KSCE Journal of Civil Engineering (2012) 16(6):1003-1010
DOI 10.1007/s12205-012-1470-3

Structural Engineering
www.springer.com/12205

Effect of the Incorporation of Wood Wool on Thermo Physical Proprieties of Sand Mortars

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Received January 27, 2011/Revised July 8, 2011/Accepted December 12, 2011

Abstract

The main objective of this study is to examine the heat insulation potentialities of the incorporation of wood wool in a sand mortar, in order to value the use of this type of lightened materials as lightweight insulating concrete. The wood wool has been incorporated, without any preliminary treatment, into a sand mortar. Four mortars containing different ratios of wool have been prepared and have been examined herein. It was shown that the incorporation of wood wool in the mortar decreases considerably its thermal conductivity and diffusivity. Thus, the thermal insulation capacity has been improved. Also, the influence of the water content on the thermo physical properties of the studied samples has been examined. Thus, the thermal conductivity increases rapidly with water content and the thermal diffusivity presents a maximum corresponding to a water content value W_m. However, the materials used for building constructions must present sufficient mechanical strength. According to the experimental results, the compressive strength values are compatible with the use of these materials as lightweight concrete. The examination of the water absorption of the studied samples shows the high hygroscopic nature of the elaborated composite.

Keywords: *lightweight concrete, wood wool, thermal insulation, thermal conductivity, thermal diffusivity*

1. Introduction

The main preoccupation of the builders is the sustainability of their constructions, which is made possible by the use of performance materials in terms of mechanical strength and durability. Generally, the thermal insulation of building walls is insufficient, which leads to internal temperatures too high in summer and too low in winter. This problem is often surmounted by use heating or cooling systems. This results an increase in energy consumption in the countries whereas households become more dependent on energy to maintain a satisfactory internal climate. These energy costs represent a large share of family budget. It is therefore important to reduce heat transmission through the walls of the building for reducing energy consumption (Astrand *et al*., 1994; UNCH, 1991).

The use of heavy walls in the construction field is one of the classical solutions to protect against climate aggressions. This solution requires an excessive consumption of materials. Moreover, this solution does not allow to achieve a satisfactory thermal comfort. New materials have then appeared, grouped under the name of lightweight concrete (Arnould, 1986). These materials refer to concretes of lower density than conventional concrete; it aims mainly at better heat insulation. A study of the thermal properties of these materials is essential in order to relate its strength qualities to the corresponding thermal comfort.

The aim of the work reported in this paper is to determine the effect of the incorporation of the wood wool on the thermal properties of sand mortar, i.e., thermal conductivity and thermal diffusivity. The study is also interested in the influence of water content on these thermal properties. The choice to use wood wool as lightener of mortar is justified not only by its insulating nature, but also by the fact that it presents the advantage to use a renewable raw material. Then, the wood fibres are naturally degradable (Trouy-Triboulot and Triboulot, 2001) which is not negligible in the current context of waste limitation.

2. Material and Experimental Set Up

2.1 Raw Materials

• The cement is a Portland cement CPJ 35. It contains a per-

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Table 1. Composition of the Used Sand

Constituents	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	LOI
Content (%)	77.1	0.07	1.09	0.26	0.02	1.01	12.23	0.51	0.14	0.05	7.03

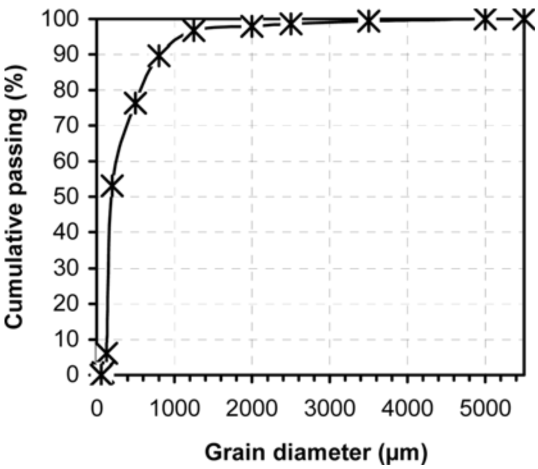

Fig. 1. Granulometric Distribution of the Used Sand

Fig. 2. Used Wood Wool

centage of Clinker in about 65%, the rest consisting of additives (limestone, fly ash, pozzolan). The CPJ 35 develops performances adapted for use in the manufacturing of unarmed concrete and all types of mortars.

