Combined experimental and numerical characterization of thermal properties of lightweight concretes used in construction

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ABSTRACT. The aim of this study is to investigate the thermal insulation properties of the construction materials used in the buildings sector. Initially, the effect of moisture on the thermophysical properties of three types of concrete (classic concrete, concrete with cork aggregate and polystyrene concrete) are investigated experimentally. Then a numerical analysis basing on finite differences method is applied in order to examine simultaneous heat and mass phenomena inside studied materials. Through this study, it was found that the presence of water in building materials, even in small quantities significantly modifies their thermophysical properties, which leads an adverse effect on their thermal insulation power. The results indicate that the addition of cork aggregates and polystyrene beads to concrete improves its thermal performance. This work comes also within an economic framework, given the abundance of cork aggregates and polystyrene beads.

RÉSUMÉ. Le but de cette étude est d'étudier les propriétés d'isolation thermique des matériaux de construction utilisés dans le secteur des bâtiments. Dans un premier temps, l'effet de l'humidité sur les propriétés thermophysiques de trois types de béton (béton classique, béton avec agrégat de liège et béton de polystyrène) est étudié expérimentalement. Ensuite, une méthode d'analyse numérique basée sur les différences finies est appliquée afin d'examiner simultanément les phénomènes de chaleur et de masse dans les matériaux étudiés. Cette étude a révélé que la présence d'eau dans les matériaux de construction, même en petites quantités, modifiait considérablement leurs propriétés thermophysiques, ce qui affectait négativement leur pouvoir isolant thermique. Cette étude a révélé que la présence d'eau dans les matériaux de construction, même en petites quantités, modifiait considérablement leurs propriétés thermophysiques, ce qui affectait négativement leur pouvoir isolant thermique. Les résultats indiquent que l'addition d'agrégats de liège et de billes de polystyrène au béton améliore ses performances thermiques. Les résultats indiquent que l'addition d'agrégats de liège et de billes de polystyrène au béton améliore ses performances thermiques. Ce travail s'inscrit également dans un cadre économique, compte tenu de l'abondance d'agrégats de liège et de billes de polystyrène.

KEYWORDS: lightweight concrete, construction materials, thermal properties, heat and mass transfer.

MOTS-CLÉS: *béton léger, matériaux de construction, propriétés thermiques, transfert de chaleur et de masse.*

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1. Introduction

The limitation of energy consumption in the building sector is based initially on the choice of materials used for the construction of the envelope. Among these materials: the concrete. It is easy to manufacture and present interesting structural properties and a good durability. However, it has a raised density from where the installation of important foundations to support the design weight. Globally, this material is performing from the mechanical view, but it is less interesting from the thermal view.

