasticity E and compressive stresses $\sigma_{5\%}$ $\sigma_{10\%}$ at around 40% moisture content were averaged. This gives an average of 14.05 kPa, 0.62 kPa, and 1.34 kPa for E, $\sigma_{5\%}$, and $\sigma_{10\%}$ respectively. These values could potentially be used as a reference point if, for example, a raw material (recycled newsprint) of different quality is used, or if the amount and/or type of additives are changed.

In order to account for the influence on the direct compaction of the material by the sprayed water, the previous results were also plotted with dry density of the samples, and compared with sam ples sprayed at the minimum 40% moisture content (MC) and compacted once dry, to artificially increase density. The results for modulus E and measured stress is shown in Fig. 9, with similar results found for measured stresses.

When measured with regards to density, the mechanical resis tance of the material behaved differently at different densities. For the typical "sprayed" densities, around 45–55 kg/m^3, the me chanical resistance increased slightly and its behaviour is similar to that of cellulose that has been dry compacted. Past a certain den sity, the mechanical resistance increased greatly, at a slope much higher than that of the compacted reference. This confirms the statement that the added sprayed water not only compacts the material, making it resist settling and fissures, but the swelling and hardening from the fibres as they dry has an important impact on the mechanical performance of wet spray cellulose insulation.

3.6. Thermal conductivity testing

The value of thermal conductivity, λ measured in W m^{-1}. K^{-1} is the main defining characteristic of a thermal insulation material. The lower the value of λ for a given material, the better it is as an insulator. Thermal conductivity measurements were applied on 150 × 150 × 50 mm^3 sprayed samples. Fig. 10 shows the variation of dry thermal conductivity with installed water dosage at average temperatures of 10 °C and 25 °C (λ_{10} and λ_{25}). Samples were

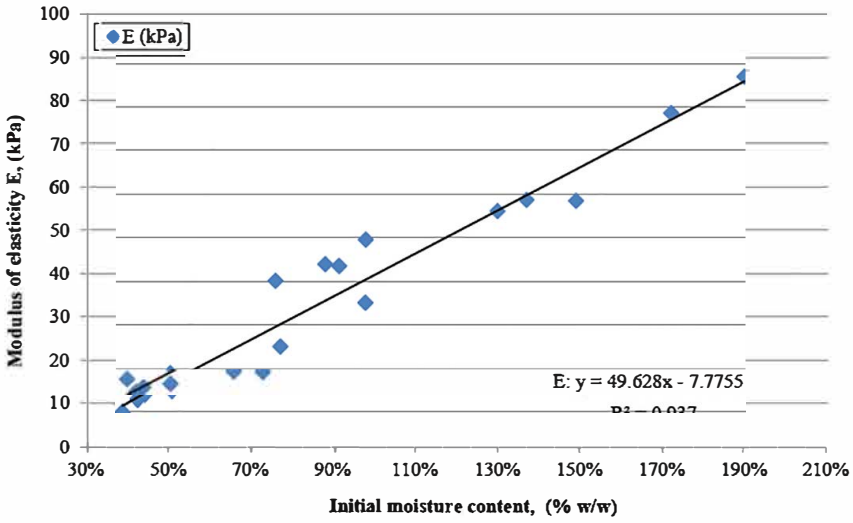

Fig. 7. Influence of installed moisture content on modulus of elasticity E of CFI samples, with linear regression line.

