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Porosity of acoustic wood-wool cement board

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Abstract

Wood-wool cement board (WWCB) is a porous composite material consisting of Portland cement inorganic binder mixed with wood-wool as reinforcement. It is widely used as thermal and acoustic insulator in buildings because of low density, high porosity, good fire resistance and compatibility with other binders and building materials. The majority of composite characteristics, including as density, strength, Young modulus, gas permeability, thermal conductivity, and thermal diffusivity, are dependent on porosity. Aside from density, the other qualities stated, including sound absorption coefficient, are affected by pore size distribution. The acoustic properties of air/WWCB interaction are described through air complex modulus and air complex effective density used in many acoustic models for porous materials. Two techniques for determining porosity are used and compared on samples of wood-wool cement board from normal manufacturing received from FRAGMAT H d.o.o. Sv. Križ Začretje, Croatia. The Archimedes technique is utilized to determine the real and apparent density of the bulk WWCB, while image analysis of the surface layer and deeper layers reached by grinding and polishing is used to analyze layer by layer porosity and pore size distribution. The approaches are compared based on their complexity, length of analysis, and the type and quality of information obtained.

Keywords*: wood-wool cement board, porosity, image analysis.*

1. Introduction

1.1. Wood-wool cement composite boards

In 1880, a patent was filed in Germany describing the production of composite materials by binding wood wool with gypsum. At the beginning of the 20th century Sorel cement, based on magnesia, was used as binder for wood-wool. Due to the water solubility of gypsum and magnesia cement, improved wood-wool boards were manufactured by using Portland cement (PC) as a mineral binder. This type of composite material has been widely produced since the 1920s, and the term wood-wool cement board (WWCB) has been synonymous with it [1]. White Portland cement is used as a WWCB binder mostly for aesthetic purposes or when quick setting and hardening is required. Over time, the manufacturing process became increasingly automated, resulting in much larger production capacity; consequently, a contemporary facility with a dozen workers could easily create more than 100 m^3 of product per day. The wood used for the usual WWCB production in FRAGMAT H d.o.o., Sveti Križ Začretje, Croatia, is spruce and fir. Many types of wood are used worldwide, especially those with a lower content of soluble organic compounds that could delay the setting and hardening of Portland cement. Wood-wool is produced from air-dried (seasoned) tree trunks cut at 50 cm long logs. The shredding machine produces wood-wool of 1-5 mm width and 0.2-0.5 mm thickness. Acoustic insulation boards use finer wood-wool. WWCB properties are easily tunable during the production process. The range of product thickness varies usually between 25-100 mm .The desired density of WWCB can be achieved by adjusting porosity (mold thickness and cement and wood-wool dose), which typically varies from 150-700 kgm^{-3}. The use of a greater amount of cement binder poses the issue of a greater amount of heat emitted during exothermic hydration processes. Green WWCB are prepared and stacked in molds, where the typical maximum temperature rise attained in the stack is around 25-30 °C over an 8-24 h timeframe. In addition to the heat released during the curing and setting of PC the high alkalinity of the cement paste and humidity impair the strength and toughness of the wood-wool by partially depolymerizing cellulose fibers. Wood-wool includes a variety of complex chemical components and sugars that interfere with cement hydration processes and lower PC final strengths. Consequently, during regular production of WWCB some setting and hardening additives for Portland cement are used. The mechanical strength of WWCB depends on final porosity i.e. density. For insulation boards, it is in the range of 250-700 kgm^{-3}, with the denser product having better mechanical properties. The thermal conductivity [1] of dry WWCB increases with increasing final density, but is below 0.16 $Wm^{-1}K^{-1}$ and is comparable to the thermal conductivity of other building materials (wood, brick and concrete). However, the thermal conductivity is not the only important material property to make final comparisons/decisions, because the density, specific heat capacity, thermal diffusivity and thermal effusivity, porosity, water vapor permeability and water content during wetting/drying periods are also very important. The acoustic characteristics of WWCB are good, however the coefficient of sound absorption is frequency dependant owing to the complexity of acoustic wave (high frequency air pressure oscillations) porous material (WWCB) interaction [2-6]. Fur-thermore, the specific method of acoustic WWCB appli-cation, such as directly on the thick wall or with an air gap, results in significantly varied sound absorption capabilities [1,7]. Not only the density of the WWCB material, i.e. the porosity, but also the thickness, permeability and pore tortuosity have a significant influence on the sound absorption coefficient.