New materials then appeared have a density lower than that of the ordinary concretes, known by the lightweight concrete name (Yasar, 2008). These materials can be obtained thanks to the substitution of the traditional aggregates by Lightweight aggregates (Shink, 2003), often artificial such as expanded clay, pumice, perlite, vermiculite, rubber, etc. A huge quantity of research revealed that this substitution of aggregates in concrete could improve its thermal performance as well use of appropriate mixes could lead to it with sufficient mechanical strength for structural use. We can mention the contributions of Schackow *et al.* (2014) who presented a comparison between mechanical and thermal properties of lightweight aggregate concrete with two kinds of lightweight aggregates, vermiculite and expanded Polystyrene (EPS). The test results showed that EPS lightweight concrete has higher strength and is lighter than with vermiculite but the vermiculite lightweight concrete had lower thermal conductivity than with EPS. Nguyen *et al.* (2014) tested seven types of fine and coarse lightweight aggregates from three different natures. They found that fine lightweight aggregate substitution significantly enhanced thermal properties. Furthermore, an experimental study was performed by Oktay *et al.* (2015) for producing new lightweight concretes with replacing normal aggregates by lightweight aggregates (LWAs) including pumice (PA), expanded perlite (EPA) and rubber aggregates (RA) at different volume, experimental investigation revealed that density and compressive strength decreased, and insulation properties improved. It indicated that the reductions in thermal conductivity and diffusivity reached to 82% and 74% respectively. Bogas *et al.* (2015) reported a study about the effects of recycled lightweight concrete aggregates (RLCA) on the properties of the concrete. The experimental results show that lightweight concrete can be used instead of the normal weight concrete, especially when light and economic solutions are required. Moreover, an investigation was conducted about the effects of vermiculite and silica fume on mortar properties by Koksal *et al.* (2015). It was found that the addition of silica fume particles in mortar increase its mechanical properties, while the vermiculite increased its thermal and silica fume and vermiculite combinations increased durability against elevated temperature. Zhang and Poon (2015) studied the influence of Furnace Bottom Ash (FBA) incorporation on the properties of lightweight aggregate concrete. The test results showed that the thermal conductivity could be lowered to around 70% of the control. Real *et al.* (2016) carried out an experimental study in order to determine the thermal properties of five different concrete mixtures, four structural lightweight aggregate (SLWAC) and a reference normal weight concrete (NWC) for comparison purposes. Results showed that SLWAC can improve the energy efficiency of buildings and thus be an attractive alternative to the use of the traditional NWC. The same behavior was noticed by Amara *et al.* (2017) who presented an experimental and theoretical study of the thermophysical properties of date palm tree fiber reinforced plaster composites.

One can still reach lower densities, by using extremely light aggregates such as cork agglomerates, and expanded polystyrene chips which are the object of this work. In the context of a characterization of these materials, interesting studies have already been conducted on lightweight concrete with expanded polystyrene beads (Madandoust *et al.*, 2011; Xu, 2012; Demirboga and Kan, 2012; Schackow *et al.*, 2014; Liu *et al.*, 2016), but very few are those relating to concretes lightened with cork aggregates (Panesar and Shindman, 2012; de-Carvalho *et al.*, 2013; Sotehi and Chaker, 2014a). However, lightweight concrete like most building materials are porous materials, and therefore very sensitive to water, they are able to fix and store moisture that can significantly modify its thermal performance, by modifying its thermophysical properties. Due to the variable ambient hygrothermal conditions, there is a transfer of this moisture within the concrete which is often linked to a thermal transfer. Besides the durability problems that it is likely to create, the coupling of these two types of transfer can, in particular, contribute significantly to energy losses.

In this context, the aim of this study is to analyze the influence of moisture content on the thermal properties of lightweight concrete. The lightweight aggregate used in this study are cork aggregate and polystyrene beads. In the first part of this paper, the measurements of density, thermal conductivity and thermal diffusivity using boxes method are presented. Secondly, a numerical modeling is undertaken in order to study heat and mass transfers occurring within the walls of a habitat constituted by this type of materials.

2. Experimental approach

We have made mixtures with an identical matrix and a different dosage of cork aggregates (CA) and polystyrene beads (PB), by replacing a portion of the volume of cement paste with CA or PB. Then we stopped as the volume occupied by the lightweight aggregates became so important that it became difficult for the mixer to mix everything. The amount of lightweight aggregates inserted is a mass fraction of the mass of cement. The dosages of fiber (CA/C) and (PB/C) were studied are: 0, 1, 2, 3 and 4 %. The used matrix consists of Portland cement (CPJ45, CMII), sand (0/4), and water.

The partners of experimental measurements are carried out within the framework of our study using a device called “thermal boxes”. This technique makes it possible to deduce thermal conductivity from tested materials in mode permanent by carrying out an energy assessment of the system. The method of the boxes has the advantage of implementation a very simple, and was the object of several publications (Azizi, 1989). The principle of the thermal conductivity measurement of tested materials is based on the realization in a permanent way of a one-way flow of heat through the box, by creating a variation in temperature between the isothermal capacity (cold source), and the transmitter of heat to constant flow (hot source). One thus imposes a uniform temperature in the box, by modifying the electric tension V applied at the boundaries of the heating film, the emission of heat is made so that the temperature inside the box (Tb) is slightly higher than the outside temperature (Ta) which is the environment temperature; (Tb-Ta)<1 °C. Measurement is carried out when the steady state is established, i.e. when the values of the temperatures approximately remain constant during more than one half an hour.