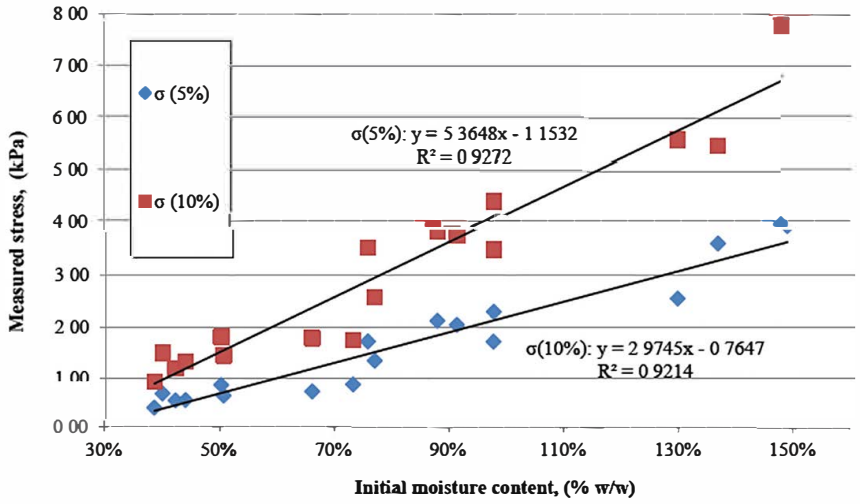

Fig. 8. Influence of installed moisture content on measured stresses, $\sigma_{5\%}$ $\sigma 10_{\%}$, of CFI, with linear regression line.

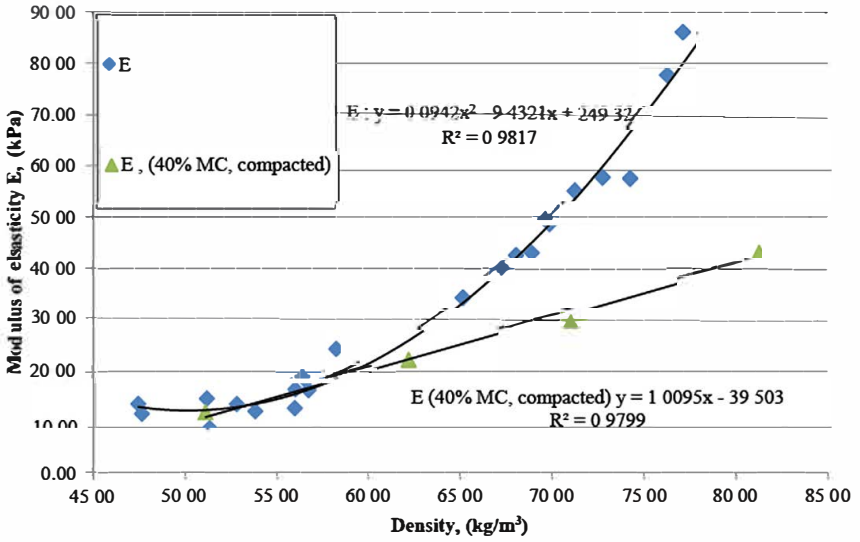

Fig. 9. Influence of final density after spraying with various water dosages on modulus of elasticity E, compared to compacted samples, with regression lines.

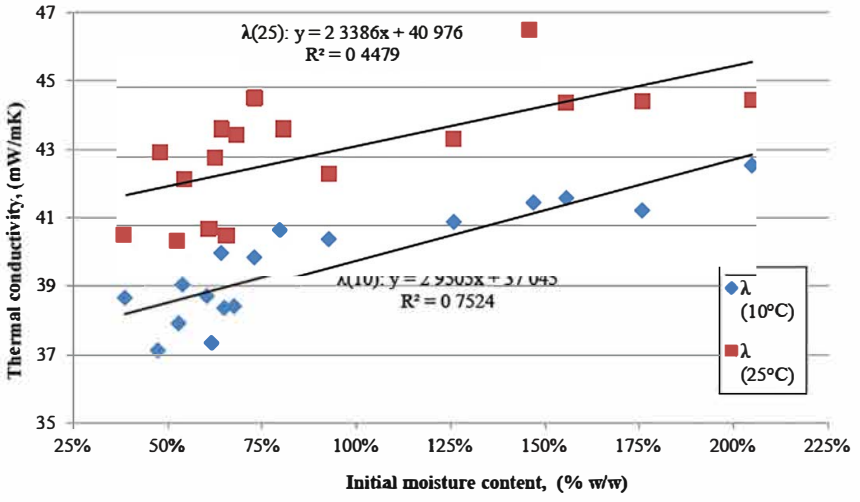

Fig. 10. Influence of installed moisture content on thermal conductivity values λ_{10} and λ_{25}, with linear regression lines.