- The sand used is beach one, from the area of Kabila (M'diq-Fnideq,Tetuan, Morocco). The chemical composition of this sand demonstrates its essentially siliceous nature (Table 1). The granulometric analysis by sieving, established according to the French standard NF P18-560 (1990), is presented in the Fig. 1. The curve shows a wide particle size distribution, with a maximum diameter reaching 5 mm. The apparent density of the sand is on the order of 1500 kg/m^3.
- The wood used in this study is a fir, due to its low bulk density and widespread application potential within the building industry. The wood wool used results from the planing of the trunks of a length between 10 cm and 20 cm. The width of fibres varies between 1 cm and 2 cm and their thickness between 0.2 mm and 0.5 mm (Fig. 2). Some proprieties of the wood wool are shown in the Table 2.
- The mixing water is drinking water from the public water supply network. Its pH is verified regularly and has a value of approximately 7.6.
- The superplasticizer is a liquid of brown colour, its density 1.05 kg/l. According to the manufacturer, the maximum dosage should not exceed 2.6% by mass of cement.

2.2 Production and Formulation of the Composite

The sand and cement are initially introduced into the mixer then mixed at low speed. Next, processed wood wall is gradually sprinkled into the mix while continuing the low speed mixing. The mixing water is then gradually added without stopping the mixing.

Table 2. Proprieties of the Used Wood Wool

Bulk density (kg/m^3)	Real density (kg/m^3)	Humidity (%)	pH
50	423	13	4.9

Table 3. Formulations of the Studied Mortars

Sample	Dosage (kg/m^3)					W/C[a]	α[b] (%)	Flow time[c] (s)
	Sand	Cement	Wood wool	Water	Superplasticizer			
P0	1280	640	0	384	0	0.6	0	10 ± 2
P1	1152	576	35	345	3	0.6	2	10 ± 2
P2	1023	512	46	307	5	0.6	3	10 ± 2
P3	961	480	58	288	7	0.6	4	10 ± 2

[a]Mass ratio of water to cement.
[b]Mass wool/(cement+sand) ratio.
[c]Flow time measured according to the French standard NF P18-452 (1988).

It was noted that the wool was added to the dry mixture in a saturated state. This choice presents a double advantage. First, the saturated particles do not monopolize the water that is useful for the hydration of the cement and then do not perturb the setting. They also play the role of water reservoir during the setting. Even so, increasing the dosage of fibres led to an important reduction in workability. This phenomenon results in a heterogeneous distribution of fibres in the mortar. Thus, maintaining a suitable workability is necessary. For this, the mass ratio of water to cement was kept constant while increasing the amount of the superplasticizer with the dosage of wood wool. Besides, for comparing the properties of different formulations the flow time of different fresh mortars was guarded appreciably the same.

Once the paste turns homogeneous, it is poured into moulds. Next, the samples are compacted using a MTS electromechanical press under a compaction constraint of 0.05 MPa. This makes it possible to ensure maximum uniform distribution of wood fibres in the mixture without damaging them (Cerezo, 2005). Finally, the specimens are preserved before and after turning out into the room test at a controlled temperature and humidity (T_a = 20ºC, *R.H.* = 60%).

The Table 3 recapitulates the used formulations. The first formulation without wood wool plays the role of reference. The formulations P1 to P3 were elaborated with an increasing proportion of wood wool.

For each formulation, three samples were tested. The results presented in this article are the arithmetic mean of the values obtained from the three repeatability tests.