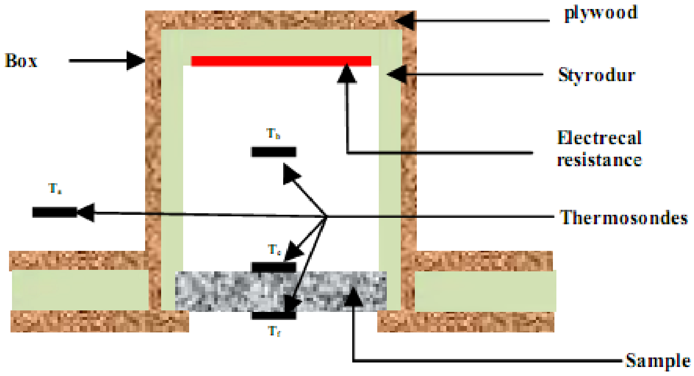

Figure 1. Box measurement of thermal conductivity

$$\lambda = \frac{e}{S\,\Delta T}\left[\frac{V^2}{R} - c(T_b - T_a)\right] \tag{1}$$

With:

λ: thermal conductivity (w/m K);

e: thickness of the sample (m);

S: surface of the sample (m^2);

ΔT: is the temperature variation between cold and heated sample faces;

V: applied tension (Volts);

R: electrical resistance (Ω);

c: coefficient of thermal loss through the box (W / K).

The inner walls of the box are reflective and the inside of the lid is provided with a source of thermal radiation (incandescent lamp of 1000 W). The thermal diffusivity is determined from the stripping of the thermogram of the non-irradiated face, using the theoretical Dégiovanni's model.

3. Mathematical modeling

The lightweight concrete used in this study as building's envelope is a porous material. It contains water in liquid or gas phase. The interior and external faces of the envelopes are at different temperatures. It results from it consequently a conduction heat transfer through material and a heat transfer accompanying each phase change. The mathematical modeling of the thermomigration phenomenon which intervenes within material carries out starting from the model of Philip and de Vries using a macroscopic approach which consists in introducing the experimental physical laws of the elementary processes into the relations of mass and heat conservation.

3.1. Mass transfer equation

The mass transfer in wet porous media is a combination of various mechanisms of vapor and liquid water transport. These transfers are done by molecular diffusion under the effect of a pressure gradient of the steam in vapor phase, and under the action of the capillary forces in liquid phase.

$$\frac{\partial}{\partial t}\left(\rho_0\, \omega_i\right) + div\, \vec{J}_i = I_i \quad (2)$$

J_i: density of the mass flux transported by diffusion.

I_i: source.

3.1.1. Mass transfer in vapor phase

The conservation equation of the vapor component is written:

$$\frac{\partial \omega_v}{\partial t} + div\vec{J_v} = I_v \quad (3)$$

The density flux of vapor mass by molecular diffusion $\vec{J_v}$ has as an expression:

$$\vec{J_v} = -[D_{mv}\nabla\omega_v + D_{vT}\nabla T] \quad (4)$$

3.1.1. Mass transfer in liquid phase

The conservation equation of the liquid component is written:

$$\frac{\partial \omega_l}{\partial t} + div\vec{J_l} = I_l \quad (5)$$

Knowing that the displacement of the liquid is governed by the law of Darcy, while revealing the gradients of temperature and of moisture, the density flux of mass in liquid phase takes the shape:

$$\vec{J_l} = -[D_{ml}\nabla\omega_l + D_{lT}\nabla T] \quad (6)$$

The mass transfer equation of the whole of the phases is written then:

$$\frac{\partial\omega}{\partial t} = \nabla(D_m\nabla\omega) + \nabla(D_T\nabla T) \quad (7)$$

