Wood waste as an alternative thermal insulation building material solution

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Abstract

Current insulation materials in the construction market, which are predominantly inorganic materials, have a high performance in relation to heat transfer, i.e. high R-values, but the environmental impacts in their production processes are significant. The use of bio-based natural fibre materials such as cork, cotton, wood fibre, hemp, etc. with their lower embodied energy, moisture buffering capacity and, consequently, improved Indoor Environmental Quality have received increasing focus in both research and application, particularly amongst environmentally-conscious clients and designers.

In this study a natural fibre material in the form of wood waste is examined experimentally to assess its suitability for use as a thermal insulation material, without the addition of any binder, within a timber frame wall construction. The wood waste is from primary production sources using untreated material. According to our experimental results, the thermal conductivity values of wood waste with different densities, ranged from 0.048 to 0.055 W/mK. These values are slightly higher than commonly used inorganic based insulation materials, although comparable to other natural insulation materials in the market, but have the economic advantage of being a low-cost by-product. The values relating to the material hygric performance including the water vapour diffusion resistance factor, water vapour permeability, and water absorption coefficient were also determined and presented, which will help facilitate future hygrothermal modelling.

Keywords

Wood waste, Thermal Insulation, Natural Building Materials, Hygrothermal.

1. Introduction

Buildings and the construction industry are major contributors to global CO_2 emissions through embodied and operational energy use. The industry is a major consumer of natural resources and many products contain materials that are detrimental to the indoor environment and human health (Pacheco-Torgal *et al.*, 2012). One of the most effective measures to reduce operational energy use is to insulate the building envelope, which confers benefits in both heating and cooling energy use. Current thermal insulation materials in the construction market are generally inorganic materials e.g. extruded polystyrene (XPS), expanded polystyrene (EPS), polyisocyanurate and polyurethane foam. These materials have a high performance in resisting heat transfer but the environmental impact of their production processes is high. Accordingly, the use of natural materials, which undergo minimal production processing, for application as building insulation is an important aspect in the creation of a healthy and sustainable environment.

Recently, many studies have been conducted into the use of bio-based/natural fibre insulation materials as a replacement for inorganic materials. Bio-based, i.e. plant- or animal-based, insulation materials are a novel class of insulation materials which include products such as cork, cotton, wood fibre, flax, hemp, coconut, cellulose, rice, sheep's wool and others. The plant-based materials sequester atmospheric carbon dioxide through photosynthesis and consequently their use in construction can reduce the net embodied carbon dioxide of a building (Lawrence *et al.*, 2013). When used appropriately, these materials can deliver thermal and acoustic insulation performance comparable to other insulation materials, but with a lower, or potentially negative, carbon footprint and fewer health issues during installation (Sutton *et al.*, 2011). Moreover, they have hygroscopic properties, which have positive effects on building energy consumption (Osanyintola and Simonson, 2006), HVAC system energy consumption in dwellings (Steeman *et al.*, 2009; Woloszyn *et al.*, 2009) and indoor air quality in buildings (Simonson *et al.*, 2002). Hygroscopic materials exposed to room air equilibrate indoor humidity through their ability to absorb, store, and release water vapour from the air (Korjenic *et al.*, 2010; Simonson *et al.*, 2004; Shea *et al.*, 2012). This property favourably influences the indoor air humidity, primarily in winter when prolonged periods of low indoor air humidity may be experienced (Korjenic *et al.*, 2011), and reduces the potential for mould growth (Hall, 2010).

In the following studies, the use of natural fibre insulation materials without the addition of any binder is discussed and their mechanical, thermal or hygrothermal characteristics are presented. Zhou *et al.* (2010) developed a binderless cotton stalk fibreboard (BCSF) from cotton stalk fibres without resins and other chemical additives by hot-pressing. The boards were produced at densities of 150–450 kg/m^3 and achieved thermal conductivity values ranging from 0.0585 to 0.0815 W/mK, which are close to those of expanded perlite and vermiculite within the same density range. Korjenic *et al.* (2011) investigated the use of jute, flax, and hemp for use in the development of novel insulating materials made from renewable resources and reported comparable thermal and mechanical properties to those of established conventional insulation materials such as mineral wool, polystyrene and polyurethane. Panyakaew and Fotios (2011) developed two low density thermal insulation boards, one made from coconut husk and another from bagasse, both formed without the use of chemical binding additives. The results of their experimental study indicated that both insulation boards had thermal conductivity values ranging from 0.046 to 0.068 W/Mk which, at the lower end, were close to those of conventional insulation materials such as mineral wool. Zach *et al.* (2012) conducted a series of measurements to evaluate the thermal performance and application of sheep's wool insulation. Results indicated that the sheep's wool had comparable thermal performance to mineral/rock wool. Furthermore, the ability of sheep's wool to absorb moisture helped to prevent condensation, regulate humidity, and created a pleasant indoor atmosphere. Briga-Sá *et al.* (2013) experimentally studied the potential applicability of woven fabric waste (WFW) and a waste of this residue, named woven fabric sub-waste (WFS), as thermal insulation for use in construction. The results showed that the WFW had better insulation characteristics than the WFS, and the thermal conductivity value of WFW was similar to the conventional thermal insulation materials, such as expanded polystyrene, extruded

99 polystyrene and mineral wool. Charca *et al.* (2015) studied the thermal properties of Ichu, which is an Andean feather
100 grass, as a local and cheap natural insulation material for rural dwellings. The results revealed that the thermal
101 conductivity varied from 0.047 to 0.113 W/mK for mats with unidirectional oriented fibres. Wei *et al.* (2015)
102 investigated the effect of high frequency heating, board density, particle size and ambient temperature on the
103 properties of a new thermal insulation material made from rice straw. The results indicated that the optimum physical
104 and mechanical properties of the boards were obtained with a moisture content of 14% and board density of 250
105 kg/m^3. Additionally, the thermal insulation boards had good thermal performance, recording a thermal conductivity in
106 the range of 0.051 to 0.053 W/mK.
107 These studies highlight that natural building materials are increasingly being investigated as viable thermal insulation
108 materials for the external envelope of new and existing buildings. The highlighted studies focused primarily on thermal
109 and mechanical properties of these materials; few of them considered their hygric behaviour.
110 In this paper, the use of Wood Waste (WW) as an insulation material for building envelopes is investigated and
111 characterisation of its thermal and hygric performance is reported. WW is a common by-product of construction and
112 demolition, packaging, municipal activities, joinery and furniture manufacture (DEFRA, 2013). The use of this material
113 within timber frame wall construction, without the addition of binder, facilitates improved management of wood waste,
114 ease of recycling, and potentially healthier indoor environments. At the present time, wood fibers are used in the
115 production of wood fibre insulation boards by adding low quantities of PUR resin in a dry process. In this case, the
116 thermal conductivity values of the boards range between 0.037-0.05 W/mK (GUTEX,2015); however, this production
117 process also requires a large amount of energy (HPBP, 2017). The use of wood waste received from local sawmills
118 without treating will reduce energy use and relatedly carbon dioxide release.
119 Wood waste can be defined as a material that has been used for some time and then disposed by the users as well
120 as the residues from primary wood processing such as sawdust (Alf-Cemind, 2017). In this study, the properties of
121 the wood waste from primary production sources using untreated material are examined. These residues are
122 industrial wastes generated by either sawmills and other millwork companies, which are primary wood product
123 manufacturers, or companies that use products from wood materials milled by primary wood, which are secondary
124 wood product manufacturers. The primary wood manufacturers produce a variety of WW including bark, chips,
125 edgings, sawdust, and slabs. These residues typically have a moisture content of 40 to 50 percent. The secondary
126 wood product industries produce a variety of WW including chips, ends, and sawdust. The moisture content of these
127 wastes varies considerably because both green, harvested wood and kiln-dried wood are used in secondary
128 manufacturing. An average moisture content of 45 percent is commonly used in the wood energy industry (EPA,
129 1996).