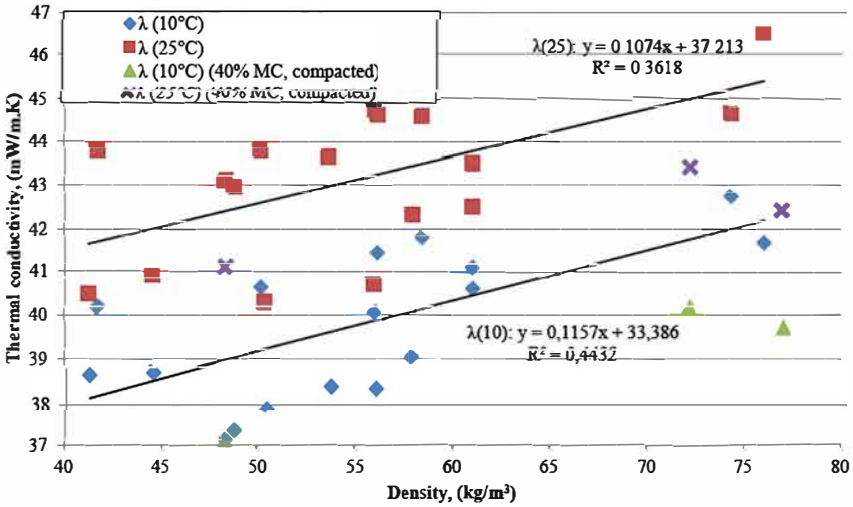

Fig. 11. Influence of installed moisture content on thermal conductivity values λ_{10} and λ_{25}, with linear regression lines.

measured in the direction they were sprayed, corresponding to the direction in a wall where thermal transfer would occur, an aniso tropic effect could occur if the samples were tested in different directions of the sprayed fibre. Similarly to the mechanical prop erties, the value of dry thermal conductivity increased with installed water content. In this case the difference in values is much smaller, making the results more prone to irregularity. Thermal conductivity values varied from 37 to 43 mW m^{-1}. K^{-1}, for mea surements made at 10 °Cand around 40–46 mW m^{-1}. K^{-1} for 25 °C. These values are comparable to traditional insulation materials such as mineral wool [23]. The high scatter could be due to the heterogeneity of the samples, or to irregularities in the contact surface between the heating plate and the sample. Since the ma terial is highly compressible it was difficult to ensure perfect con tact between the plates and the samples without compressing the samples, which would increase its density and thermal conduc tivity. While this increase in values of λ with applied moisture content is slight, it is still unfavourable to a wall's thermal perfor mance. It is in the cellulose installers' best interest to use the lowest feasible water dosage in order to ensure optimum insulation ca pacity of the material.

The influence of density, of samples with varying spray dosage, is shown on Fig. 11. The values are compared with samples com pacted sprayed at minimum dosage once they were dry. Ideally the relation with density should give a clearer indication on the trend of thermal conductivity, but results show a high scatter as well, due to the closeness between values and the measurement issues mentioned previously. Nevertheless, in general terms, an increase was observed with thermal conductivity and as a function of den sity of the material. As it was found with compression tests, a slightly higher thermal conductivity was found from the sprayed samples than with the dry compacted samples, for samples with similar density. This could be due to the decrease in porosity from the swelling and drying of fibres, which differ from the decrease in porosity from compaction. The voids formed from these changes in porosity directly impact the thermal conductivity of the material. More points of measurement are needed for the linear relation of dry compressed samples to be established.

4. Conclusion

Cellulose insulation installed via the wet spray process was characterized. In order to study its relation with water, dynamic vapour sorption, and differential scanning calorimetry to deter mine bound and unbound water content measurements were realized. The study of on the behaviour of the fibres with water give indications on the moisture absorption and subsequent drying once cellulose insulation is applied with the wet spray method.