2.3 Measurement Techniques

2.3.1 Thermal Conductivity Measurement

For measuring the thermal conductivity the "Boxes method" has been used. This method has been used by several researchers (Ezbakhe, 1986; Mourtada, 1988). The installation of measure (Fig. 3) consists of following elements:

- An enclosure A of internal dimensions (200×100×45 cm) playing the role of the cold atmosphere. It is maintained at a low temperature (until -10ºC) by using a heat exchanger G situated on its base and fed by glycoled water cooled by a cryostat K. This enclosure is insulated from the external atmosphere by extruded polystyrene.
- Two identical boxes B offering the possibility to operate on two different materials. These boxes are made in plywood insulated in the inside by the extruded polystyrene. Each box has an open face and contains on the interior of its superior face an electrical resistance heating R. The interior of boxes plays the role of the hot atmosphere.
- The measurement samples of dimension (27×27×2 cm) are inserted between the box B and the enclosure A. The geometry of the sample and the precaution taken in order to limit the lateral heat lost allow us to consider the unidirectional heat transfer.

When the permanent regime is established, the thermal conductivity is given by:

$$\lambda = \frac{e}{S\Delta T}(q + C\Delta T') \quad (1)$$

C: Thermal loss coefficient of the box (W/ºC)
e: Sample thickness (m)
q: Flow supplied by the electrical resistance (W)
S: Sample area (m^2)
ΔT: Temperature difference between the hot face and the cold face of the sample
$\Delta T'$: Temperature difference between the outside atmosphere and the internal atmosphere of the box B

For measuring the thermal conductivity of the wood wool, the fibres are placed in a special frame, having an identical shape to that of the consolidated specimens (Fig. 4). The two principal faces traversed by the heat flow are composed of copper plates of

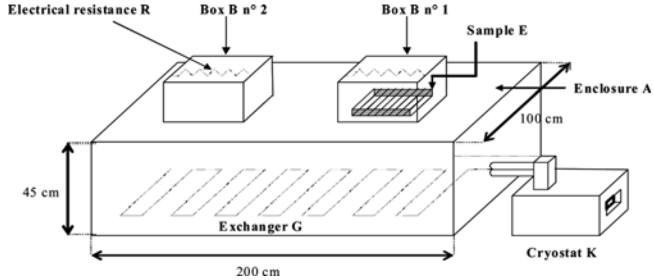

Fig. 3. Experimental Setup of the Box Method

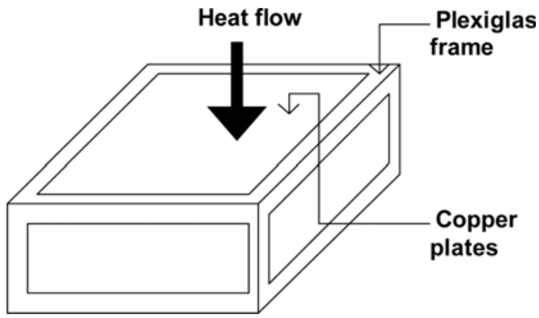

Fig. 4. Frame Used for Measuring Thermal Proprieties of Wood Wool

thickness of 1 mm. The thermal conductivity of copper at 20ºC is on the order of λ=389 W/mºC (Sacadura, 1979). The four sides are of plexiglas of 15 mm of thickness. The thermal conductivity of plexiglas at 20ºC is on the order of λ=0.2 W/mºC (IEA, 1991). The tightness of the frame after closing is ensured by several screws.

The choice of copper plates is justified by Martin (1988). The author shows that it is as if the heat flow is directly applied to the granular or fibrous material and that the taking of temperature is also carried out directly on the material. This physical reality is the fact that thermal conductivity of copper is very high compared to that of insulating materials.

The introduction of fibres in the frame is made by a series of vibrations and compression. These operations serve to realize a perfect contact between the copper plates and fibres.