Our paper reports the characterisation of the aforementioned WW from experimental testing of samples under a range of environmental conditions as this is necessary to assess the performance of a thermal insulation material used in the building envelope.

2. Hygrothermal Behaviour

The assessment of building envelopes subject to temperature and moisture gradients is a prerequisite in the investigation of building energy efficiency and the evaluation and creation of a comfortable indoor environment (Moon *et al.*, 2014). If such environmental conditions are not assessed with a holistic approach and appropriate solutions integrated into the building design, the resulting building may suffer from excess energy use through increased heat transmission coefficients of the building envelope elements. The building may also experience structural damage from interstitial condensation and elevated moisture content, e.g. leading to timber decay, or surface condensation damage in the form of mould which will lead to poor indoor air quality and an unhealthy environment. The building element or zone response to temperature and moisture gradients is generally referred to as 'Hygrothermal behaviour'. This behaviour considers the simultaneous and inter-dependent occurrence of heat absorption, storage, and release, and moisture (liquid/vapour) absorption, storage and release (Hall, 2010). In air with a given relative humidity and temperature, a porous building material, after some period of time exposed to such an environment, will reach a state of equilibrium with this environment, exchanging the water in its pores with the ambient air. This relationship between the water content and relative humidity is described by the sorption isotherm (Hansen, 1986). If the equilibrium is achieved during drying, desorption isotherm is produced, and if achieved during wetting, the sorption isotherm is realised (BS EN ISO 12571, 2013).

3. Material

The WW material used in the experiments was taken from a Welsh saw mill, and was the by-product of furniture and joinery manufacturing. The material was used as received without addition of binders. The material particle size was variable but within the range of approximately 1 - 4 mm and in a shape of long and thin curl (Fig.1).

Fig. 1. Wood waste as received from the saw mill (Source: Plant Fibre Technology ©)

WW can be applied to timber frame wall construction in the same way as the current application of cellulose fibres (CF). CF can either be installed by 'loose fill' or 'wet spray method'. In the loose fill application, CF are first separated

by pneumatic equipment, and then are delivered by air pressure into wall cavities through a hose. In the wet spray application, a separate pump is used to spray water and CF simultaneously in order to increase the adherence of the fibres (Hurtado *et al.*, 2016). For both applications, when WW is used, it can slump under its own weight creating a void at the top of the insulated space. The settlement serves to reduce the overall thermal resistance due to increased heat transfer in the, relatively wide and un-filled, air void (Shea *et al.*, 2013). Generally, for all practical insulation densities, thermal conductivity increases with increasing density and it is, therefore, important to place WW into the wall construction at a density that balances adequate thermal resistance against ability to resist slump.

The hygroscopic nature of wood permits absorption and desorption of water vapour from the surrounding environment, tending only to reach an equilibrium condition when the atmospheric relative humidity is stable. Under varying environmental relative humidity conditions, typical of most occupied buildings, the moisture of wood is changing continuously and an equilibrium is rarely reached (Popescu and Hill, 2013). Therefore, determining both the thermal and hygroscopic properties of WW, as a wood residue, will be beneficial in order to facilitate dynamic simulation of its performance and support design decisions for its use in timber frame wall construction as a thermal insulation material.

4. Experimental Methods

The experiments conducted to determine the apparent (bulk) density, thermal conductivity, water vapour transmission properties, true (absolute) density, water absorption coefficient and hygroscopic sorption/desorption properties of WW are explained in the following sections along with a description of the test equipment, sample preparation, and test procedures.

4.1. Determination of Apparent (bulk) Density

The apparent (bulk) density of WW was determined in accordance with BS EN 1602 which specifies the equipment and procedures for determining the apparent density under reference conditions (BSI, 2013a).

Preparing Samples and Test Procedures

Three simple timber frames with the dimension of 400 x 400 mm were constructed and a 400 x 400 OSB sheet with a thickness of 9 mm was fixed to the frame to form a rigid base to contain the WW material for laboratory testing. The depths of the frames were 60, 50 and 40 mm in order to produce the samples with different densities, but equal masses. These depths of containers were selected to suit the value required in the standard for testing loose-fill materials (BSI, 2001a; ISO 8301), which must be at least 10 times the mean dimension of the beads, grains, flakes, etc. of the loose-fill material.

The WW material was first dried in the oven at 50^{o}C until its mass became constant. The mass was accepted to become constant when the change of mass between three consecutive weighings became less than 0,1 % of the total mass according to BS EN ISO 12571 (BSI, 2013c). The oven temperature was lower than prescribed in BS EN ISO 12570 (BSI, 2013) but was chosen to limit surface scorching of low density WW, which was experienced at

higher temperatures. Accordingly, whilst stable mass was attained for all samples it is likely that some moisture may remain in the material. When the material had attained a constant mass, generally after around 48 hours, the samples were removed from the oven and placed into a conditioning room at controlled conditions of 23±3°C and relative humidity of 50±5%. The time required for the conditioning of the wood waste was between 20 and 25 days. Fig. 2 presents the drying and conditioning facilities used for the WW material.

(a)   (b)

Fig. 2. a) Drying WW, b) Conditioning WW.

After conditioning, the WW material was placed into a wood frame with a depth of 60 mm to a density that it would not slump under its own weight; the resulting mass of this material was measured by an electronic balance with a maximum capacity of 32 kg and resolution of 1 g. As the material does not have a rigid form, its volume was taken to be equal to the internal volume of the frame. The apparent density of WW in the frame, ρ, in kg/m^3, was then calculated using Equation 1.

$$\rho = m / V \qquad \text{(Equation 1)}$$

where

m is the mass of the test specimen, in kg;

V is the volume of the test specimen, in m^3.

The same mass of material as used in the 60 mm deep container was placed, under compression, into the other frames which had depths of 50 mm and 40 mm, and the density was then determined using the same approach.

