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Influence of the proportion of wood on the thermal and mechanical performances of clay-cement-wood composites

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Abstract

The introduction of wood aggregates to produce low density composites is an interesting technique allowing the reuse of wastes from both the aggregate-mining and wood processing industries. This paper describes the influence that the proportion of wood aggregates has on the thermal and mechanical performance of a clay-cement-wood composite. First, the composite material and its production technique are presented. Then, the thermal conductivity, mechanical strengths and the porosity of the matrix are experimentally evaluated. Finally, it is shown that the addition of wood to clayey concrete improves its insulation characteristics, reduces its mechanical strength and increases its deformability.

Keywords: Mechanical strength; Thermal conductivity; Wood aggregates; Cement; Clay

1. Introduction

Clayey concretes: adobe, cob, daub, clay and straw mortar have been the subject of much research work conducted over the past 20 years as a result of the necessity to enhance the use of local materials in developing countries, to rehabilitate existing buildings and, in some areas, to reuse the by-products of local industrial operations.

Most of the work performed has focused on mechanical stabilization, notably through processes leading to the increase of the density: compaction, extrusion and/or chemical properties so as to improve the durability. The addition of fibers has also been the topic of many studies. Work carried out has shown that while the thermal inertia of such low-cost materials does allow for thermal comfort, this is attained by means of a significant increase in the dimensions of the building envelope [1]. To the extent that mechanical performance is not compromised, a reduction in the density could therefore constitute a key objective. The weight reduction process also reduces the thermal conductivity and can favour the utilization of low density materials in rehabilitation work. This prospect has served to guide a portion of our research efforts [2–14]. The emphasis herein has been placed on the environmental impact of the materials employed. The set of imperatives established were: manufacturing at minimal energy costs, using a small amount of energy-consuming materials and enabling the reuse of industrial wastes.

Different weight reduction processes have been developed [12]. Among them, the introduction of wood aggregates deserves special mention. This technique allows reusing wastes from two types of industries: the aggregate-quarrying industry, and the wood processing industry. In some developing countries, this technique allows the reuse of resources which are locally abundant and, at times, improperly utilised. Furthermore, wood is a renewable raw material.

A lot of papers can be found in literature which make reference to wood/cement composites [15–27]. However lightweight clayey concretes formulated with wood aggregates have not been studied before.

The potential for using a particular building material can only be determined from the results of a multi-criteria analysis. The application of insulation materials, for example, always necessitates a compromise between

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thermal and mechanical performance. Therefore, our study will focus specifically on the influence of wood on these two measures of performance.

2. Materials and operating techniques

For the purposes of this research work, the clayey material used was an alluvial aggregate waste. The mineralogical study has shown that this material was composed essentially of kaolinite along with a percentage of quartz below 5% [13].

The upper granular limit value was near 70 μm. The granulometric evaluation, conducted from a sedimentation analysis reveals that the fraction ($2 < \varnothing < 70$ μm) represents 45% of cumulative passing while the clay fraction, according to the strictest definition of the term (i.e. $\varnothing < 2$ μm), corresponds to 55%. It must be noted that the separation of the clay part is made by leaching with addition of a flocking agent. The real silt part is certainly overestimated. Nevertheless it is necessary to bear in mind that the purpose of this work is the reuse of the waste as it stands. The plasticity index, as estimated from the Atterberg limit, was $I_p = 12\%$. This indication is all the more high that the proportion of clay is larger and that this clay is finer. In the present case, it can be estimated, taking into account results of the mineralogical analysis, that the flocculation gives rise to clayey particles agglomerations.

The cement used was a CPA CEM I 52.5 (NF 15301).

The wood aggregates, consisting of wastes from joiners' workshops, were composed of 60% northern deal and 40% tropical wood (sipo).

The apparent specific gravity was around 0.5.

The composition by weight of the materials studied is given in Table 1. The weight percentage of cement was 20% and the sum of wood aggregates and clay represented 80% of the dry mixture.

Mixing was performed in accordance with the standard for normalised mortars (EN 196-1). As opposed to the techniques generally used for lightweight aggregates, the components were initially dry mixed. Pre-wetting tests on wood aggregates have shown the difficulty involved in obtaining a homogeneous mix under these conditions, most likely due to the particular geometry of the aggregates [14]. Next, water was added in accordance with the empirical formula: $W = 0.35\text{Ce} + 0.70\text{Cl} + 1.5\text{Ag}$ [12], which takes into account the water being absorbed by wood aggregates and thereby enables operating at a constant workability. W, Ce, Cl and Ag are the weight percentages of water, cement, clay and wood aggregates, respectively.

