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GAMMA RAY ATTENUATION TECHNIQUE TO THE MEASUREMENT OF MOISTURE CONTENT PROFILES IN POROUS BUILDING MATERIALS

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Abstract

The knowledge of moisture transport in porous building materials and components is crucial to predict and avoid several pathologies and is essential to increase the durability. It is easy to know the amount of water that, for example, some material absorbs when in contact with water. However, it is very difficult to determine where the water is, the water transport process, the water movement, etc. Using the gamma ray attenuation technique, it is possible to determine the water content along a building material or component and obtained the water content profile in different moments. So, with this tool, several phenomena can be studied such as: the wetting and drying processes, the thermal performance, waterproof behavior, etc,. This paper presents the gamma ray attenuation technique, the way that the water content profiles can be obtained, some interesting water content profiles obtained for a material, monolithic and multilayered and the discussion of those results.

Keywords: Moisture content profiles, Gamma-ray attenuation, Porous building materials

1. INTRODUCTION

The knowledge of moisture transport in porous building materials and components is crucial to predict and avoid several pathologies and is essential to increase the durability [1,2,3].

In order to avoid the increasing number of buildings that suffered damages due to moisture, it is essential to predict this type of deterioration studying the moisture transfer in building materials and components in the wetting and in the drying phases.

Over the years, some experimental methods have been developed to determine the progression of moisture based on the evolution of water content profiles in porous building materials. Some of them involve the destruction of the test sample each time the moisture profile is measure, for instance, the slice–dry-weigh-method and thermal imaging. However, most of them, such as neutron radiography, computer tomography and gamma-ray attenuation method, do not destroy the specimen.

Considering the few experimental techniques that allows the determination of water content profiles the gamma ray attenuation technique is an interesting and uncommon one.

This paper aims to evaluate the results attained by HUMIGAMA, that is a gamma ray attenuation device developed by the Building Physics Laboratory (LFC) of University of Porto, Faculty of Engineering (FEUP), by analysing the water content profiles obtained for a porous building material.

2. METHODS TO MEASURE MOISTURE CONTENT PROFILES

There are several experimental methods available that allows the determination of moisture content profiles in porous building materials. Although some of these methods do not involve the destruction of the test sample each time the moisture profile is measured (non-destructive methods), they are usually time consuming and require expensive equipment.

The most common procedures are the following:

- **Slice–dry-weigh-method:** is a destructive method where the specimen is quickly sliced into discs that are weighed, dry and weighed again, whenever is intended to obtain the moisture content profiles. The water in the discs evaporates during the drying process which allows the calculation of the moisture content from the weight loss. This is one of the most accurate method, as long as the splitting of the samples into thin discs is ensured, because the actual amount of water in the specimen is measured [4].
- **Thermal imaging:** is a simple destructive method based on the decrease of the temperature when the water starts evaporate. Every time is intended to measure the moisture content profile the specimen is split into two halves, perpendicularly to the exposed surface. The temperature distribution on the split surface is measured with an infrared camera and the moisture content profiles can be consequently obtained [4].
- **Electrical methods:** two non-destructive electrical methods are available: the resistance method (based on electrical conductivity variations) and the capacitance method (based on electrical capacitance variations). In the first method the electrical conductivity is measured with two electrodes and the water content is evaluated through a calibration curve of the material under study. The second method uses the tested material as a dielectric and the capacitance variations as a measure of the water content in the material. Both methods are relatively inexpensive [4,5].
- **Neutron radiography:** is a non-destructive method similar to gamma-ray attenuation but here a neutron beam is used to interact mainly with the hydrogen nuclei of the materials under study. The attenuation of the neutron beam is directly related to the total water content of the material. To perform a neutron radiography test safety measures and trained operators are required [6,7,8].
- **Nuclear magnetic resonance (NMR):** is a non-destructive method where an exterior permanent magnetic field is applied to the material tested, causing

the absorption of some energy. The amount of energy absorbed is proportional to the number of hydrogen nuclei which is a measure of the water content in the material. According to some authors this method can provide more accurate results than gamma-ray attenuation and neutron radiography and has the advantage that no radioactivity is involved in the process. [5,8]