4.2. Determination of Thermal Conductivity

The thermal conductivity of the WW material was determined in accordance with BS EN 12667 and ISO 8301. BS EN 12667 specifies principles and testing procedures for determining, by means of the guarded hot plate or heat flow meter methods, the thermal resistance of test specimens having a thermal resistance of not less than 0.5 m^2·K/W (BSI, 2001a). ISO 8301 defines the use of the heat flow meter (HFM) method to measure the steady-state heat transfer through flat slab specimens and the calculation of the heat transfer properties of specimens (ISO, 1991). Two types of thermal test instruments, ISOMET 2114 (for small samples) and Lasercomp FOX 600 Heat Flow Meter (for larger sample sizes up to 600 x 600 mm, but not less than 250 mm x 250 mm), were used for thermal conductivity testing.

The Applied Precision ISOMET 2114 is a portable hand-held measuring instrument for direct measurement of thermal transfer properties of a wide range of isotropic materials including cellular insulating materials, plastics, glasses and

minerals. It is equipped with two optional types of measurement probes: needle probes for soft materials and surface probes for hard materials. The instrument applies a dynamic measurement method, which results in a much reduced measurement time in comparison with steady state measurement methods. The ISOMET measures the quantities of thermal conductivity (W/mK), volumetric heat capacity (J/m^3K), thermal diffusivity (m^2/s), and temperature (^oC) (AP, 2011).

The Lasercomp FOX600 is a Heat Flow Meter (HFM) instrument. In a heat flow meter, a specimen is positioned between two temperature controlled plates. These plates establish a user-defined temperature difference across the sample (LaserComp, 2010). The sample thickness can be set to match the target thickness of compressible samples, or, in the case of our test, the actual sample dimension, as detected by four in-built optical encoders. The resulting heat flux from steady-state heat transfer through the specimen is measured by two proprietary thin film heat flux transducers covering a large area of upper and lower sample surfaces and the thermal conductivity determined by reference to a calibration standard.

Preparing Samples and Testing Procedure

The tests using the ISOMET 2114 were performed for three different densities determined in Section 4.1, and two different moisture states, namely, oven-dried and conditioned to 50% RH. The material was placed into a cylindrical plastic container (Fig. 3). A plastic plate with a hole in the middle was installed over the container, and then the container was completely sealed with an aluminium foil to limit interaction between room air and the contained material. The needle probe of the ISOMET was inserted into the material, and the thermal conductivity of the material was measured.

Fig. 3. Thermal conductivity testing using the ISOMET 2114 thermal analyser.

Heat Flow Meter thermal conductivity measurements

Prior to testing in the HFM, the wood frames and the WW were conditioned to the maintained condition of the University conditioning chamber, as described in Section 4.1. The weights of the WW material and the frames were measured throughout the conditioning process until they had achieved a constant mass, which was the state that the change of mass between three consecutive weighings, each made at least 24 h apart, became less than 0,1 % of the total mass. After drying, the interior surfaces of the frames were lined with an aluminium foil to limit exchange of moisture between the test material and the frame or external environment, which could affect the thermal measurements of the WW material. Finally, equal amounts of WW were placed into the wood frames and covered

with an OSB sheet and sealed (Fig. 4a). These samples, prior to being placed into the HFM instrument, were surrounded by a thermal insulation board, which was made from polyisocyanurate (λ - 0.022 W/mK), to further limit edge heat losses (Fig. 4b).

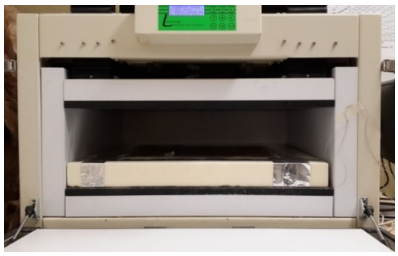
(a)   (b)

Fig. 4. a) WW and foil-lined OSB frame, b) WW and insulation in the HFM instrument.

The WW placed into the frame with the greatest volume (depth equal to 60 mm) was achieved through simple light compression by hand. However, the same amount of material placed into the frame with the thickness of 50 mm required compression from a series of G-clamps (Fig. 5a); and for the smallest volume frame (depth equal to 40 mm) a press was used to apply a pressure of 25 kN (Fig. 5b).

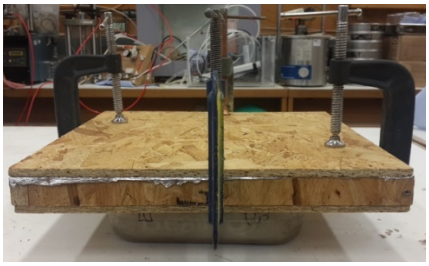
(a)   (b)

Fig. 5. a) The compression of wood frames by G-clamps, b) heavy-duty press machine.

Since the apparent (i.e. measured) thermal conductivity of materials will change depending on their temperatures as well as their densities and moisture contents, the samples were tested at different temperatures as presented in Table 1.

In a HFM, a temperature gradient is established through closely-controlled heating or cooling of the two plates that sandwich the test specimen. Within the range for which the HFM is calibrated (-15C to 65^{o}C) and depending on external cooling capacity, the temperature of each plate and hence heat flow direction can be selected by the user. In agreement with the recommendations of the relevant test standards, all tests were conducted with an upward heat flow direction and thus the lower plate was hotter than the upper plate. These tests, similar to the tests performed by ISOMET, were carried out for two different moisture states, namely, oven-dried and conditioned to 50% RH.

Table 1. HFM temperature set-points for all specimen samples.

Plate and mean temperatures (Samples 1, 2 and 3)		
$T_{upper\ plate}$ (°C)	T_{mean} (°C)	$T_{lower\ plate}$ (°C)
10	20	30
20	30	40
30	40	50

The raw HFM test results represent the total thermal resistance of both the frames and the WW material, i.e. the whole sample, including the OSB and timber frame. The thermal conductivity of the WW material alone was determined using Equation 2.

$$R_{WHOLE\ SAMPLE} = R_{WOOD\ FRAME} + R_{WOOD\ WASTE}$$

$$d_{WS}/\lambda_{WS} = d_{WF}/\lambda_{WF} + d_{WW}/\lambda_{WW} \quad \text{(Equation 2)}$$

where

R : thermal resistance;

d : thickness;

WS : the whole sample;

WF : the wood frame;

WW : the wood waste.

Equation 2 treats the sample as if formed of three, horizontal, homogeneous layers comprising OSB sheet, WW material, OSB sheet. The middle layer of the test sample clearly comprises both a perimeter wood frame and a thin vertical OSB edge, however, non-planar heat transfer is assumed to be negligible and is ignored as the area over which HFM measurements are recorded (a central thermopile core of approx. 254 mm x 254 mm) is much smaller than the area of the test specimen (400 mm x 400 mm), which is further surrounded by rigid insulation as indicated in Fig. 4b.

4.3. Determination of Hygroscopic Sorption/Desorption Properties

The hygroscopic sorption/desorption properties of the wood waste material were determined in accordance with BS EN ISO 12571 (BSI, 2013) using the desiccator method with suitable salt solutions to attain the desired range of relative humidity.