Table 1
Weight composition of the standardized samples

Dry composition			Water added W (%)
Ag (%)	Cl (%)	Ce (%)	
10	70	20	71
20	60	20	79
30	50	20	87
40	40	20	95

Note: Ag, Cl, Ce, W are the weight percentages of wood aggregates, clay, cement and water, respectively – W (%) = 0.35Ce + 0.70Cl + 1.5Ag.

The maximum size of wood aggregates used was about 20 mm. This value was taken into account in order to dimension the test samples according to French standard NF P 18-400. Cylindrical samples (160 × 320 mm) were used for the compressive tests while prismatic samples (140 × 140 × 560 mm) were used for the bending tests, in accordance with the French standards NF 18-406 and NF 18-407, respectively.

A study of both axial and transverse strains under the action of a compressive uniaxial stress was conducted using strain gauges connected to an extensometer bridge. The loading rate was set at 1000 N/mm, following the predetermination of the maximal stress. The values indicated by each gauge were recorded in steps of 200 N. The test was continued until the rupture of the cylinder.

Flexure studies were carried out with the use of the standardized apparatus for prismatic samples of concrete (NF P 18407). The values indicated on the micrometers were detected for each loading step of approximately 100 N. The test is continued until rupture.

The diagrammatic representations of the stress–strain relations allow determination of the initial tangent modulus (static modulus). Although a single relation based on physical behaviour does not exist between the two moduli [28], the dynamic modulus was also determined by application of a longitudinal ultrasonic vibration according to standard XP P 18-418. The velocity of the ultrasonic wave is related to the physico-mechanical characteristics of the material by the relation: $C_L = \sqrt{(E_d/\rho)(1-\nu)/(1+\nu)(1-2\nu)}$, where C_L (m/s) is the velocity of the ultrasonic wave, E_d (N/m^2) the dynamic modulus of elasticity, ρ (kg/m^3) the bulk density and ν is the Poisson's ratio. The dynamic modulus of elasticity can be expressed as: $E_d = K(\nu)E_d^*$, where E_d^* is the overestimated dynamic modulus of elasticity and $K(\nu)$ is a factor depending on the Poisson's ratio.

The Poisson's ratio was determined from the ratio of the lateral strain to the longitudinal strain for a proportion stress on ultimate strength equal to 0.33.

A study of the thermal conductivity was carried out on cylindrical samples (150 × 150 mm) using the so-called "Line Source Method" with the help of a thermal cylindrical probe of weak inertia [29,30]. It is 100 mm long and the diameter is 3.5 mm. The temperature rise at the middle of the probe is related to the thermal conductivity λ (W/m K) of the surrounding medium by the relation: $\Delta T = (Q/4\pi\lambda)(\mathrm{Ln}(t) + C)$ using a least squares approach to the data acquired between 220 and 400 s (linear region). Q (W/m) is the power per unit length supplied to the thermal probe. ΔT (°C) is the temperature rise measured at the time t (s). C is a constant depending on experimental conditions and material. The thermal conductivity obtained using a "Line Source Technique" is typically accurate to within ±5%.

A MEB PHILIPS SEM 505 was used for the microstructural investigations. Fragments of specimen were extracted and the free water in the samples removed by means of vacuum drying. The samples were then covered with a thin layer of evaporated gold before they were examined in Scanning Electron Microscopy.

Throughout this entire study, the values indicated correspond to an average of three samples.

3. Experimental results and discussion

3.1. Influence of the percentage of wood on the density

Table 2 collects the values of the dry density for the various samples studied. These values decrease from about 1200 to 500 kg/m^3, as the percentage of wood aggregates increases from 0% to 40% with the chosen matrix composition, i.e. containing 240–100 kg/m^3 of cement in the dry consolidated material. This density corresponds to a total calculated porosity that varies from about 50% to 80%. Fig. 1 shows a plot of composite dry density versus aggregates content which gives the empirical relationship: ρ (kg/m^3) = 1184 − 17Ag (%).