- **Computer tomography:** this non-destructive method measures the intensity loss of a narrow beam of X rays that passes through the specimen. The amount of absorbed radiation depends on the material density and is evaluated by using the CT-value. The difference in the CT-value between air and water is an indicator for measuring the water content in the material [4,9].
- **Microwave bean:** is a non-destructive method that uses a microwave beam to measure the moisture content profiles. During the measurement the sample is placed between a transmitter and a receiver and the attenuation of the beam is measured. The magnitude of the attenuation is related to the water content of the material under study [4].
- **Thermal conductivity:** in this non-destructive method, a known amount of heat is locally generated in the specimen and then the temperature vs time curve is calculated, which is a measured of the thermal conductivity of the material. In this way, the moisture content can be calculated if the relation between the moisture content and the thermal conductivity is known [4].
- **Gamma-ray attenuation:** in this method a narrow beam of gamma-ray photons cross through the specimen and interact with the orbital electrons of the material which will be absorbed or scattered. The intensity loss of the emitted radiation is used to determine the water content of the material. This is a non-destructive method which allows the measurement of the moisture content in an almost continuous way. The equipment is rather expensive and special safety arrangements are necessary due to the radioactivity involved in the process [2,5].

3. MEASUREMENT OF MOISTURE CONTENT PROFILES BY GAMMA-RAY ATTENUATION

This technique is based on a radioactive source, gamma photons, which crosses the material with a certain thickness and suffer an attenuation, allowing the measurement of the material moisture content. Many documents, as the thesis of Marten Janz in 1997 and the PhD of Vasco Freitas in 1992, cover detailed information of the procedures and expressions involved in this method as well as references and experimental results. It is a non-destructive technique, which allows the measurement of moisture content of near-continuous form attended by a good accuracy of results. However, it is an expensive equipment, difficult to find in research laboratories.

The radiation is absorbed/attenuated by the material depending on the photon energy, the material composition and the distance between the source and the detector. It is possible to establish a correlation between emitted and transmitted radiation, depending on the sample thickness, the attenuation coefficient and the material density.

A moisture-measuring device based on non-destructive method of gamma rays attenuation, allows measures to deepen concepts in building physics related to the moisture transfer; study the influence of the interface between layers in moisture transfer; analyse the influence of gravity on absorption and drying of different building materials; study the kinetics of absorption and drying of walls of one or more layers; analyse the importance of the temperature gradient in the movement of moisture; calculate the coefficient of water diffusivity of some building materials.

Regarding the determination of moisture in building materials an atomic nucleus of a radioactive element can emit three radiation types, alpha/beta particles and gamma rays. There are some differences between the natures of these elements: the alpha and beta particles have rest mass, while the gamma radiation does not have, and can travel through vacuum at 300,000 km/s. The alpha particles present doubly ionized helium nuclei and are positively charged; beta particles have negative charge and gamma rays have no load and therefore interact with matter differently.

The working principle of this measurement technique consists in the emission from a small amount of radiation, gamma photons, to cross the material with a certain thickness, suffer an attenuation, and may establish the following exponential relationship between the number of photons emitted and received:

$$I = I_0 \, . e^{-\mu \rho x} \qquad (1)$$

where:

I – Intensity of received radiation [counts/s]
I_0 – Intensity of emitted radiation [counts/s]
μ – Material attenuation coefficient [m²/kg]
ρ – Density [kg/m ³]
x – Sample thickness [m]

The particles that constitute the radiation range feature an energy, expressed in electron-volt, which are dealt according to a spectrum with one or more peaks depending on the radioactive source nature. Since the gamma measurement requires the use of "monoenergy" radiation, it is necessary to consider only the photons whose energy is between two levels near a peak. The emission of photons is a random phenomenon that obeys the Poisson law. The total absorption of gamma radiation by the material for an energy lower than 1000 KeV, depends crucially on two mechanisms:

- photoelectric effect in which the photons are relinquishing all their energy to the electron of a deep layer;
- compton effect in which the photons deviates after the shock with a free electron wasting energy.