Preparing Samples and Testing Procedure

Three samples with the dimensions of 100 mm x100 mm were prepared. The samples of oven-dried WW were contained in a plastic mesh to achieve a density of 117 kg/m^3 (Fig. 6a). The open mesh of the container allowed the WW to exchange moisture with the conditioned air in the desiccator chamber until equilibrium with the environment was attained. Table 2 presents the relative humidity values selected for measuring sorption/desorption at the air temperature of 23°C and the required salt solutions.

Table 2. Relative humidity and salt solutions.

No	Salt	Relative Humidity (%)
1	$MgCl_2.6H_20$	33
2	$Mg(NO_3)_2.6H_20$	53
3	NaCl	75
4	KNO_3	93

The sorption test was initiated with the solution prepared by mixing $MgCl_2.6.H_2O$ and distilled water. This solution was put into a glass plate first, and then this plate was placed to the container to maintain the required relative humidity. A metal mesh was installed at 5 cm above the plate to raise the samples above the fluid level. A thin watertight, but vapour permeable, insulation layer was placed on the mesh to protect the samples from the solution. Prior to placing the samples in the desiccator, the mass of each sample was measured. After placing the samples, all joints between the container and its cover were sealed with an aluminium tape (Fig. 6b). Finally, the entire container was placed in a conditioning room which maintained an air temperature of (23±0.5)°C and a relative humidity of (50±5)%. The mass of the samples was periodically measured until they were in equilibrium with the environment (constant mass), which was the state that the change of mass between three consecutive weighings became less than 0,1 % of the total mass. When the alumininum tape was opened to measure the weight of the samples during the test, the relative humidity and the temperature inside the container were also checked with a humidity- temperature meter. This checking procedure can be seen in Fig. 6c. The measurements showed that the salt solutions provided the target conditions. After reaching the equilibrium, the test was repeated with $Mg(NO_3)_2.6H_20$, NaCl, and KNO_3 respectively.

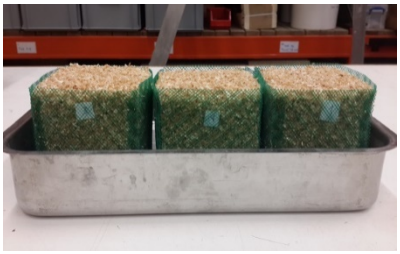
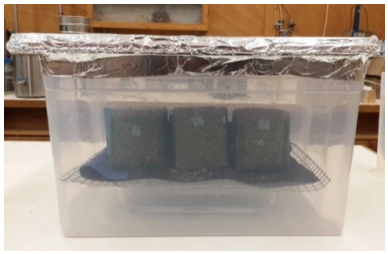
(a)  (b)  (c) 

Fig. 6. a) The samples, b) The test set-up for desiccator method,
c) The humidity / temperature meter inside the container.

The desorption test began with the solution of KNO_3 and distilled water, and the test was then repeated with NaCl, $Mg(NO_3)_2.6H_20$, and $MgCl_2.6.H_2O$ respectively.

4.4. Determination of Water Vapour Transmission Properties

The water vapour transmission properties of WW were determined in accordance with BS EN ISO 12572 which specifies a method based on cup tests for determining the water vapour permeance of building products and the water vapour permeability of building materials under isothermal conditions (BSI, 2001b).

Preparing Samples and Testing Procedure

Tests were conducted for both 'dry and wet cup' states, which provided information about the performance of the WW material under low and high humidity conditions respectively. The accepted test conditions according to BS EN ISO 12572 are presented in Table 3.

Table 3. Water vapour transmission test conditions.

Set	Condition (°C - RH%)	Tolerances		
		Temperature (°C)	Relative humidity (RH, %)	
			Set point	Tolerance
Dry State	23 - 50	23 ± 0,5	0	+3
Wet State	23 - 50	23 ± 0,5	93	±3

Three plastic containers with length and width each of 150 mm and a height of 80 mm were cut, leaving the upper and bottom surfaces open. The bottom surfaces of these containers were covered with a plastic mesh, and filled with the conditioned WW, to a density of 117 kg/m^3. Every sample was then placed over the mouth of a test cup having approximately the same size aperture as the plastic container, which included silica gel for the dry cup test. The joints between the containers and the test cup were sealed with an aluminium tape. Finally, the test samples were placed into the conditioning room. The weights of the samples were periodically measured to determine the rate of water vapour transmission in the steady state; the containers remained sealed for the duration of the test. For the wet cup test, the samples were prepared in the same manner as for the dry cup test but with Potassium nitrate (KNO_3) solution to provide a relative humidity of 93% (Fig 7).

Fig. 7. The samples during the wet cup test.

4.5. Determination of True (Absolute) Density and Porosity

The true density of WW is determined by helium pycnometer, which gives the closest approximation to the true density of a material. In this method, the helium penetrates the smallest pores, approaching the real volume (Donato and Lazzara, 2012) and this value was then used to calculate the porosity value of WW.

An AccuPyc 1330 gas displacement pycnometer was used during the tests. In our tests, helium gas was used to provide rapid and accurate results. The test procedure with regards to number of purges, purge fill pressure, number of runs, and equilibration rate is presented in Table 4.

Table 4. The parameters for the true density tests

Parameters	Data
Number of purges	10
Purge fill pressure	19500 psig
Number of runs	10
Equilibration rate	0.0050 psi/min

The test set-up comprised of the pycnometer device and the cylinder containing helium as shown in Fig. 8.

Fig. 8. The test set-up for determining true density.

The porosity value of WW is calculated by Equation 3:

$$P = 100 \times (1- (d_b / d_t)) \quad \text{(Equation 3)}$$

where

d_b : Bulk density

d_t : True density

Preparing Samples and Testing Procedure

The oven-dried WW was used for this test to prevent the distorting effect of water vapour on the volume measurement. An empty sample cup was first measured, and then the dried material was placed into the cup (Fig. 9). The amount of this material was calculated for the density of 117 kg/m^3. The sample was then inserted into the cell chamber of the pycnometer device. After modifying the test parameters, the test was initiated. The value of the true density was obtained at the end of 10 purges and 10 runs. The test was repeated three times, and then the mean value of three measurements was calculated.

(a)   (b)

Fig. 9. a) The cup including WW b) The cup inserted into the cell chamber.

4.6. Determination of Water Absorption Coefficient

The water absorption coefficient of WW was determined in accordance with BS EN ISO 15148 which specifies a method for determining, by partial immersion with no temperature gradient, the short-term liquid water absorption coefficient (BSI, 2002). Since there is no other standard for loose materials, this method was applied for determining the water absorption coefficient of WW.

Preparing Samples and Testing Procedure

The test conditions given in Table 5 were adjusted in accordance with BS EN ISO 15148.

Table 5. The water absorption test conditions.