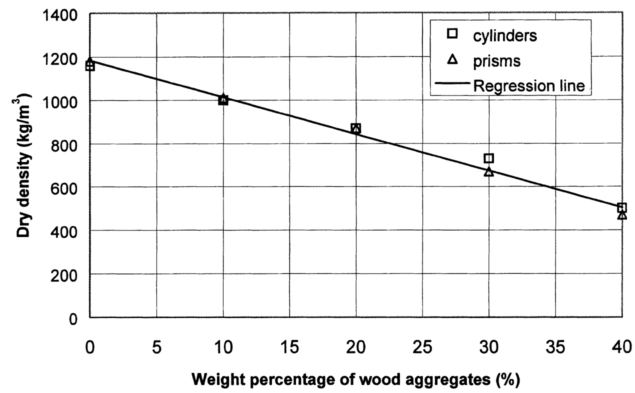


Fig. 1. Influence of the weight percentage of wood aggregates on the dry density.

3.2. Study of the thermal conductivity

Fig. 2 and Table 2 show that the thermal conductivity λ decreases from 0.24 to 0.08 W/m K as the percentage of wood aggregates rises from 10% to 50%, i.e. densities of between 1010 and 370 kg/m^3. In this range, the curve $\lambda = f(d)$ (see Fig. 3) can be represented by a linear equation: λ (W/m K) = $0.228d - 0.006$ with a correlation coefficient of 0.99 where d is the ratio: dry density/10^3 expressed without unit.

3.3. Mechanical performance

3.3.1. Failure strength

Fig. 4 presents the change of mechanical strength as a function of the percentage of wood aggregates.

Compressive strengths have been studied on cylinders of 160 × 320 mm and cubes of 140 mm generated from the prismatic test-cubes used in tension. This set-up

Table 2
Experimental results of thermal conductivity and compressive and flexural strengths as a function of the percentage of wood aggregates

Wood aggregates (%)	0	10	20	30	40	50
Average dry density (kg m^{-3})	1170 ± 10	1010 ± 5	870 ± 15	700 ± 20	490 ± 10	370 ± 20
Bulk density (kg m^{-3})	2530 ± 5	2430 ± 5	2370 ± 3	2200 ± 10	2180 ± 7	2180 ± 5
Porosity (%)	54	58	63	68	78	83
Thermal conductivity (W/m K)	0.24 ± 0.02	0.22 ± 0.03	0.16 ± 0.01	0.14 ± 0.02	0.10 ± 0.02	0.08 ± 0.01
Compressive strength R_{c_1} (MPa) (cylinder samples)	–	2.42 ± 0.05	1.90 ± 0.05	1.11 ± 0.10	0.34 ± 0.09	–
Compressive strength. R_{c_2} (MPa) (cubic samples)	–	2.67 ± 0.08	2.35 ± 0.05	1.35 ± 0.10	0.31 ± 0.04	–
Flexural strength R_f (MPa) (prismatic samples)	–	0.59 ± 0.04	0.63 ± 0.08	0.41 ± 0.06	0.14 ± 0.04	–
Elasticity modulus (compression) E_c (MPa)	–	958	819	371	94	–
Elasticity modulus (flexion) E_f (MPa)	–	915	976	432	115	–
Strain in compression $\varepsilon_c = \frac{R_c}{E_c}$ ($\times 10^3$) (%)	–	2.53	2.32	2.99	3.64	–
Strain in flexure $\varepsilon_f = \frac{R_f}{E_f}$ ($\times 10^3$) (%)	–	0.64	0.64	0.95	1.23	–
Poisson's ratio ν	–	0.17	0.18	0.14	0.13	–
Velocity C_L (m/s)	–	1117 ± 8	1084 ± 16	998 ± 12	734 ± 13	–
Overestimate dynamic modulus E_d^* (MPa)	–	1388	1026	723	267	–
$K(\nu)$	–	0.93	0.92	0.95	0.96	–
Dynamic modulus	–	1294	940	687	257	–

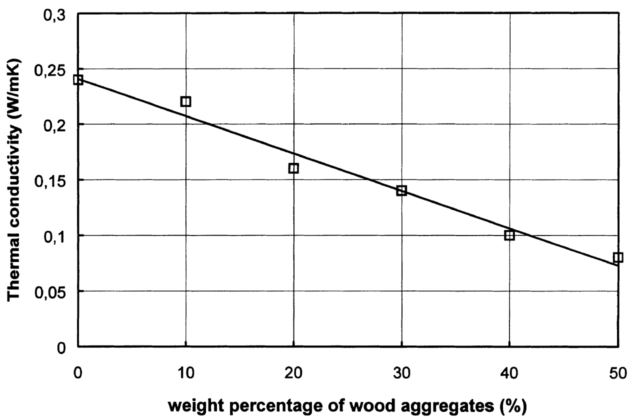


Fig. 2. Influence of the weight percentage of wood aggregates on the thermal conductivity.