Porous materials are formed by a solid skeleton itself, by the liquid phase, and may also exist other materials involving the specimens under study. So, the law of attenuation shall be expressed:

$$I = \underbrace{I_0 \cdot e^{-\mu_i \cdot \rho_i \cdot x_i}}_{\text{Surrounding}} \cdot \underbrace{e^{-\mu_0 . \rho_0 . d(1-\varepsilon)}}_{\text{Porous Structure}} \cdot \underbrace{e^{-\mu_w \cdot \rho_w . d . \varepsilon . S}}_{\text{Liquid Phase}} \quad (2)$$

where:

μ_i – surrounding material attenuation coefficient [m²/kg]
μ_0 – porous structure attenuation coefficient [m²/kg]
μ_w – Water attenuation coefficient [m²/kg]
ρ_i – Density of the surrounding materials [kg/m ³]
ρ_0 – Density of the porous material [kg/m ³]
ρ_w – Density of the water [kg/m ³]
x_i – Surrounding thickness i [m]
d – Porous material thickness [m]
ε – Porosity [%]
S – Saturation [%]

Performing the measurement with the completely dry material gets a value for the intensity of the received radiation what is known as I_0^* so the expression goes on to present the following configuration:

$$I = I_0^* \cdot e^{-\mu_w \cdot \rho_w d . \varepsilon . S} \quad (3)$$

The volumetric moisture content (θ = ε. S [m³/m³]) or weight (W [kg/kg]) can be easily calculated from the known water attenuation coefficient µw and volumetric mass of the dry material:

$$\theta = -\ln\left(\frac{I}{I_o *}\right) \cdot \frac{I}{\mu_w \, \rho_w . d} \quad \text{or} \quad W = \frac{\theta}{\rho_0} \quad (4)$$

Nielson, Kumaran-Bomberg, Vasco Freitas proceeded to the experimental determination of water absorption-coefficient µw corresponding to a source of Americium 241 having found equal values of 0.0191 (m²/kg).

If I_{sat} correspond to the received radiation intensity when it crosses a completely saturated sample, it can be considered that:

$$I_{sat} = I_0^* \cdot e^{-\mu_w \cdot \rho_w d . \varepsilon} \quad (5)$$

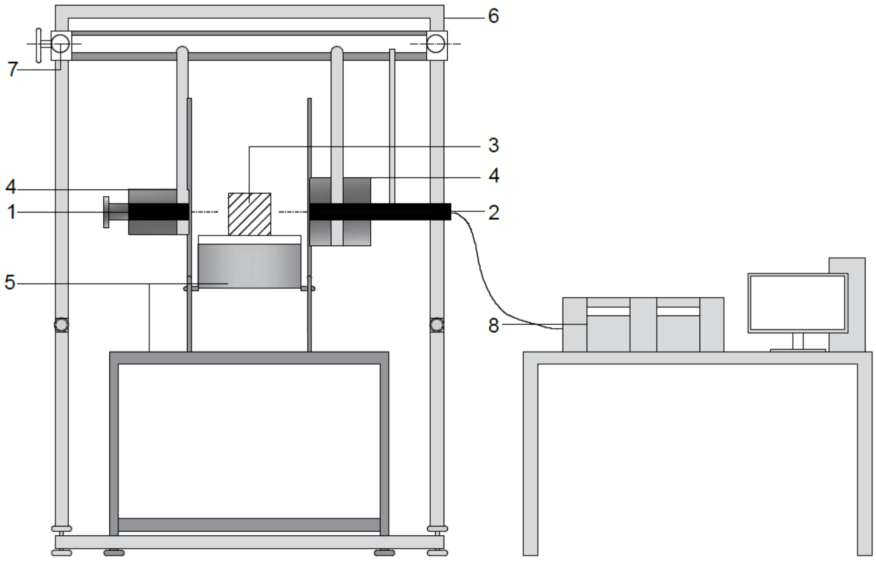
Replacing in the expression it is possible to get the following relationship that allows the calculation of the saturation degree:

$$S = \frac{ln\left(\frac{I}{I_0 *}\right)}{ln\left(\frac{I_{sat}}{I_0 *}\right)} \quad (6)$$

Knowing the saturation degree, the moisture content by volume (θ = εS) and the moisture content by weight (W = Wsat. S) are easily obtained. Since, there is a great difficulty in obtaining moisture saturation levels for some building materials, such as autoclaved cellular concrete (ACC), equation (4) is used for the concrete and equation (6) for the ceramic material.