Temperature (°C)	Relative humidity (%)
20 - 26	40 - 60

In accordance with the standard, and because of the difficulty in sealing a low density loose fill material, the WW was placed into a tightly-fitting tube supported on a wire mesh placed over the mouth of the tube. In this test, six plastic tubes with a diameter of 100 mm and a length of 80 mm were cut from a plastic pipe. The bottom surfaces of these tubes were covered with a plastic mesh with very small holes (approximately 2 mm in diameter) that prevented the particles from falling into the water. The containers were filled with the conditioned WW, to a density of 117 kg/m^3. A metal grid was then placed into a larger plastic container filled with water. This grid allowed the bases of the samples remain clear of the bottom of the container. The level of the water in the container was controlled during the test to ensure that it remained at 5 mm (± 2 mm) above the bases of the samples. Finally, six samples were placed over the grid, and a timer was used to record the partial immersion time. After approximately 5 minutes the samples were removed from the water, the surfaces were blotted with a damp sponge, and weighed. This procedure including immersion, removal, surface drying and weighing was repeated at durations of 20 min, 1 h, 2 h, 4 h, 8 h, 12 h, 21 h and 24 h to provide a series of masses m_t at times t. The procedures of blotting and weighing were carried out within a minute and then the samples were returned to the water immediately afterwards. Fig. 10 presents the test set-up including the container, grid, samples, scale, timers and sponge.

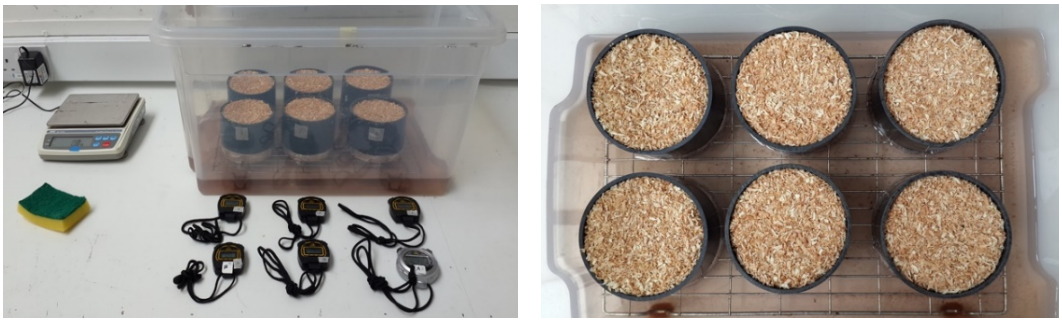


Fig. 10. The test set-up for the water absorption test.

This test was repeated for the WW sample with a density of 158 kg/m^3 in order to examine the effect of density on the water absorption of WW.

5. Experimental Results and Discussions

The results of the experiments carried out for determining apparent density, thermal conductivity, hygroscopic sorption/desorption curves, water vapour diffusion resistance factor, true density and water absorption coefficient are presented in this section.

5.1. Apparent Density

The apparent densities of three samples prepared with the conditioned WW were calculated using Equation 1, as described in Section 4.1. The first one, 117 kg/m^3, is the density at which the WW would resist slump under its own weight. The others, 158 kg/m^3 and 167 kg/m^3, are the resultant values after compression in to shallower containers. All results are presented in Table 6. As required and expected, the density of WW increased as the thickness of the frame decreased since the cavities in the frame reduced due to the increased compression of the (same mass of) material.

Table 6. The apparent densities of WW in the different wood frames.

Samples	Density (ρ - kg/m^3)
Sample 1 (d= 60mm)	117
Sample 2 (d= 50mm)	158
Sample 3 (d= 40mm)	167
d : thickness of the sample	

5.2. Thermal Conductivity

The thermal properties i.e. thermal conductivity, volumetric heat capacity, and thermal diffusivity, measured by the ISOMET dynamic thermal analyser for different densities are given in Table 7. The results are presented for both the oven-dried WW and the conditioned WW.

Table 7. The thermal properties measured for the different densities of WW by ISOMET.

MATERIAL	Density (ρ - kg/m^3)	Thermal Conductivity (λ- W/mK)	Volumetric Heat Capacity (VHC - 10^6 J/m^{3}K)	Thermal Diffusivity (a - 10^{-6} m^2/s)
Oven-Dried Material	117	0.0528	0.1026	0.5153
	158	0.0554	0.1830	0.3080
	167	0.0558	0.1760	0.3168
Conditioned Material	117	0.0568	0.1546	0.3674
	158	0.0622	0.2249	0.2765
	167	0.0629	0.2133	0.2951

Fig. 11 presents the thermal conductivity values of WW measured by both the ISOMET device and the Heat Flow Meter. The HFM results are presented for the case of a 20^{O}C temperature difference between measurement plates

and a mean temperature of 30^{O}C. The values measured by HFM were consistently lower than the values measured by the ISOMET unit. The ISOMET applies a dynamic heat flux measurement method, which enables it to reduce the measurement time in comparison with steady state measurement methods. The HFM use a steady-state heat flux measurement method as explained in Section 4.2. The stated accuracy of the two devices is 1% for the Heat Flow Meter (LaserComp, 2010) and 5% of reading+0.001 W/mK for the ISOMET device (AP, 2011). The results taken from both instruments, as expected, indicated that the increased moisture content due to conditioning of the material caused the thermal conductivity to increase.

Whilst the expected general trend of increasing apparent thermal conductivity with increasing density, increasing moisture content, and increasing temperature is apparent (Figures 11 and 13), it is evident that, accepting the different degree of error between the HFM and ISOMET devices, there is a consistently higher value of thermal conductivity reported by the ISOMET device (Figure 11) relative to the HFM; the difference between the apparent thermal conductivity being greatest for the conditioned samples. The transient measurement method employed by the ISOMET needle probe, a variation of the Hot Wire method, has some advantages relative to the Heat Flow Meter e.g. reduced sample material quantity, small temperature gradient, and short test duration. However, other investigators (Campanale and Moro, 2016) have identified that the heating sensor causes a latent heat exchange due to the phase changes in the water inside the specimen close to the sensor, and this influences the thermal conductivity measured value. Whilst the Heat Flow Meter causes moisture migration between hot and cold plates it has been demonstrated (Deganello et al., 2013, cited in Campanale and Moro, 2016) that for specimens with a moisture content lower than 8.5% the error due to phase changes and moisture redistribution is less than 2.5% if the thermal conductivity is derived from the HFM measurements recorded after reaching steady state, which is the case for our presented results.