1.2. Theoretical background about sound propagation

By definition, sound wave is a wave of compression and rarefaction, by which sound is propagated in an elastic medium such as air. Sound energy balance is given by Eq. (1). Incident sound wave has incidence energy Einc and after hitting the wall (WWCB), energy can be divided into three components, as shown in Fig 1. One portion of the energy is reflected back (Eref), while another portion (Etran) is able to transmit through the material. Eabs represents the part of the absorbed sound energy which is converted into heat due to the internal friction and visco-elastic effects.

$$E_{inc} = E_{ref} + E_{abs} + E_{tran} \tag{1}$$

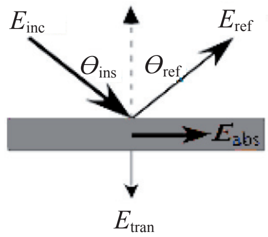

Fig. 1. Sound energy balance on the phase boundary [8, 9]. It is worth noting that in general, acoustic wave impignes the boundary at an angle θ_{ins}.

1.3. Methods for measuring sound absorption coefficient

Generally sound absorption coefficient is adopted as the index for evaluating the sound absorbing performances of a material [8,9]. The effectiveness of a sound absorber is quantified by the absorption coefficient Eq. (2), which defines the part of acoustical energy of the incident wave that is actually absorbed by the material.

$$\alpha = E_{abs} / E_{inc} \tag{2}$$

The part of sound wave which is transferred to the material enters its pores and a certain amount of its energy is converted into heat because of the friction and the viscosity resistance between the air molecules and the wall of pores. In this way, the sound energy is absorbed [5, 6, 9]. Sound absorption coefficient is measured using different measuring techniques, each with its own advantages and limitations. Standard techniques for measuring sound absorption coefficient are reverberation room (random incidence sound wave) and impedance tube (normal incidence sound wave only). Reverberation room tech-nique is used for measuring diffuse absorption sound coefficient in diffuse sound field i.e. in similar conditions as occur in practice. This method examines sound decay time needed for incident sound pressure to reduce for 60 dB. Reverberation room method is based on the Sabine formula [10] given by Eq. (3):

$$T = 0{,}05V / aS \tag{3}$$

where:

V – volume of the room (m^3)

a – average absorption coefficient

S – area of sample material (m^2)

The method requires a large sample area and a large volume of reverberation room and it is suited for investigating the sound absorption of massive building materials such as plaster boards, concrete and wood composite materials.

The sound absorption coefficient of an acoustic material at normal incidence is measured using the impedance tube method, since only a standing wave at normal incidence is maintained during the measurement. The impedance tube is generally used to measure the sound absorption of small samples on a laboratory scale, usually with a diameter of 30 or 40 mm. Two methods are generally used to measure the sound absorption coefficient at normal incidence for small samples: the standing wave ratio method (ISO 10534-1 standard), and the transfer-function method, standardized by ISO 10534-2. The usual outline of an impedance tube is shown in the Fig 2.

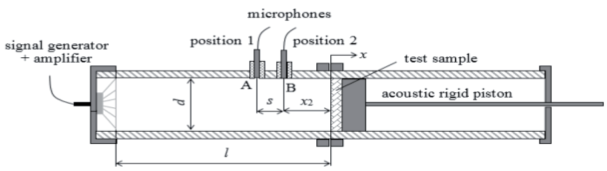

Fig. 2. Standard impedance tube [11]

A loudspeaker is frequently used as a sound source, microphones monitor dynamic pressure oscillations at various points in the tube, and the test sample is connected with a moveable acoustically rigid piston. Microphone signals are frequently amplified, filtered and recorded by PC software.