3.1. Heat transfer equation

The expression of the conservation of the enthalpy in the different phases: solid, liquid and vapor make it possible to obtain the heat transfer equation:

$$\rho_0 C_p \frac{\partial T}{\partial t} = \nabla(\lambda\nabla T) + L_v\nabla(D_m\nabla\omega) \quad (8)$$

Where: ρ_0 is density solid matrix, C_p is specific heat of plate, λ is thermal conductivity of plate, L_v is latent heat of vaporization, D_m is moisture diffusivity, D_T is global thermomigration coefficient.

The resulting equations (7) and (8) form a system of partial nonlinear and coupled differential equations. Its solution is difficult to obtain using analytical methods. In this study, we use the differences method to solve it.

4. Results and discussion

The tested samples will be referenced as follows:

- RC: reference concrete (without fiber);
- CC: cork concrete;
- PC: polystyrene concrete.

The associate numbers with the CC and PC notations are used to account for the different percentages of cork aggregates and polystyrene beads added to the concrete.

4.1. Density

The influence of the incorporation of the aggregates of cork and polystyrene chips on the density of the concrete was studied. The obtained results are represented by the curves of figure 2.

It appears clearly on this figure, that the density of the lightweight concrete is decreasing function with the fibers percentage, this result is noticed for the two types of studied concretes. For example the density of a concrete reinforced by 4% of polystyrene (PC4) is of 1097 kg/ m^3, which corresponds to 49% of reduction. One notices without ambiguity that this reduction is very large in the case of the polystyrene concrete compared to that in the case of the cork concrete, which can be easily explained by the fact why the polystyrene density (24 kg/m^3) is much lower than that of cork (180 kg/m^3). Moreover, we can note that in the case of the polystyrene concrete there exist stages for which the density decreases remarkably. Thus, one can note a very fast reduction (15%) in the density between RC and PLWC1, followed by an additional decrease of 10% between PC1 and PC2, then another very fast reduction (16%) between PC2 and PC3, and a last stage (7%) between PC3 and PC4.

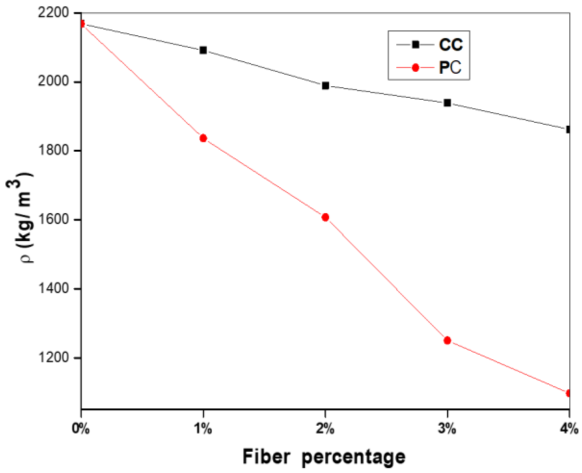

Figure 2. Density of the tested samples

4.2. Thermal conductivity

We present in this part the results of the thermal conductivity measurements carried out in our laboratory. Initially, the samples are studied in a normal state where they are permanently with the free air, under the natural conditions of temperature, pressure and moisture of the measurement room. In this state, their water content is not worthless. Indeed, the presence of this residual water content checked when we put the samples at the drying oven. The values of measured conductivities gathered in table 1.