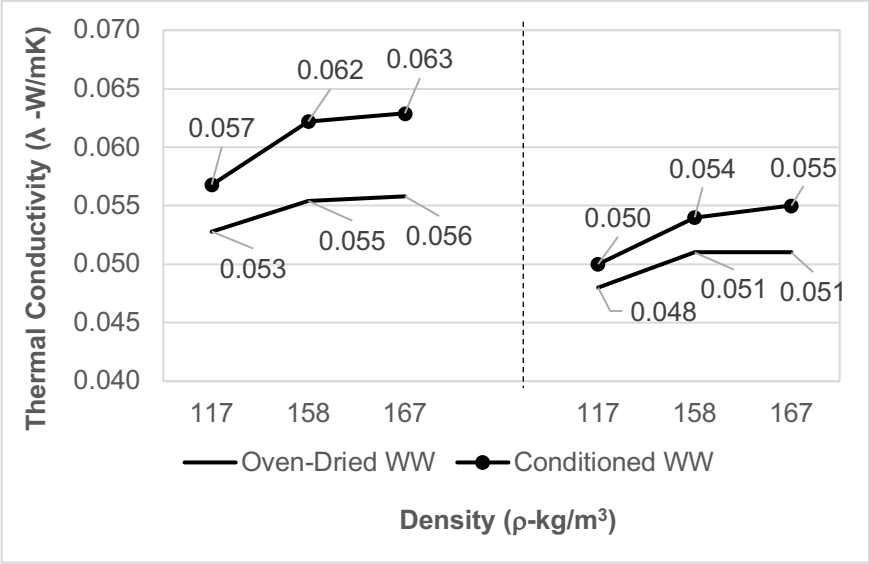


Fig. 11. The thermal conductivity values for different densities of WW by HFM and ISOMET.

In addition to variations due to moisture, density and temperature, there are numerous other factors that could influence the measured thermal conductivity in both test methods including, for example, surface contact resistance, inhomogeneity in the material sample, sample geometry, directional-dependencies (anisotropy) etc. For the oven dried samples, the difference between HFM and the ISOMET device is +/-10%. Rides et al. (2009) performed inter-comparison tests of a range of methods including both Hot Wire probes and Heat Flow Meters and observed variations of 6% for thermal conductivity, albeit on a more homogeneous and isotropic plastic material.

The measured thermal conductivity of oven-dried value of WW (0.048 W/mK) with the density of 117 kg/m^3 is similar to that of the lower density wood chipping material reported in Gellert (2010); and better than cereal and reeds of similar density (Fig. 12).

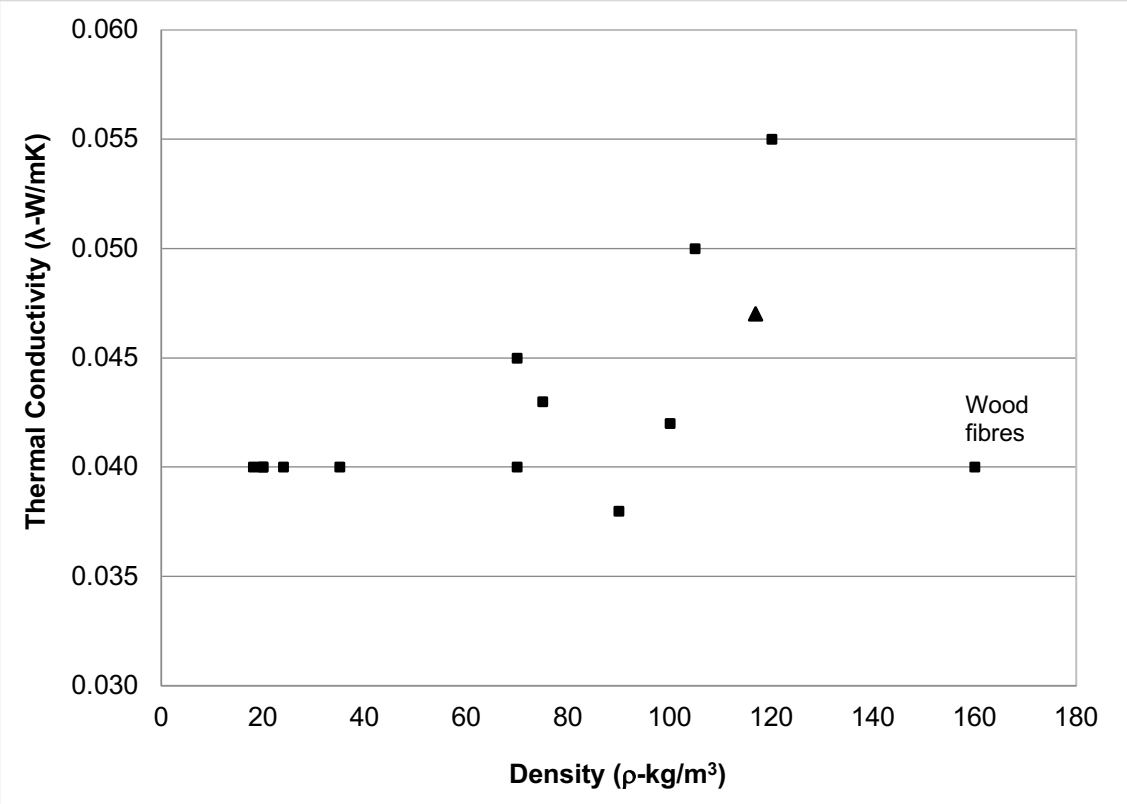


Fig. 12. Thermal conductivity versus density for different natural insulation materials

Fig.13 presents the temperature-dependent thermal conductivity, as measured using the HFM, of the oven-dried and conditioned WW for all densities.

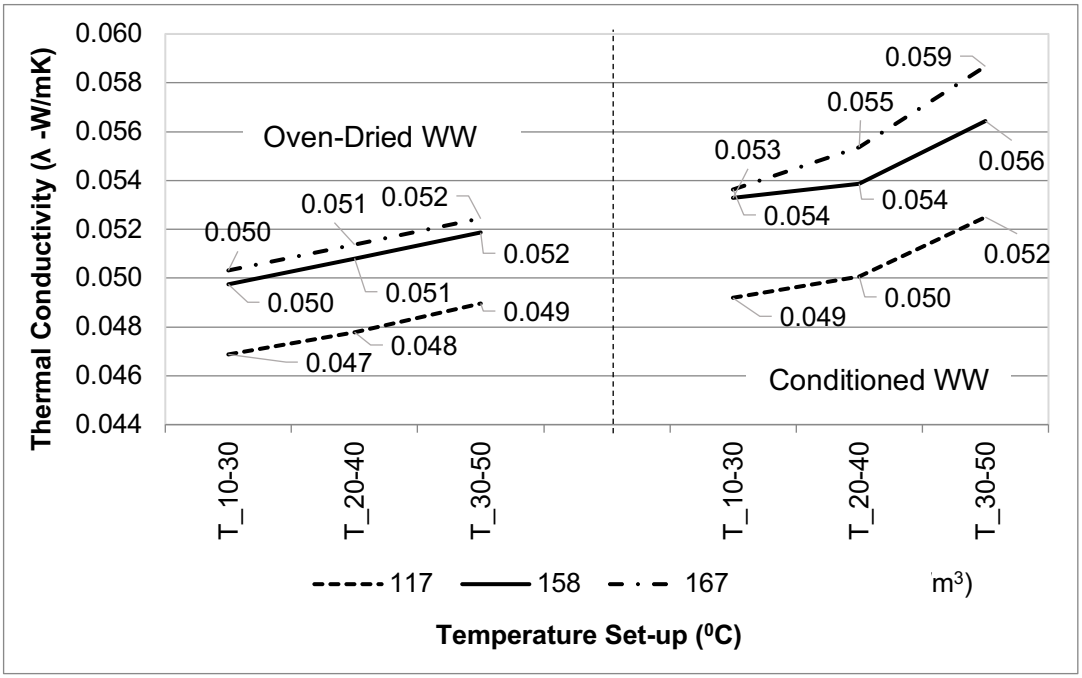


Fig. 13. Thermal conductivity values measured by HFM for WW.