1.4. WWCB as porous sound absorber material

WWCB boards act as acoustic absorbers due to their high porosity. The incoming sound wave periodically forces the air in the porous structure of the material, where the sound energy is lost through viscoelastic effects and friction with the pore wall. The vibration of the air in the open pores dissipates the mechanical energy in the form of heat. The main acoustic characteristic of WWCB (Fig. 3) is strong sound absorption in the higher frequency range (1000-4000 Hz) due to the open porosity of the WWCB. Also the morphology of the pores and their size contribute to sound absorption at higher frequencies. At lower frequencies (<1000 Hz) the sound is poorly ab-sorbed in the material due to a large difference between the sound wavelength and material thickness. Other acoustic materials used in construction exhibit comparable properties.

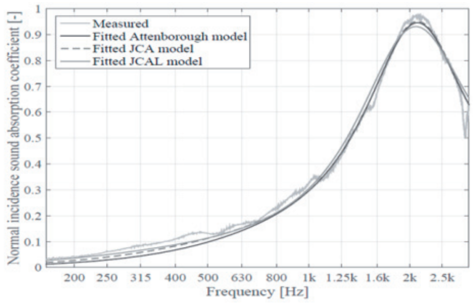

Fig. 3. Characteristic sound absorption coefficient for WWCB [7]

Acoustic models used [2-6] describe the interaction of acoustic wave/porous materials where the effect of vibration of the material frame is excluded. Those models are able to predict energy dissipated by the air that vibrates inside the pores.The frequently applied models are Delany-Bazley-Miki [2], Zwikker and Kosten [3], Attenborough [4], Johnson-Champoux-Allard (JCA) [5] and Johnson-Champoux-Allard-Lafarge [6] (JCAL) model. Delany-Bazley-Miki model describes sound wave propagation in fibrous materials. This model is simple and it has only one parameter, flow resistivity (σ/Pasm^{-4}). Zwikker and Kosten describe sound propagation in cylindrical pores of porous materials. The equation of Zwikker and Kosten in Eq. (12) is analogous to the Helmholtz equation, which describes sound propagation in free air without dissipation. .Because of porosity, the effective density and effective bulk modulus of air are complex functions of the frequency and material morphology:

$$\nabla p + \omega^2 \frac{\rho_{eq}}{K_{eq}} p = 0 \tag{12}$$

where p is the acoustic pressure (Pa), ω the angular frequency (s^{-1}), ρ_{eq} is the effective density (kgm^{-3}) and K_{eq} is the effective bulk modulus (kgm^{-1}s^{-2}). Attenborough [4] model includes four parameters; porosity, tortuosity, flow resistivity and pore shape factor. This model is best suited for granular materials as soils, sands and resin-bonded materials. Tortuosity is one important parameter which is related to the curvature of the pore path through the material [12, 13] The Johnson-Champoux-Allard [5] model has five parameters: porosity, flow resistivity, tortuosity, viscous characteristic length and thermal characteristic length. Only porosity and flow resistivity values are often not fitted but rather obtained by independent measurement. There are two new physical parameters which have been considered in the model: viscous characteristic length and thermal characteristic length, which are related to microstructure of the pores. It is worth mentioning Wilson model [14, 15] that uses viscous and thermal characteristic length for empirical modeling of acoustic materials. Effective density (ρ_{ef}) and bulk modulus (K_e) in JCA model [5] are given by equations (13) and (14).

$$\rho_e(\omega) = \frac{\alpha_\infty \rho_0}{\phi}\left(1 + \frac{\sigma\phi}{i\omega\rho_0\alpha_\infty}\sqrt{1 + \frac{4i\alpha_\infty^2\eta\rho_0\omega}{\sigma^2\Lambda^2\phi^2}}\right) \tag{13}$$

$$K_e(\omega) = \frac{\frac{\gamma P_0}{\phi}}{\gamma - (\gamma-1)/\left(1 + \frac{8\eta}{i\rho_0 \omega N_{pr} \Lambda'^2}\sqrt{1 + \frac{i\rho_0 N_{pr} \Lambda'^2}{16\eta}}\right)} \tag{14}$$

where:

d – thickness of the sample (m)