Table 1. Thermal conductivity of the studied concrete samples in a normal state

Designation	*RC*	CC1	*CC2*	CC*3*	CC*4*	*PC1*	*PC2*	*PC3*	*PC4*
λ (W/ m. K)	0.770	0.656	0.650	0.568	0.524	0.441	0.359	0.186	0.109

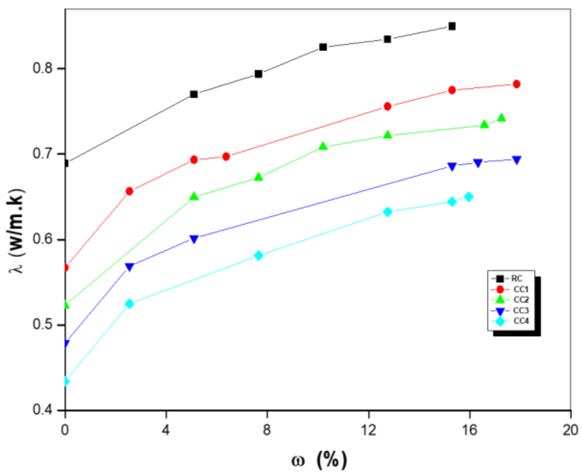

Figure 3. Thermal conductivity in terms of water content of cork lightweight concrete

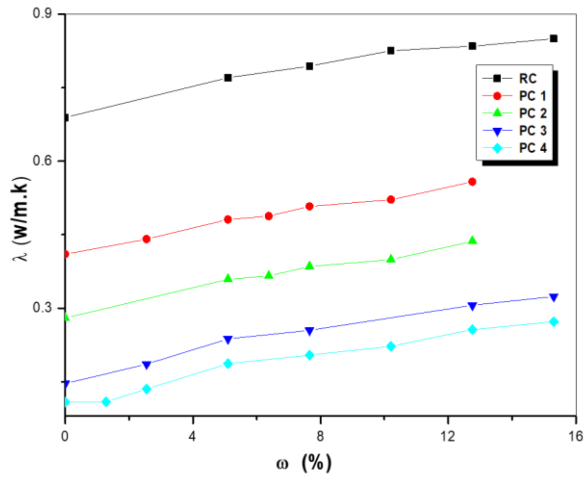

Figure 4. Thermal conductivity in terms of water content of polystyrene lightweight concrete

The analysis of the curves of figures 3and 4, makes it possible to observe an increase of the thermal conductivity with the increase of the water content. This is explained by the fact why the materials which we studied are porous. In a dry state, the thermal conductivity is function only of those of the solid matrix and the air (approximately 0.26W/m. K at 20 °C), the latter is much lower than the thermal conductivity of water (approximately 0.60W/m. K at 20°C), which will gradually replace the air contained in the pores, during humidification, it follows an increase in the apparent material thermal conductivity (Sotehi and Chaker 2013; 2014b). This result has been observed on other materials such as the hollow brick of ground stabilized with cement (Meukam *et al.*, 2003), mortar containing cement (Boukhattem *et al.*, 2007), gas concrete (Boutin, 1996), classical concrete (Khab and Chaker, 2009).

4.3. Thermal diffusivity

The results relating to the thermal diffusivity evolution as function of the moisture content for samples RC, CC2 and PC2 are presented in figure 5.

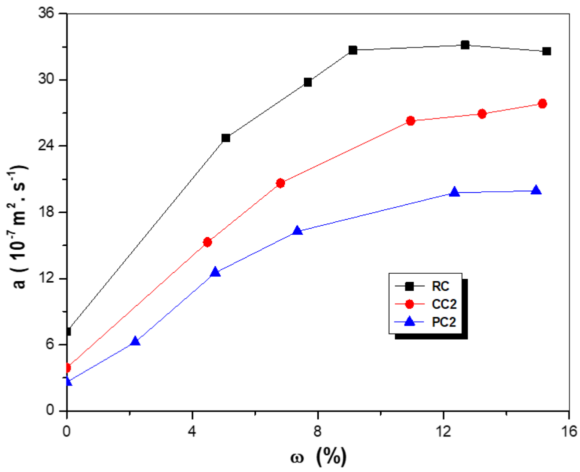

Figure 5. Thermal diffusivity in terms of water content concrete

It is noted that these curves of general shape very close to those found for the thermal conductivity, they show an increase of the thermal diffusivity with the growth of the water content, it results from the presence of the water which facilitates the diffusion of the energy in the material. In the case of the RC sample, there is an increase in the thermal diffusivity with the increase of the water content in general beyond ω = 12% but for the CLWC2 and PLWC2 samples the increase of the thermal diffusivity is less important.