Taking into account that the heat flow through simultaneously the surfaces of plexiglas frame and fibres, a correction of the thermal conductivity measurement is necessary (Martin, 1988):

$$\lambda = \left(\frac{S_T}{S_f}\right)\lambda_{mes} - \left(\frac{S_p}{S_f}\right)\lambda_p \quad (2)$$

S_f: Area occupied by the wood fibres
S_p: Plexiglas area
$S_T = S_f + S_p$: Total area of the frame
λ_p: Thermal conductivity of plexiglas
λ_{mes}: Measured thermal conductivity

2.3.2 Thermal Diffusivity Measurement

The measurement apparatus used in this study is the same as that for thermal conductivity measurement. In addition, the box B is fitted with an incandescent lamp of 1000 W at its superior

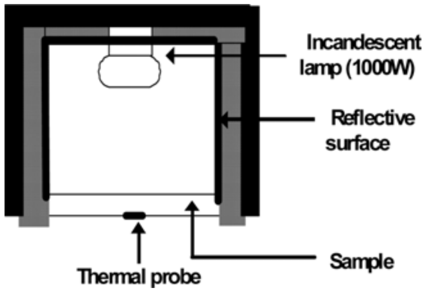

Fig. 5. Thermal Diffusivity Measurement Apparatus

face instead of the heating resistance (Fig. 5). The internal faces of the box are reflective in order to homogenize the flow on the irradiated face of sample. Diffusivity measurement is undertaken by using the flash method (Parker *et al*., 1961). A uniform short pulse of energy is applied on one face of the sample and then the thermal diffusivity a is evaluated from the temperature variation of the non irradiated face of sample, using existing theoretical models.

2.3.3 Compressive Strengths Measurement

The moulds and the mechanical press used in the compressive tests are identical to those proposed by the standard EN 196-1 (1995). Measures were carried out on 16×4×4 cm parallelepiped samples, using a 200 kN capacity Walter Baibag press, with a speed loading fixed at 2.4 kN/s.

2.3.4 Water Absorption Measurement

The test of water absorption by immersion consists of two major steps: saturating the specimens followed by drying. First, the concrete specimens are immersed in water until the change in mass during 24 hours is less than 0.1%. The obtained saturated mass is called M_s. Afterwards; the specimens are dried in a ventilated oven at a temperature of 80ºC until the difference in mass during 24 hours is less than 0.1%. The dry mass is called M_d. The water absorption by immersion W is expressed as the water uptake relative to the dry mass:

$$W = \frac{M_s - M_d}{M_d} \tag{3}$$

3. Results and Discussion

3.1 Lightening of the Composite

The mortar, due to its small granularity is lighter than concrete. The introduction of wood wool reduces it more (Fig. 6). This lightness is essentially due to the porous structure of wood. The addition of wood wool increases the porosity of the material and therefore makes it lighter. For a mass percentage of wood wool ranging from 0 to 4%, the reduction in the density is about 15.5%. Thus, the first advantage of the use of wood wool is the lightening of the composite. This type of effect was already noted by Aouadja *et al*. (1995) on concrete lightened by wood residues.

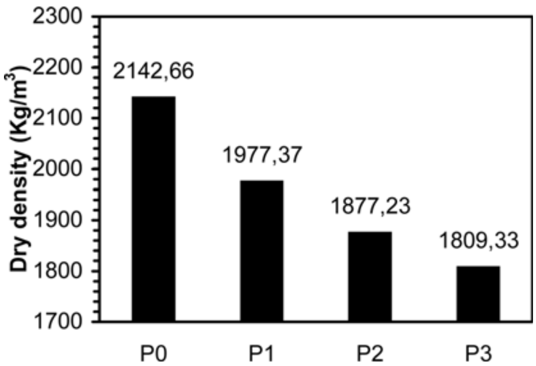

Fig. 6. Dry Density of the Four Studied Mortars

3.2 Thermal Conductivity

In addition to presenting experimental measurements of thermal conductivity, they are compared with two combinations of the series and parallel models.