As expected, the thermal conductivity of the material increased as the temperature increased for both the oven-dried and conditioned WW, and all densities. The thermal conductivity of the conditioned samples was higher due to their increased moisture contents. While the differences between the oven-dried and conditioned samples changed 7-11% when measured by ISOMET, they changed 4-7% when measured by HFM because of the different measurement methods of the devices as discussed in Section 5.2.

5.3. Determination of Hygroscopic Sorption/Desorption Properties

The moisture contents at each relative humidity were calculated using Equation 4 as presented in BS EN ISO 12571 (BSI, 2013). These values and their standard deviations for each relative humidity are given in Table 8. According to the results, the biggest difference in the moisture contents of the samples were calculated for 93% RH during the sorption.

$$u = (m-m_0)/m_0 \quad \text{(Equation 4)}$$

where

m : the mass of the test specimen at each relative humidity.

m_0 : the initial mass of the test specimen

Table 8 The moisture contents at each relative humidity.

Samples	Moisture contents at sorption				Moisture contents at desorption			
	33%RH	53%RH	75%RH	93%RH	93%RH	75%RH	53%RH	33%RH
Sample 1	0,045	0,068	0,109	0,153	0,159	0,118	0,086	0,069
Sample 2	0,045	0,065	0,106	0,143	0,159	0,123	0,082	0,072
Sample 3	0,044	0,067	0,109	0,149	0,158	0,116	0,082	0,067
St Deviations	0,0005	0,0017	0,0019	0,0050	0,0005	0,0036	0,0023	0,0024

The moisture contents of WW versus the relative humidities inside the plastic container during the test are given in Fig. 14. In common with isotherm test results for many other materials, hysteresis was observed in the material. The duration of the tests varied between 20 and 30 days depending on the target relative humidity. It took approximately one month for the high relative humidity values to be obtained. The moisture content of WW from 33%RH and 93%RH increased approximately 11% at sorption, and decreased approximately 9% during desorption across the same range. In addition, the moisture content increased more rapidly from 53%RH upwards.

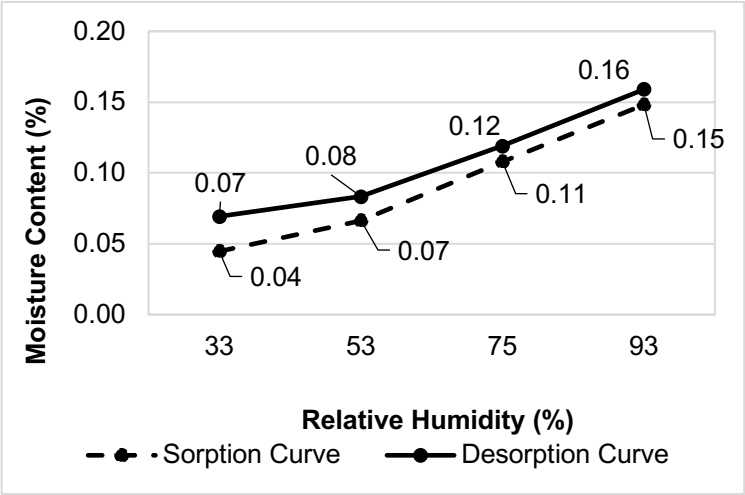


Fig. 14. Sorption and desorption curves for WW.

5.4. Determination of Water Vapour Transmission Properties

Table 9 presents the results of the dry and wet cup tests for WW calculated using Equations 5-10, and the standard deviation values calculated for three samples. As expected, these results indicate that WW has a low water vapour resistance at high relative humidity compared to the low relative humidity conditions. Moreover, the permeability of WW was higher at high relative humidity, i.e. the permeability of the material increased as the relative humidity increased.

521 Table 9. The results of the dry and wet-cup tests for WW.

Water Vapour Transmission Properties	**Eq (5-10)**	**Dry Cup Test**	**Standard Deviation (three samples)**	**Wet Cup Test**	**Standard Deviation (three samples)**
Water Vapour Permeability (δ) - (kg/msPa)	$\delta = W.d$ (Eq.5)	2.20E-11	4,27E-13	4.92E-11	1,07E-12
Water Vapour Diffusion Resistance Factor (μ) - (--)	$\mu = \delta_{air}/\delta$ (Eq.6)	9,06	1,76E-01	4,05	8,92E-02
Water Vapour Diffusion Equivalent Air Layer Thickness (s_d) - (m)	$s_d = \mu.d$ (Eq.7)	0.68	1,32E-02	0.30	6,69E-03
Water Vapour Transmission Rate (g) - (kg/m^2s)	$g = G/A$ (Eq.8)	4.19E-07	8,16E-09	9.39E-07	2,05E-08
Water Vapour Permeance (W)- (kg/m^2sPa)	$W = G/A.\ \Delta p_v$ (Eq.9)	2.93E-10	5,70E-12	6.56E-10	1,43E-11
Water Vapour Resistance (Z) - (m^2sPa/kg)	$Z = 1/W$ (Eq.10)	3.42E+09	6,65E+07	1.53E+09	3,31E+07

Other Abbreviations
d : Layer thickness
s_d : Water Vapour Diffusion Equivalent Air Layer Thickness
G : Water vapour flow rate through specimen
Δp_v : Water vapour pressure difference across specimen
A : Area of specimen
Eq : Equation

522
523 The results of the dry and wet cup tests conducted by Vololonirina *et al.* (2014) for wood fibre (WF) material are
524 compared to our results for wood waste (WW) in Table 10.

525 Table 10. The results of the dry and wet-cup tests for WW and WF.

	Dry Cup Test		Wet Cup Test	
	WF	WW	WF	WW
Water Vapour Permeability (δ) - (kg/msPa)	3.60E-11	2.20E-11	8.30E-11	4.92E-11
Water Vapour Diffusion Resistance Factor (μ) - (-)	6	9.06	2	4.05

526
527 The cup tests demonstrate that WW has slightly increased resistance to water vapour diffusion relative to the WF
528 material; proportionally more so at the higher humidities of the Wet Cup test where the transport of liquid water
529 increases and vapour transport diminishes. Where transfer is dominated by vapour diffusion, WW records diffusion
530 resistance more than 50% higher than WF.