The experimental equipment used in the tests was developed by *Vasco Freitas* at Faculty of engineering - University of Porto, FEUP [2]. It is mainly composed by: a radioactive source of Am^{241}, a crystal detector of sodium iodide, a set of electronic measuring equipment for counting the number of impulses throughout the experience and a support structure that ensures the attached movement of the detector and the source in the horizontal direction.

The radioactive source and the detector are inserted into collimators in order to minimize the particles spread. A scheme of the equipment is represented in Figure 1 and the correspondent picture in Figure 2.



1	-	Radioactive source	5	-	Adjustable table for supporting the sample
2	-	Detector	6	-	Metal support structure
3	-	Teste sample	7	-	Horizontal displacement control crank
4	-	Collimators	8	-	Electronic measuring equipment

Figure 1. Operating scheme of the gamma-ray measuring equipment

Figure 2. Gamma-Ray equipment

The HUMIGAMA device, described in the above section, and used in a previous works reported by Freitas [2], allowed, in the context of the present work, to obtain the following contributions:

- A better definition of use related to the equipment and the software to read the results;

- Development of a protocol for use;
- Calculation of the water attenuation coefficient used in the imbibition process;
- Measurement of the geometry and weight in the test specimens used for the imbibition process;
- Study of the imbibition kinetics of test specimens.

4. RESULTS AND DISCUSSION

As one of the objectives of this research is to study the influence of interface between layers, monolithic and multi-layered (two layers with a "perfect contact") test pieces of ceramic bricks were submitted to vertical imbibition process.

The measurements made by gamma ray equipment were done on ceramic bricks samples with the following dimensions: 100mm x 50mm x 50mm. Before starting the measurement process, the following precautions were taken into account: the stones was placed with the small end down (50mm x 50 mm); tape was placed around the sides of the stone to make the moisture flow one dimensional (no evaporation from the sides); the top was open; the stones was places on approximately 1mm layers of water absorbing paper; the points measured were for each 5mm height. Each measurement took 1.5min; all measurement is done in the same heights (it has been checked that the motor drive is accurate and at least five readings at the same point and time were done to get the mean point as the number of photons emitted and received are aleatory so some tiny differences can occur).

The first measurements before the capillary test are used in the calculation as 1% - the equilibrium moisture content in laboratory condition. The thickness is the 50mm. The test is started at time 0 and measurements are done from the bottom to the top of the stone. The reduce measurement in point with high water content it is defined that if two values in the lowest point above the water is above for instance 20% then this point is not measured next time. This gives maximum number of measurements of the moisture front.

The moisture content profiles obtained during the measurements for the monolithic and multi-layered ceramic brick are represented in Figure 3 and Figure 4, respectively. Each profile was measured at a specific hour during the free water uptake experiment, which was performed in isothermal conditions, T_{amb}=25ºC, with 50% of relative humidity, RH_{amb}, according to the European Standard "Thermal performance of buildings and building components

One of the most important characteristics of these profiles is that it is possible to predict the amount of water content existing at a given instant of time for a certain point of the material.