Consider a two-phase medium made up of a matrix and an insulator having volume fractions (1-θ) and θ respectively. When the two phases are thermally in parallel in the direction of heat flow, the effective thermal conductivity of the sample is given by:

$$\lambda_{//} = \theta\lambda_i + (1-\theta)\lambda_m \tag{4}$$

Likewise, when the two phases are thermally in series in the direction of heat flow, the effective thermal conductivity is given by:

$$\lambda_{\perp} = \frac{1}{\dfrac{\theta}{\lambda_i} + \dfrac{(1-\theta)}{\lambda_m}} \tag{5}$$

where λ_m is the thermal conductivity of the matrix, λ_i the thermal conductivity of the insulator.

For an intermediate distribution of phases, Willy and Southwick (1954) propose in their model a weighted arithmetic mean:

$$\lambda = F\lambda_{//} + (1-F)\lambda_{\perp} \tag{6}$$

Chaudhary and Bhandari (1968) propose in their model a weighted geometric mean:

$$\lambda = \lambda_{//}^{F}\lambda_{\perp}^{(1-F)} \tag{7}$$

Where F is assumed to be numerical correlation factor and may be defined as F^{th} fraction of the material oriented in the direction of heat flow and remaining $(1\text{-}F)^{th}$ fraction is oriented perpendicular to the direction of heat flow. The value of F used in this study is $F = 0.35$, which is proposed by Bhattacharya *et al*. (2002).

Table 4 includes the experimental values of the dry thermal conductivity, and those calculated theoretically by the proposed models. It may be noted that the reference mortar P0 play the role of the matrix and the wood wool play the role of the insulator with λ_i=0.065 W/mºC.

The effect of incorporating wood wool in the mortar is to decrease its thermal conductivity. This finding is similar to

Table 4. Thermal Conductivities of the Studied Mortars

Sample	θ(%)	λ_{exp}^{d} (W/m°C)	Willy and Southwick model		Chaudhary and Bhandari model	
			λ (W/m°C)	% error	λ (W/m°C)	% error
P0	0	0.420	0.420	0	0.420	0
P1	7.86	0.340	0.328	3.52	0.325	4.41
P2	12.62	0.305	0.293	3.93	0.287	5.90
P3	15.85	0.283	0.274	3.18	0.266	6

[d]Experimental value of thermal conductivity.

published results concerning mortar lightened by wood shavings (Bederina *et al*., 2007). The authors compare the mixture with dune sand and that with river sand. The decrease of thermal conductivity can be explained by the fact that the thermal conductivity of wood is very lower compared to that of mortar. Furthermore, the decrease of density entrains a reduction of thermal conductivity. This dependence is always verified on materials with mineral matrix and vegetable fibres according to Alrim *et al*. (1999) which used a clayey matrix or, according to Khedari *et al*. (2004) which used matrix based on portland cement.

The comparison of the experimental measurements of the conductivity to the theoretical approaches indicates that theoretical results correspond well to the values obtained during the experiments. Moreover, it is found that the percentage deviation is least for Willy and Southwick model. On this basis, the presented theoretical models can be used by engineers and researchers to predict thermal conductivity of the composite at a given dosage of wood wool.

3.3 Thermal Diffusivity

For calculating the thermal diffusivity, two models have been chosen among the existing ones in the literature. Opting for these models is justified by the fact that they suit the used experimental conditions:

- Degiovanni model (Degiovanni, 1977): the author supposes the unidirectional heat transfer and takes account of heat losses on all faces of the sample. In these conditions the expressions of the thermal diffusivity are given as follows:

$$a_{1/2} = e^2\frac{(0.761\ t_{5/6} - 0.926\ t_{1/2})}{t_{5/6}^2} \tag{8}$$

$$a_{2/3} = e^2\frac{(1.150\ t_{5/6} - 1.250\ t_{2/3})}{t_{5/6}^2} \tag{9}$$

$$a_{1/3} = e^2\frac{(0.617\ t_{5/6} - 0.862\ t_{1/3})}{t_{5/6}^2} \tag{10}$$

where $t_{i/j}$ is the time corresponds to the ratio i/j of the maximum temperature.