531

5.5. Determination of True (Absolute) Density and Porosity

The true density values measured by the Pycnometer device and the porosity (P, %) values calculated by Equation 3 for the density of 117 kg/m^3 of are presented in Table 11. Since the true density measurements repeated three times gave similar results to each other without obtaining any extreme value, their means were given in the table.

Table 11. The measured true densities and the calculated porosity values for different densities.

Apparent (Bulk) Density (g/cm^3)	True (Absolute) Density (g/cm^3)	Porosity (%)
0.117	4.348*	97
* The mean value of three measurements.		

The porosity results revealed that WW is comparable to other natural fibre materials such as those recorded by Palumbo *et al.* (2016) which included hemp fibre, wood wool and wood fibre which were 97%, 96% and 86%, respectively.

5.6. Determination of Water Absorption Coefficient

The mean mass change of six samples, and for two densities, versus the square root of the weighing times, is presented in Fig. 15. The difference between the mass at each weighing and the initial mass were divided by the area of the open end of the sample (Equation 11), and plotted against the square root of the weighing times, $\sqrt{t}$.

$$\Delta m_t = (m_t - m_i) / A \qquad \text{(Equation 11)}$$

where

m_t mass of sample 24 h after the start of the test;

m_i initial mass of sample;

A area of open end of sample;

t time.

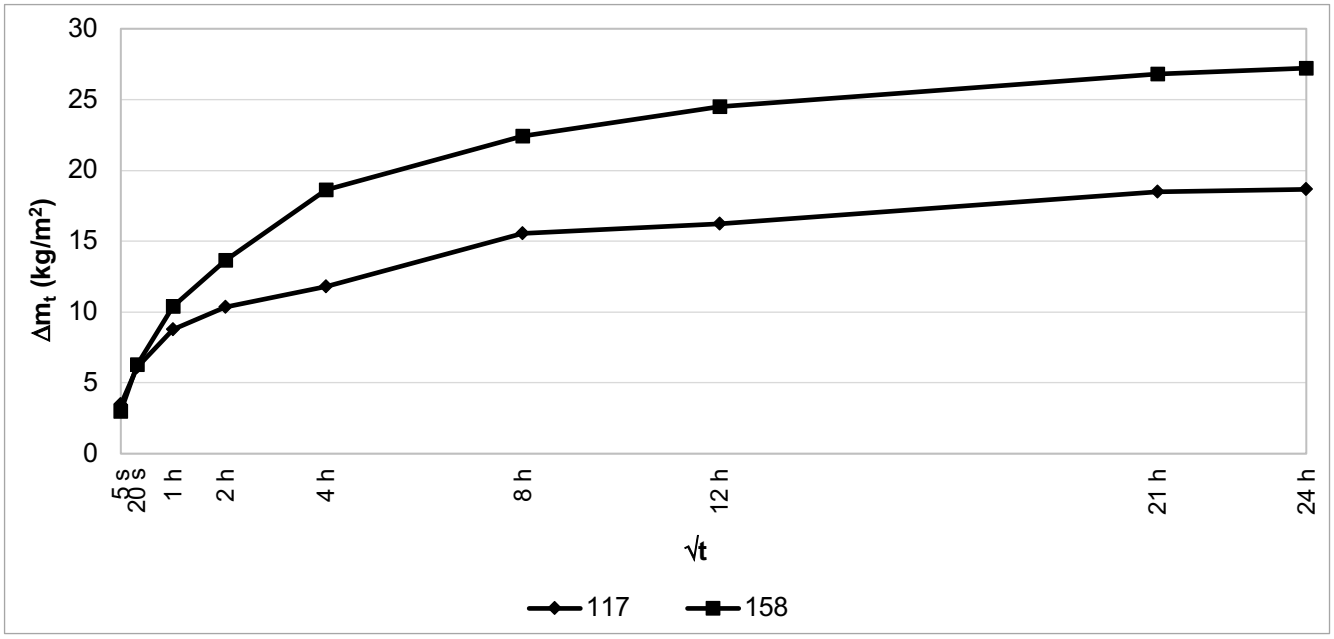


Fig. 15. The mass changes versus weighing times for two densities.

The water absorption coefficients for two densities were calculated according to BS EN ISO 15148 (BSI, 2002) by using Equation 12, and the results were given in Table 12.

$$A_{w24} = m_{tf} / \sqrt{}_{86400} \quad \text{Equation (12)}$$

where

m_{tf} : the value of *mt* 24 h after the start of the test

Although limited to sample of just two different densities, the water absorption coefficient increases as the density increases. The samples with the density of 158 kg/m^3 absorbed the water approximately 48% more than the ones with the density of 117 kg/m^3 due to increasing the amount of particles.

Table 12. The water absorption coefficients for different densities

Density (ρ - kg/m^3)	Water absorption coefficient (A - kg/m^{2}s$^{0.5}$)
117	0,063
158	0,093

According to Mukhopadhyaya *et al.* (2002) white pine wood, red clay brick and concrete have water absorption coefficients of 0.0112 kg/m^{2}s$^{0.5}$, 0.084 kg/m^{2}s$^{0.5}$ and 0.184 kg/m^{2}s$^{0.5}$, respectively, at a temperature of 21^{0}C. When these values are compared to our results, it is seen that WW's water absorption coefficient is very close to red clay brick's.

6. Conclusions

Current insulation materials used in construction industry are generally inorganic based materials such as extruded polystyrene, expanded polystyrene, and polyurethane foam. Although these materials have a high performance with regards to the resistance to conduction heat transfer, their environmental impacts during the building life cycle period, and especially in the production process, are generally high. Therefore, the use of bio-based materials instead of inorganic based materials has become an important issue in terms of reducing environmental impacts and improving building whole life cycle performance primarily with regards to reduced embodied energy.

For this research, the characterisation of the hygrothermal properties of waste wood (WW) was undertaken with the aim to provide greater understanding of the material performance and its application as an insulation material in timber frame wall construction.

WW can be applied to timber frame wall construction by manual filling or mechanical blowing of the loose fill material between the studs of the frame and without any binder. The density of 117 kg/m^3 was found to be a functional density level that can be achieved without mechanical compression and has thermal performance comparable to similar materials. However, its suitability at full-scale requires further investigation to ensure that the material does not slump under its own weight, which would lead to overall increased heat loss. According to the experimental results obtained

583 in this investigation, WW could be efficiently used as a thermal insulation material. Its measured thermal conductivity
584 value was close to the values of wood fibres, wood chippings and straw bale, and lower than reeds and cereal, which
585 have already been used as natural insulation materials in the construction market. When compared to inorganic
586 insulation materials, it has a higher thermal conductivity value. The moisture content at a range of relative humidities
587 during sorption and desorption testing was similar to reported values for wood fibre material. Additionally, we have
588 reported a range of hygric and thermal material properties at a range of densities, which can be used to facilitate
589 Hygrothermal analysis, e.g. through computer simulation with tools such as WUFI, which can in-turn provide valuable
590 supporting information for evaluation of low impact building designs employing this natural low cost and low impact
591 locally available material.

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