ρ_0 – air density (kg m^{-3})

c_0 – speed of sound in air(m s^{-1})

α_∞ – tortuosity

σ – airflow resistivity (Pa s m^{-4})

φ – porosity

ω – angular frequency (s^{-1})

η – dynamic viscosity of air (Poiseuille) (1.84x10^{-5} Pa s at 20 °C)

Λ – viscous characteristic dimension (m) (range 10-1000 μm)

Λ' – thermal characteristic dimension (m) (range 10-1000 μm)

p_0 – atmospheric pressure (Pa)

γ – specific heat ratio (adiabatic exponent) equals 1.40 for air

N_{Pr} – Prandtl number (for air at 20 °C equals 0.71)

JCA is one of the most widely used in acoustic engineering for porous materials nowadays. Botterman [7] shows acceptable agreement between theoretical and measured values of sound absorption coefficient for WWCB. Because closed pores do not contribute to sound absorption, open porosity, accessible to air passage, is one of the most essential elements of an acoustic model. Pore size distribution must be considered for porous materials because some pores are too small and others are too big for efficient dampening of sound wave energy.

1.5. Method for measuring porosity of building materials

The porosity of building materials such as WWCB can be considered as macro porosity. It contains a lot of voids, cavities and interconnected pores which are not straight and neither cylindrical. There are many methods for measuring porosity of bulk materials like helium pycnometer, computed tomography (CT) [16] or by digital image analysis [17]. As previously mentioned, pores in materials can be closed or open. Closed pores have an influence on physical properties of a material such as bulk density, mechanical strength and thermal conductivity but they are not acoustically effective. On the other hand, open pores are interconnected inside the material which is effective for damping sound wave energy.

2. Experimental procedure

Two wood-wool cement boards from regular production obtained from FRAGMAT H d.o.o. Sv. Križ Začretje, Croatia, were used for the purposes of this work. Boards were 2.5 cm and 1.0 cm thick. The surface layer and the deeper layers of WWCB, which are accessible by grinding and polishing, are used for the layer-by-layer determination of the porosity by image analysis. The main goal of the research was to discover correlations between different methods of measuring density. Three different methods were used in this work: theoretical density calculation method, Archimedes method and digital image analysis. The methods are compared in terms of complexity, duration of analysis and type and quality of the information obtained.

2.1. WWCB density calculation method

WWCB is a material which consists of Portland cement, wood-wool (spruce) and water. The standard WWCB has about 20-25 mass percent wood wool in the material. If the mass fractions of three main components of WWCB are known, it is possible to calculate theoretical density of the composite material for different porosities. Eq. (15) defines density with 0% porosity as follows:

$$\rho_0 = \frac{\sum m}{\sum V} = \frac{m_{ww} + m_{cem} + m_{wat}}{\frac{m_{ww}}{\rho_{ww}} + \frac{m_{cem}}{\rho_{cem}} + \frac{m_{wat}}{\rho_{wat}}} \tag{15}$$

where:

m_{ww} – mass of wood-wool (g)

m_{cem} – mass of cement (g)

m_{wat} – mass of water (g)

ρ_{ww} – density of dry wood-wool; 0,421 g cm^{-3}

ρ_{cem} – density of cement; 3,00 g cm^{-3}

ρ_{wat} – density of water; 0,997 g cm^{-3}

The calculation of the WWCB density with different composition is given in Table 1. Due to the comparison with WWCB from the manufacturer, mass fractions of wood-wool employed in calculations are taken in a tight range. The calculation is for wet WWCB from production (w/c=0,45). Water is consumed in excess (more than is required for complete theoretical hydration) of cement). The density of porous solids depends on porosity according to the Eq. (16):

$$\rho_{apparent} = \rho_0(1-P) \tag{16}$$

where P is porosity (total pore volume divided by total solid volume), ρ_0 is true density of material under study (kg m-3) and ρapparent is apparent solid density (kg m-3) taking also pore volume into account.

Table 1. Calculated theoretical density of wet WWCB. Porosity varies from 50 to 70%.