- Yezou model (Yezou, 1978): in addition to the previous conditions, the author takes account of the pulse duration t_0. The terms of the thermal diffusivity that results, are given by:

$$a_{5/6} = \frac{e^2}{t_{5/6}+t_o/2}\left[0.713\left(\frac{t_{1/2}+t_o/2}{t_{5/6}+t_o/2}\right)^2 - 1.812\left(\frac{t_{1/2}+t_o/2}{t_{5/6}+t_o/2}\right) + 1.037\right] \tag{11}$$

Table 5. Thermal Diffusivities of the Studied Mortars

Sample	a (10^{-7} m²/s)		Relative difference (%)
	Yezou model	Degiovanni model	
P0	3.435	3.668	6.56
P1	2.475	2.997	19.07
P2	2.001	2.166	7.91
P3	1.872	2.139	13.31

Table 6. Thermal Proprieties of the Used Wood Wool

λ (W/m°C)	a^Y (10^{-8} m²/s)	a^D (10^{-8} m²/s)
0.065	6.48	6.89

[Y]Yezou model.
[D]Degiovanni model.

$$a_{1/2} = \frac{e^2}{t_{1/2}+t_o/2}\left[-0.4032\left(\frac{t_{1/2}+t_o/2}{t_{5/6}+t_o/2}\right)^2 + 0.1103\left(\frac{t_{1/2}+t_o/2}{t_{5/6}+t_o/2}\right) + 0.2027\right] \tag{12}$$

For each model, the value of the thermal diffusivity is calculated as being the arithmetic mean of the given expressions.

Table 5 gives the values of the dry thermal diffusivity calculated using the two aforesaid models. Results show that thermal diffusivity decreases with the incorporation of wood wool. This result is in agreement with the results found for thermal conductivity. Thus, the lightening of mortar by wood wool has a positive effect on its thermal insulation capacity. That is expected, because of the low thermal proprieties of wood wool (Table 6). The difference observed between the values calculated by Digiovanni model and those obtained by Yezou one is normal, because of the difference between the basic hypotheses used in each model.

3.4 Influence of Water Content on Thermal Conductivity

The evolution of the thermal conductivity with the mass water content of the various samples is illustrated on the Fig. 7. The thermal conductivity increases rapidly with water content. A moist material, therefore conducts more heat than a dry one; indeed, thermal conductivity of liquid water is much greater than that of air. Numerous works (El bouardi, 1991; Kricher and Kroll, 1963; Laurent and Guerre-chaley, 1995) bring to light this dependence (conductivity/water content) on other building materials. Certain studies have considered that the dependence between the thermal conductivity and the water content is quasi-linear (CEB, 1978). However, these conclusions were obtained by covering a limited range of water contents. Boutin (1996) shows by homogenization, that the dependence between λ and water content is not linear but curvilinear. Anyway, whatever the mathematical form of the relationship between water content and thermal conductivity, it is important to retain that the presence of water decreases the insulating capacity of materials in important proportions.

3.5 Influence of Water Content on Thermal Diffusivity

The curves of the variation of the thermal diffusivity (Yezou model) in function of the mass water content are shown in Fig. 8. A maximum of thermal diffusivity is observed for values of