As the results have shown, the increase of water not only delays drying times after installation, but also increases the density and thermal conductivity wet sprayed cellulose insulation. The increase in density and drying time with increased water dosage remain important factors to consider when applying cellulose insulation. A method to determine the mechanical behaviour of wet sprayed cellulose was designed. The testing method gives an indication of how the installed moisture content strengthens the material in order to prevent sagging or tearing of the material. When applied at the minimal dosage of 40% moisture, a baseline of 14.05 kPa modulus of elasticity E was defined as a minimum resistance of the material (at ambient humidity conditions) to prevent sagging. It was found that the applied water not only densifies the material, but as the fibres swell and become rigid during drying, an increase in the mechanical resistance can be observed.

Mechanical tests such as the one developed in this work could help verify that with the proper applied water dosage, the material can maintain a minimum mechanical resistance to prevent settling. Thermal conductivity values ranged around 40 mW m^{-1}. K^{-1}, with a slight increase with increasing applied moisture. While these changes in thermal conductivity could be considered insignificant, there is still a loss in thermal efficiency of the material once an excessive amount of water has been used. In general, an applied moisture range of 40–60% is recommended to ensure a cohesive, fast drying, low density and thermal conductivity insulating material.

In a practical sense, it would be pertinent to have a quality control system which the wet spray water dosage was measured in a test sample before applying to an entire wall. Cellulose appliers should also regularly measure the moisture content of wet sprayed walls to ensure the correct dosage was used and verify the proper drying of the material. Other potential issues with spraying with high moisture include the increase in risk of fungal development, ether through the cellulose insulation or by transmission of hu midity to other lignocellulose materials, such as the OSB wall cavity. High humidity mighg also cause these kinds of materials to warp and bend.

These results will serve as a basis to better understand the

behaviour of cellulose insulation with added additives which improve its drying time and mechanical resistance properties. Other factors for future innovation in this material should be considered. The different types of source material, recycled paper, as well as the fibre morphology, and chemical composition could have an influence on its properties. Finally, the use of environ mentally friendly addittives to improve durability, fire and fungal resistance should be investigated to replace borates and further optimize the material.