4.4. Comparison of the thermal power of insulation of studied materials

For the same proportions of cork and polystyrene in concrete (CA/C=PB/C = 1, 2, 3 and 4%), a comparison of the insulating powers of the studied concretes (CC and PC) was carried out. The results of measurements of the thermal conductivities, in a dry state of studied materials are illustrated by figures 6.

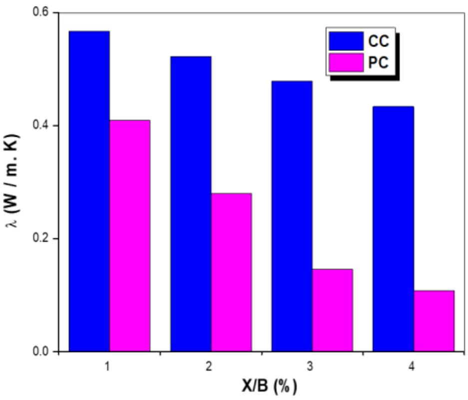

Figure 6. Comparison of thermal conductivities of the CC and PC

The analysis of the results of the histograms, makes it possible to notice that whatever the mass fraction (X/C) of fiber used and although the thermal conductivity of polystyrene (λ = 0,045 W/m. K) is higher than that of cork (λ = 0,036 W/ m. K), best the thermal performances are obtained with the polystyrene concrete, its thermal conductivity is definitely lower than that of the concrete. This can be explained by the fact that polystyrene has a low density (very small in front of that of cork), it results from it that for the same fiber proportioning (cork aggregates and polystyrene chips), the quantity of polystyrene introduced into the concrete is very large compared to that of cork and consequently the volume occupied by polystyrene in the concrete is very large compared to that occupied by cork. It is also noted that the difference between thermal conductivities increases as the fraction of lightening of the concrete grows some is the hygroscopic state of materials (figures 7 and 8).