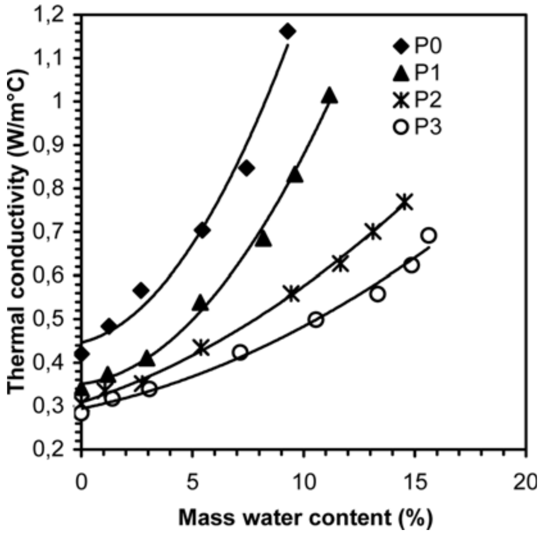

Fig. 7. Thermal Conductivity as Function of Water Content

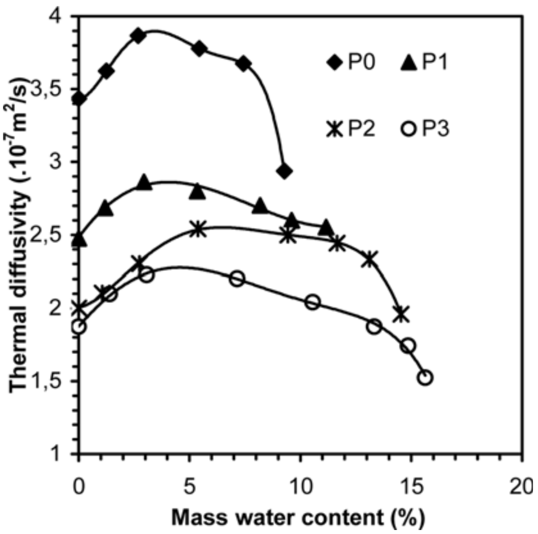

Fig. 8. Thermal Diffusivity as Function of Water Content

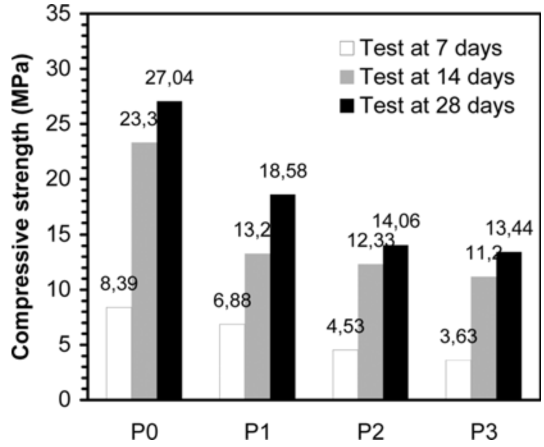

Fig. 9. Compressive Strength of the Studied Mortars

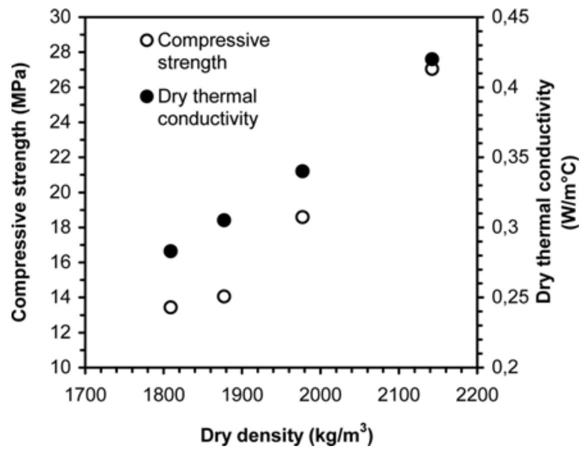

Fig. 10. Compressive Strength and Dry Thermal Conductivity as Function of Dry Density

water content of 4% for P0 and P1, 8% for P2 and 5% for P4. This phenomenon has been observed on other materials (Foures *et al*., 1981; Meukam *et al*., 2004). The presence of this maximum is explained by the fact that the volumetric heat capacity (ρc) varies linearly with the water content, while the thermal conductivity presents an unmonotonous variation.

3.6 Mechanical Properties

Lightweight concretes are generally used in domestic constructions. Most codes specify a requirement on the material's minimum compressive strength. The Fig. 9 shows that the compressive strength decreases by increasing the content of wood wool. This is in agreement with the works of Soderhjelm (1976) who studied a composition of mortar with addition of sludges from the pulp and paper industry. The decrease of compressive strength can be explained not only by the additional porosity introduced into the matrix, but also by a poorer wool/matrix adhesion. It should be noted that the loss in compressive strength is replaced by a profit of the thermal insulation capacity. Other authors announced this result and even showed that with certain treatments applied to the wood, the mechanical performances of the material are improved (Eustafievici *et al*., 2002; Jennifer *et al*., 2004).