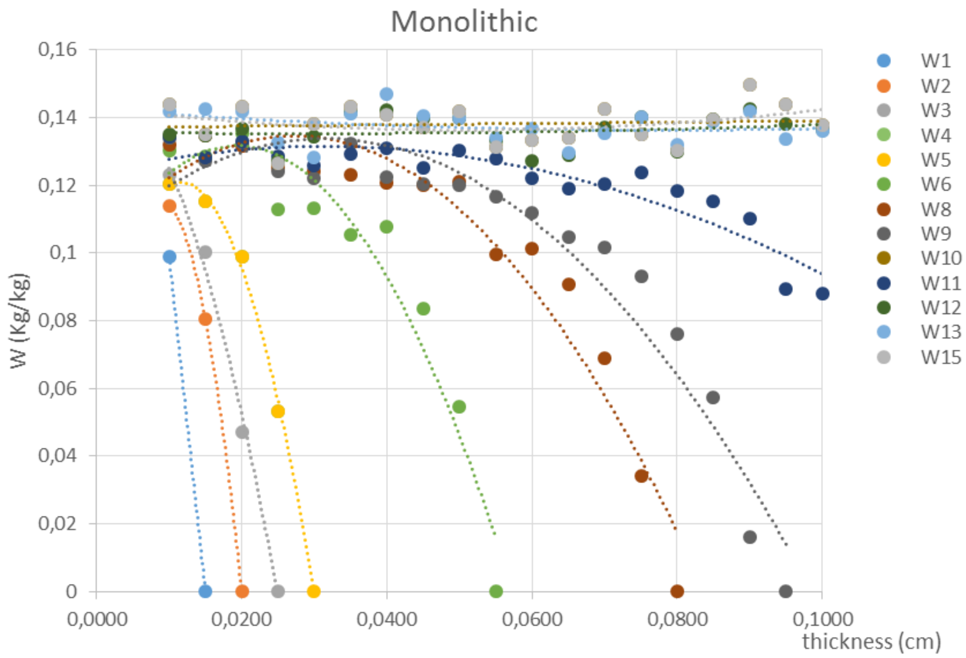


Figure 3. Water content profiles obtained for a monolithic material

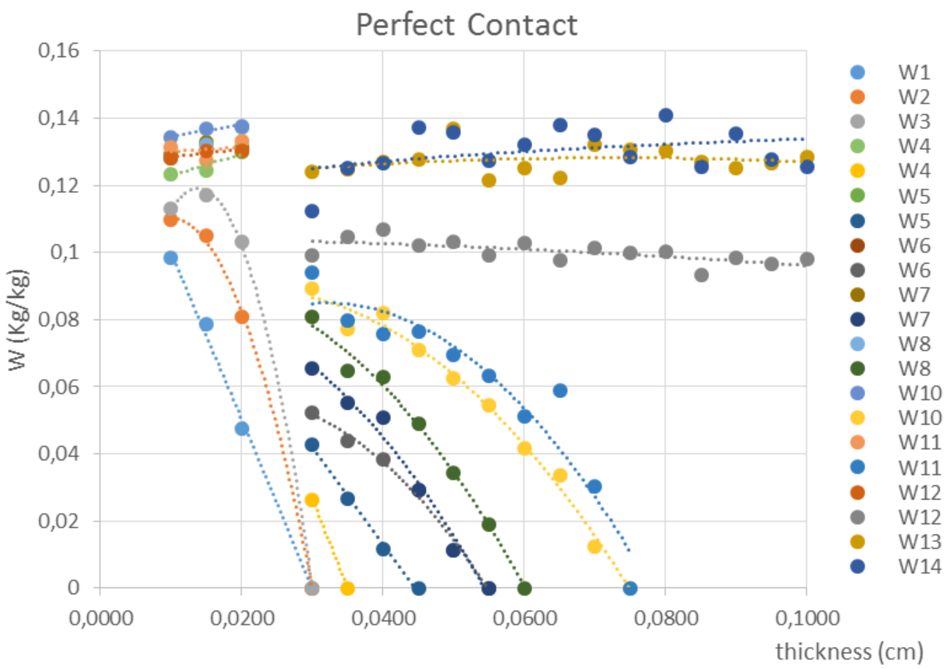


Figure 4. Water content profiles obtained for a multi-layered material

Figure 4 shows that when the flow reaching the interface is less than the maximum flow transmitted - FLUMAX there is no disturbance in the development of the water profiles. However, when flow's interface is higher than FLUMAX, it can be seen that the first layer quickly meets a moisture content close to saturation while the humidification of the second layer is very slower than the first layer.

CONCLUSION

According to the performed study some conclusions can be highlighted. The knowledge of moisture transport in porous building materials and components is crucial to predict and avoid several pathologies and is essential to increase the durability. It is essential to predict this type of deterioration studying the moisture transfer in building materials and components in the wetting and in the drying phases. It was studied the influence of interface between layers, monolithic and multi-layered (two layers with a "perfect contact") test pieces of ceramic bricks were submitted to vertical imbibition process. In the monolithic tests, the results attained by HUMIGAMA show the continuous absorption along the specimen and the time.

In the multi-layered tests, the results attained by HUMIGAMA show that: when the flow reaches the interface is less than the maximum flow transmitted - FLUMAX there is no disturbance in the development of the water profiles; when flow's interface is higher than FLUMAX, it can be seen that the first layer quickly meets a moisture content close to saturation while the humidification of the second layer is very slower than the first layer.

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