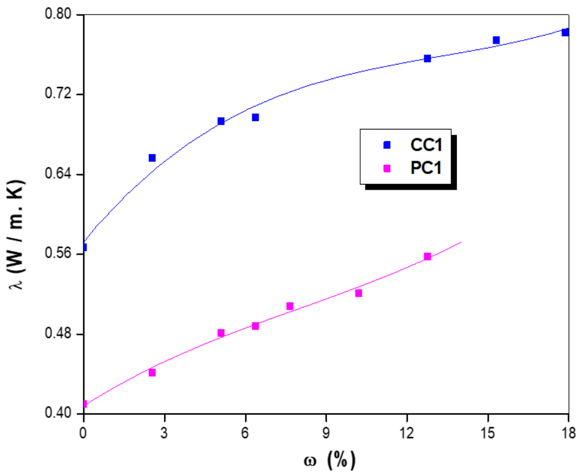

Figure 7. Comparison of thermal conductivities of CC1 and PC 1

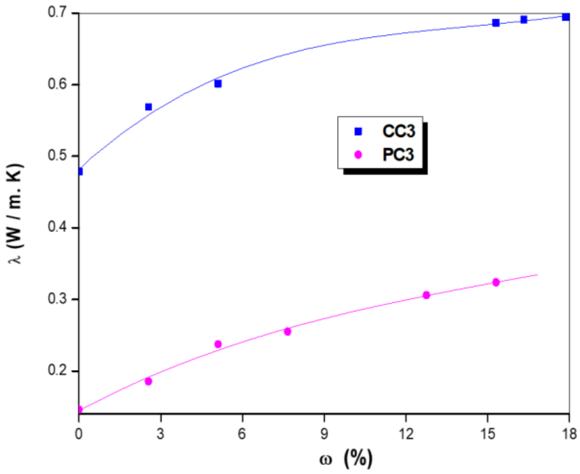

Figure 8. Comparison of thermal conductivities of CC3 and PC 3

4.5. Influence of the nature of material on heat and mass transfer

The set of the results presented in this part relates to the study of coupled heat and mass transfer that occur in four types of walls made with cork lightweight concrete and polystyrene concrete of thickness e equal to 4 cm. Initially, they have a constant temperature T_0 equal to 20 °C lower than the ambient temperature (T=45°C), the initial water content ω_0 is around 0.2 kg / kg (Sotehi and Chaker, 2014a).

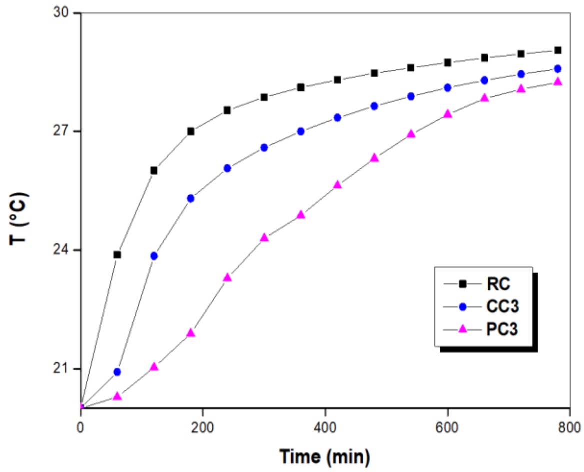

Figure 9. Influence of the nature of material on the temperature profile

The curves of figure 9 illustrate the temporal evolution of the average temperatures of the three types of concretes: RC, CC3 and PC3. It is noticed that the temperatures of the materials which initially are equal to the temperature of the interior air, increase gradually until they reach a value close to the temperature of the surrounding air. It is noted that the slope of the profiles of these temperatures is weaker for PC3 and CC3 which are more insulating than the material RC. As for the temperature, we also traced the profiles of the water content for three studied materials (figure 10). One can note that the water content evolves in a similar way through the three walls, but with different slopes. This is explained by the fact why the polystyrene and cork addition within the concrete, supports the existence of the pores within material and makes it more hygroscopic.

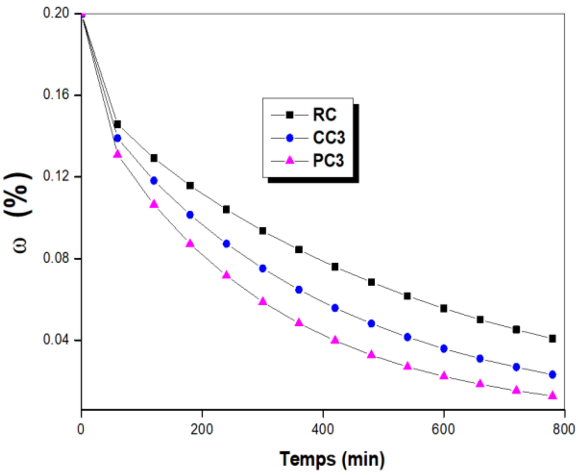

Figure 10. Influence of the nature of material on the water content profile

5. Conclusion

The exploitation of the got results, enabled us to quantify most thermophysical sizes characteristic of the samples which we worked out.

The analysis of these results showed clearly that the presence of water in building materials, even in small quantity modifies their thermophysical properties considerably. In addition, it appears without ambiguity that the introduction of polystyrene fibers and cork aggregates into the concrete during its preparation has a favorable influence on its thermal performances (conductivity and thermal resistance). The density remains one of the essential parameters to follow the evolution of the thermophysical parameters of materials because it makes it possible to assess their insulating qualities overall. They have also show that the incorporation of cork and polystyrene in the concrete slows down the transfer of heat through the wall and supports best the release of the water contained in the concrete.

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