$w_{wood\,wool}$	$w_{cem+water}$	w/c	w_{cem}	w_{wat}	ρ_0	P=50%	P=55%	P=60%	P=65%	P=70%
0	1		0,690	0,310	1,848	0,924	0,832	0,739	0,647	0,554
0,15	0,85		0,586	0,264	1,225	0,613	0,551	0,490	0,429	0,368
0,2	0,8		0,552	0,248	1,101	0,551	0,496	0,441	0,385	0,330
0,25	0,75		0,517	0,233	1,000	0,500	0,450	0,400	0,350	0,300
0,3	0,7		0,483	0,217	0,916	0,458	0,412	0,367	0,321	0,275
0,35	0,65	0,45	0,448	0,202	0,845	0,423	0,380	0,338	0,296	0,254
0,4	0,6		0,414	0,186	0,784	0,392	0,353	0,314	0,275	0,235
0,45	0,55		0,379	0,171	0,732	0,366	0,329	0,293	0,256	0,220
0,5	0,5		0,345	0,155	0,686	0,343	0,309	0,274	0,240	0,206
0,55	0,45		0,310	0,140	0,645	0,323	0,290	0,258	0,226	0,194
0,6	0,4		0,276	0,124	0,609	0,305	0,274	0,244	0,213	0,183

where $w_{wood\text{-}wool}$ is mass fraction of wood-wool, $w_{cem+water}$ mass fraction of cement paste; w/c water/cement factor, w_{cem} and w_{wat} mass fraction of cement and water for given w/c factor, ρ_0 density of WWCB with 0% of porosity, P (50-70%) density for given porosity of WWCB

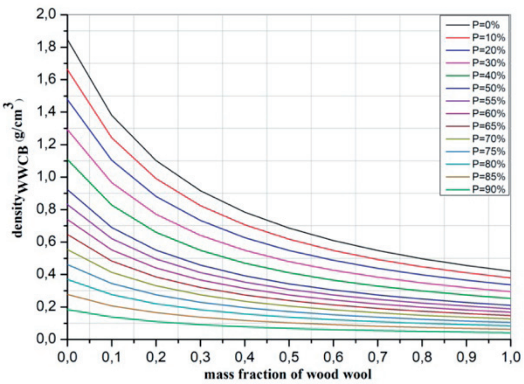

Fig. 4. Calculated density of WWCB for a wider range of mass fraction of wool wool

The calculation method is also carried out for the dry WWCB, whereby a w/c ratio of 0.24 is theoretically required for the complete hydration of Portland cement. The density of WWCB with changing porosity is given in Table 2.

Table 2. Calculated theoretical density of dry WWCB. Porosity varies from 50 to 70%.

$w_{wood\,wool}$	$w_{cem+water}$	w/c	w_{cem}	w_{wat}	ρ_0	P=50%	P=55%	P=60%	P=65%	P=70%
0	1		0,806	0,194	2,160	1,080	0,972	0,864	0,756	0,648
0,15	0,85		0,685	0,165	1,334	0,667	0,600	0,533	0,467	0,400
0,2	0,8		0,645	0,155	1,183	0,591	0,532	0,473	0,414	0,355
0,25	0,75		0,605	0,145	1,063	0,531	0,478	0,425	0,372	0,319
0,3	0,7		0,565	0,135	0,965	0,482	0,434	0,386	0,338	0,289
0,35	0,65	0,24	0,524	0,126	0,883	0,442	0,397	0,353	0,309	0,265
0,4	0,6		0,484	0,116	0,814	0,407	0,366	0,326	0,285	0,244
0,45	0,55		0,444	0,106	0,756	0,378	0,340	0,302	0,264	0,227
0,5	0,5		0,403	0,097	0,705	0,352	0,317	0,282	0,247	0,211
0,55	0,45		0,363	0,087	0,660	0,330	0,297	0,264	0,231	0,198
0,6	0,4		0,323	0,077	0,621	0,310	0,279	0,248	0,217	0,186