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References

[1] AFNOR, NF EN 826 Thermal Insulating Products for Building Applications. Determination of Compression Behaviour, 2013.
[2] AFNOR, NF EN 12667 Thermal performance of Building Materials and Products-Determination of Thermal Resistance by Means of Guarded Hot Plate and Heat Flow Meter Methods-Products of High and Medium Thermal Resistance, 2001.
[3] F. Asdrubali, F. D'Alessandro, S. Schiavoni, A review of unconventional sustainable building insulation materials, Sustain. Mater. Technol. 4 (2015) 1 17, http://dx.doi.org/10.1016/j.susmat.2015.05.002.
[4] M. Bomberg, C.J. Shirtliffe, Comments on standardization of density and thermal resistance testing of cellulose fibre insulation for horizontal applications, Build. Res. Note 147 (1979) 17.
[5] M. Bomberg, K.R. Solvason, How to ensure good thermal performance of cellulose fiber insulation. Part II. Exterior walls, J. Build. Phys. 4 (1980) 119 133, http://dx.doi.org/10.1177/109719638000400204.
[6] S. Cerolini, M. D'Orazio, C. Di Perna, A. Stazi, Moisture buffering capacity of highly absorbing materials, Energy Build. 41 (2009) 164 168, http://dx.doi.org/10.1016/j.enbuild.2008.08.006.
[7] CIMA Technical Bulletin #3 CIMA, Standard Practice for Installation of Sprayed Cellulosic Wall Cavity Insulation, 1998.
[8] S. Elfordy, F. Lucas, F. Tancret, Y. Scudeller, L. Goudet, Mechanical and thermal properties of lime and hemp concrete ("hempcrete") manufactured by a projection process, Constr. Build. Mater. 22 (2008) 2116 2123, http://dx.doi.org/10.1016/j.conbuildmat.2007.07.016.
[9] T.J. Godish, D.R. Godish, Mold infestation of wet spray-applied cellulose insulation, J. Air Waste Manag. Assoc. 56 (2006) 90 95.
[10] M.A. Hubbe, R.A. Venditti, O.J. Rojas, 2007. What happens to cellulosic fibres during papermaking and recycling? A review, BioResources 2 (4) (2007).
[11] T. Kalamees, J. Vinha, Hygrothermal calculations and laboratory tests on timber-framed wall structures, Build. Environ. 38 (2003) 689 697, http://dx.doi.org/10.1016/S0360-1323(02)00207-X.
[12] M. Karoglou, A. Moropoulou, Z.B. Maroulis, M.K. Krokida, Water sorption isotherms of some building materials, Dry. Technol. 23 (2005) 289 303, http://dx.doi.org/10.1081/DRT-200047948.
[13] P. Lopez Hurtado, A. Rouilly, V. Vandenbossche, C. Raynaud, A review on the properties of cellulose fibre insulation, Build. Environ. 96 (2016) 170 177, http://dx.doi.org/10.1016/j.buildenv.2015.09.031.
[14] NAHB Research Center, Air Infiltration of Wood Frame Walls, 2009.
[15] K. Nakamura, T. Hatakeyama, H. Hatakeyama, Studies on bound water of cellulose by differential scanning calorimetry, Text. Res. J. 51 (1981) 607 613.
[16] A. Nicolajsen, Thermal transmittance of a cellulose loose-fill insulation material, Build. Environ. 40 (2005) 907 914, http://dx.doi.org/10.1016/j.buildenv.2004.08.025.
[17] T.V. Rasmussen, Prediction of density for prevention of settling of hygroscopic and nonhygroscopic loose-fill insulation in walls, J. Therm. Envelope Build. Sci. 28 (2005) 245 267, http://dx.doi.org/10.1177/1097196305048596.
[18] T.V. Rasmussen, Verification of density predicted for prevention of settling of loose-fill cellulose insulation in walls, J. Therm. Envelope Build. Sci. 27 (2003) 49 69, http://dx.doi.org/10.1177/1097196303027001004.
[19] T.V. Rasmussen, Modelling settling of loose-fill insulation in walls, part II determination of coefficients, J. Build. Phys. 25 (2002) 189 208, http://dx.doi.org/10.1177/0075424202025003605.
[20] T.V. Rasmussen, Modelling settling of loose-fill insulation in walls. Part I, J. Therm. Envelope Build. Sci. 25 (2001) 129 141, http://dx.doi.org/10.1106/F5UH-5A2X-9VRA-FHPF.
[21] C. Rode, Organic insulation materials, the effect on indoor humidity, and the necessity of a vapor barrier, Proc. Therm. Perform. Exterior Envelope Build. VII (1998) 109 121.
[22] M. Salonvaara, M. Pazera, A. Karagiozis, Impact of Weather on Predicting Drying Characteristics of Spray-Applied Cellulose Insulation, 2010.
[23] S. Schiavoni, F. D'Alessandro, F. Bianchi, F. Asdrubali, Insulation materials for the building sector: a review and comparative analysis, Renew. Sustain. Energy Rev. 62 (2016) 988 1011, http://dx.doi.org/10.1016/j.rser.2016.05.045.
[24] B. Svennerstedt, Analytical models for settling of attic loose-fill thermal insulation, J. Build. Phys. 19 (1995) 189 201, http://dx.doi.org/10.1177/109719639501900208.
[25] R.P. Tye, S.C. Spinney, A study of the effects of moisture vapour on the thermal transmittance characteristics of cellulose fibre thermal insulation, J. Build. Phys. 2 (1979) 175 196, http://dx.doi.org/10.1177/109719637900200402.
[26] S. Vėjelis, I. Gnipas, V. Kersulis, Performance of loose-fill cellulose insulation, Mater. Sci. (medziagotyra) Vol. 12 (4) (2006).
[27] U. Weise, T. Maloney, H. Paulapuro, Quantification of water in different states of interaction with wood pulp fibres, Cellulose 3 (1996) 189 202, http://dx.doi.org/10.1007/BF02228801.
[28] I. Zabalza Bribián, A. Valero Capilla, A. Aranda Usón, Life cycle assessment of building materials: comparative analysis of energy and environmental impacts and evaluation of the eco-efficiency improvement potential, Build. Environ. 46 (2011) 1133 1140, http://dx.doi.org/10.1016/j.buildenv.2010.12.002.