Density d, mechanical strength R_C and thermal properties are crucial for choosing the type of concrete to use. The dual diagram of Fig. 10 describes the relationship $R_C = f(d)$ and $\lambda = f(d)$. It shows that increasing the compressive strength is achieved at the expense of lightness and thermal insulation, the knowledge of the resistance level sufficient for a given use is therefore crucial for the optimal exploitation of the insulation and lightness qualities. Anyway, the compressive strength values obtained in this study are compatible with the use of the elaborated materials as bearing insulator concretes, according to the functional classification of RILEM (RILEM, 1978).

3.7 Hydrous Behaviour

Figure 11 represents the water absorption of the several composites. It shows that the addition of wood wool in the mortar is translated by an important increase of its water absorption. That can be explained partially by the fact that wood is a very

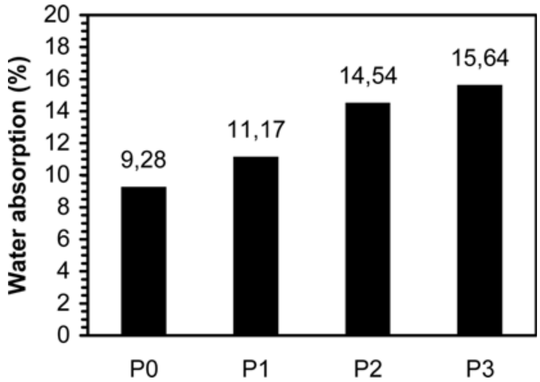

Fig. 11. Water Absorption of the Mortars

hygroscopic material. This problem constitutes an inconvenience for this material. High shrinkage is expected because of this high hygroscopic nature.

Dimensional stability is an important parameter that can affect the durability of building materials. Shrinkage and swelling phenomena are susceptible to cause damages. The works realized by Ledhem (1997) on the dimensional variations of wood concretes of clayey matrix brought to light a method for minimizing dimensional variations of this type of material. Ledhem *et al.* (2000) have shown that the processing of wood shavings with oil intended for disposal allows significantly decreasing the water absorption of the shavings as well as that of wood-cement-schistous fines composite. The dimensional variations of the composite can be halved without any of the mechanical properties or thermal conductivity being adversely affected. Bederina *et al.* (2009) have shown that the treatment of the wood shavings reduced considerably the water absorption and shrinkage of concrete lightened by wood shavings. The compressive strength is considerably improved, the insulation capacity is slightly influenced, the structure of the composite is more homogeneous and compact, and the wood–matrix adherence is better.

4. Conclusions

The purpose of this work was the study of the influence of the addition of wood wool on the thermal properties of sand mortars. The insulating properties of this composite should find it an important use in constructions (floor formwork, suspended ceilings, screeds, interior masonry blocks…). Another interesting data is that the wood is a renewable and degradable material. In general, the following conclusions were made:

- The increase in wood wool content lightened the sand mortar by distinctly decreasing its density;
- The increase in wood wool content increases the insulating capacity of mortar by decreasing its thermal conductivity and diffusivity;
- The thermal conductivity and thermal diffusivity were strongly influenced by the material's water content. The obtained behaviours show a rapid increase of thermal conductivity with water content, and a maximum diffusivity corresponding to a water content W_m;
- The increase in wool content reduces the mechanical strength of mortar. However, the obtained values remain compatible with the use of these materials as bearing insulators (RILEM, 1978);
- The main inconvenience of these materials is their high water absorption. However, several methods existent in the literature allow to solve this problem;
- The fibre orientation in the elaborated composites is random. Since orientation of fibres plays important role of thermal and mechanical behaviour, it will be interesting to lead a detailed study in order to analyze the influence of fibre inclination angle.

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