2.2. Digital image analysis

This paper introduces a novel approach for determining the porosity of WWCB. Image analysis is a simple, low-cost, and straightforward approach for measuring the porosity of various materials, including WWCB. A freeware programme such as ImageJ© enables simple image processing, e.g. calculating the percentage of pixels of a certain red-blue-green component (RGB). On this basis, the contrasts in the picture may be distinguished and, finally, it is possible to determine which portion of the pixels belongs to the material and which part is associated with the pores of WWCB. The samples were prepared by coloring the surface of WWCB material with a thin film of white color to increase the contrast between the surfaces and pores of the material. Subsequently, such prepared samples were scanned and the image was refined using ImageJ© to determine the ratio of white surface pixels and darker pixels representing the pores. In the next step the surface of the composite was polished in an equal layer, with 0.5 to 1 mm of surface material removed. This process was repeated 25 times to establish the porosity of the composite board through its cross section.

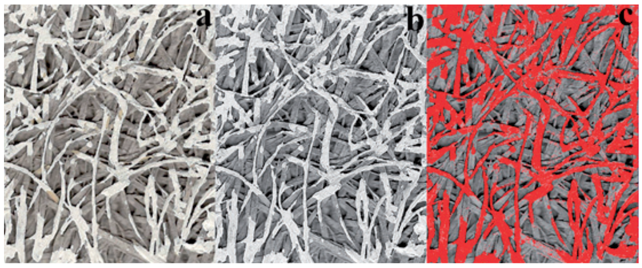

Fig. 5. Example of scanned image treatment in ImageJ. Colored and scanned composite board (a), scanned image transformed to 8 bit image (b) and processed image with already determined surface pixels (c).

2.3. Archimedes method

Archimedes method is applied for true and apparent density determination of the bulk WWCB. Fluids (liq-uids and gasses) in the gravity filed exert buoyancy on the immersed objects. The net buoyancy force is di-rected upward (opposite of the body weight) according to the following formula:

$$F_{buoyancy} = V_{body} \cdot \rho_{fluid} \cdot g \tag{17}$$

where V_{body} is immersed body volume (m^3), ρfluid is fluid density (kg m^{-3}) and g is the local gravity acceleration, around 9.81 m s^{-2} at 45° latitude. The Archimedes method of density determination is routinely performed in many laboratories for unknown liquid or solid density measurement. The simple measurement setup could be bought with a laboratory scale/balance.

The ambient temperature should be steady, all elements of the apparatus and the sample should be at the same temperature, and there should be no vibrations or air turbulence for optimal stability and precision. However, one should take into account that if the mass of the solid sample is weighted in air, a correction for air buoyancy (i.e. air density) must be performed.

The open pores are accessible to the fluid, and could be fully saturated with a measuring fluid, while closed pores are not accessible to the fluid, and the sample is usually broken into fine powder thus effectively break-ing all closed pore spaces and making true solid density determination possible. If the solid density is larger than the liquid density, sample density may be calculated by simply weighing the sample in air and submerged in fluid.

However, if the apparent solid density is less than the fluid density, the sample must be forced below the fluid surface. This applies to WWCB (wood-wool cement board) samples with porosities greater than 50%. The WWCB sample for the determination of the apparent density (the penetration of liquid into the pore space must be avoided) is prepared by placing the sample in plastic vacuum bags and sealing the bag. Now, the correction for the immersed plastic bag and solid shaft volume should be made in order to make apparent density measurement. Measuring the actual density of WWCB (the average density of spruce wood and hydrated cement) is relatively easy, as the sample is slightly saturated with the liquid (the open porosity consists of large pores).

3. Results and discussion

3.1. Archimedes method (calculation for WWCB without pores)

m_{WWCB}=69.69 g

m_{d0} =55.50 g

$\rho_{H2O(25°C)}$=0.997gcm^{-3}

V_{d0}=55.50 g / 0.998 g cm^{-3}=55.67 cm^3

ρ_{WWCB}= 69.69 g / 55.67 cm^3 =1.252 g cm^{-3}

3.2. Archimedes method (calculation for WWCB with pores)

m_{WWCB}= 69.69 g

V_{d1}= 162.65 cm^3

after making correction for plastic bag and solid shaft:

V_{d2}= 155.93 cm^3

ρ_{WWCB}= 69.69 g / 155.93 cm^3 = 0.447 g cm^{-3} (WWCB with pores)

3.3. Porosity calculation for WWCB (2.5 cm thick)

From Eq. (16): 1-P=ρ/ρ_0

P=64,3%

m_{WWCB} - is mass of WWCB (g), m_{d0} - mass of displaced water for WWCB (g), V_{d0} – volume of displaced water for WWCB (cm^3), ρ_{WWCB} – density of WWCB (g cm^{-3}), $\rho_{H2O(25°C)}$ – density of water (g cm^{-3}), V_{d1} - volume of displaced water due to WWCB, plastic bag and solid shaft (g cm^{-3}), V_{d2} - volume of displaced water due to WWCB after correction (cm^3)

3.4. Digital image analysis results

The "wall effect" in the WWCB was revealed in the first results of digital image analysis. The first layer scanned had a higher porosity (70.06%) than the subsequent layer after the first polishing of the board (64.37%). Fig 6. shows the “wall effect” and the difference between the porosities of these two layers.

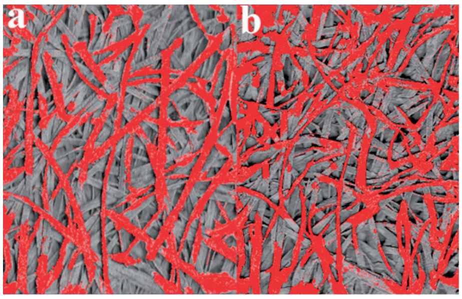

Fig. 6. Difference between the first layer with the “wall effect” (a) and the second layer with 1 mm of material removed (b)

Figure 7 depicts the determined porosity values through the cross section, with the average porosity including and omitting the less porous initial layer. The average porosity of 25 layers including the first layer is 64.19 % and the determined porosity without the "wall effect" is 63.94 %.

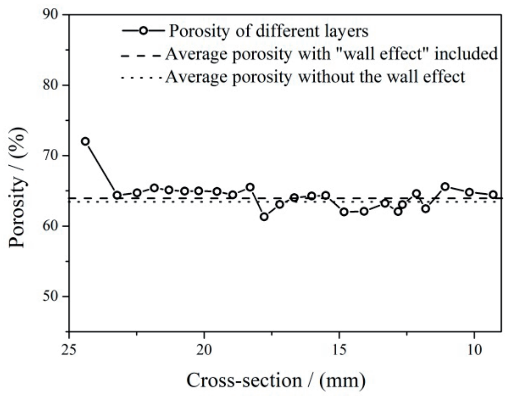

Fig. 7. Graphical representation of porosity throughout the WWCB and average porosities

4. Conclusion

Wood-wool cement board is a lightweight building material used for thermal and acoustic insulation of buildings. The inorganic binder Portland cement contributes to the mechanical strength of the composite while wood-wool contributes to the toughness of the composite. Lower density (more porosity) board has lower thermal conductivity but also worse mechanical properties. The acoustic properties of WWCB depend on the complex interaction between sound waves and porous material, and not only the total porosity but also the pore size distribution and the tortuosity of the pores influence the frequency-dependent sound absorption. Lower frequencies are less attenuated, therefore work is being done to enhance sound attenuation of WWCB at lower frequencies by surface texturing and extra acoustic material sandwiching.

The method of theoretically calculating the porosity of WWCB as a function of raw material composition is satisfactory, but it does not provide details of the pore space as obtained from digital image analysis of the polished surfaces, nor of the porosity gradient observed near the board surface. This phenomenon is explained by the “wall effect”, similar to the packing density of granular materials near the walls of the container. The original and actual

WWCB density can be determined by the Archimedes method, and the calculated porosity agrees with the results of digital image analysis. This method is cost-effective. However, it necessitates the preparation of numerous polished surfaces in order to maintain the integrity of the pores, which renders this method laborious. The use of computational tomography measurements has the potential to reduce this burden and provide a de-tailed pore structure; however, this may incur a high cost and result in a low sample rate.

5. Acknowledgment

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