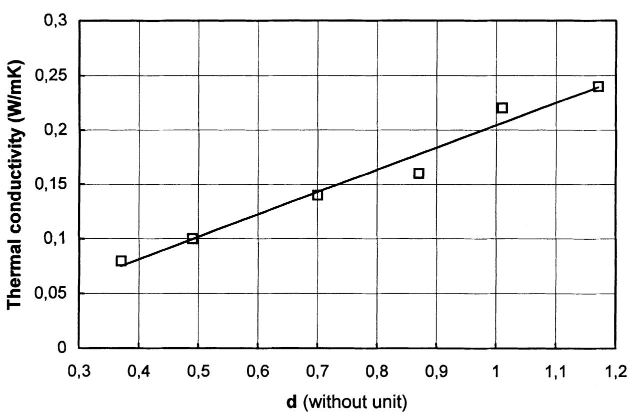


Fig. 3. Thermal conductivity as a function of the dry density.

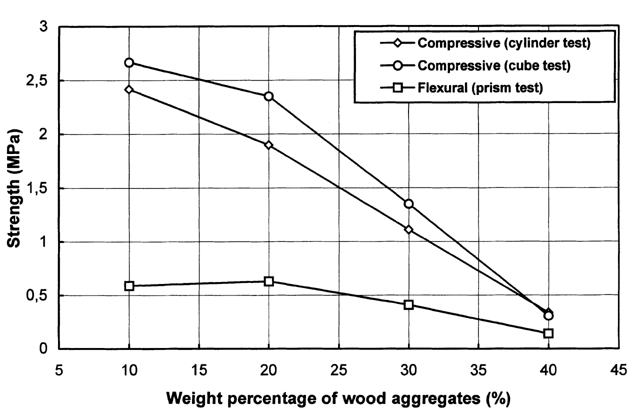


Fig. 4. Influence of the weight percentage of wood aggregates on the mechanical strengths.

makes it possible to evaluate the effect of geometry; as expected, failure strengths are slightly greater for cubes than for cylindrical specimens. For both cylinders and cubes, the compressive strength correlates with density and decreases regularly in correspondence with the wood aggregate content. The plots of compressive strengths are given in Fig. 5. The flexural strength increases slightly up to between 10% and 20% aggregate content (Table 2). This finding can be explained by the superposition of two competing phenomena: an effect of fibre, which is related to the geometry of the wood aggregates; and a weakening response following a reduction in the volume proportion of the matrix mix as the percentage of wood aggregates increases. The effect of fibre appears also in the facility to prepare large test samples. Without wood aggregates, probably due to the high percentage of water, a lot of cracking occurs, caused by shrinkage. Therefore, the results of the mechanical tests were considered only from 10% of wood aggregate content.

A number of empirical relations between compressive and tensile strengths have been suggested [31]. Many of them are of the type: $R_f = k(R_c)^n$. Fig. 6 shows that the

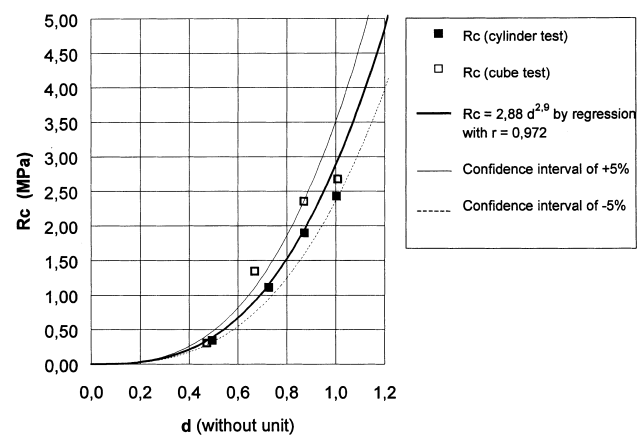


Fig. 5. Compressive strength as a function of the dry density.

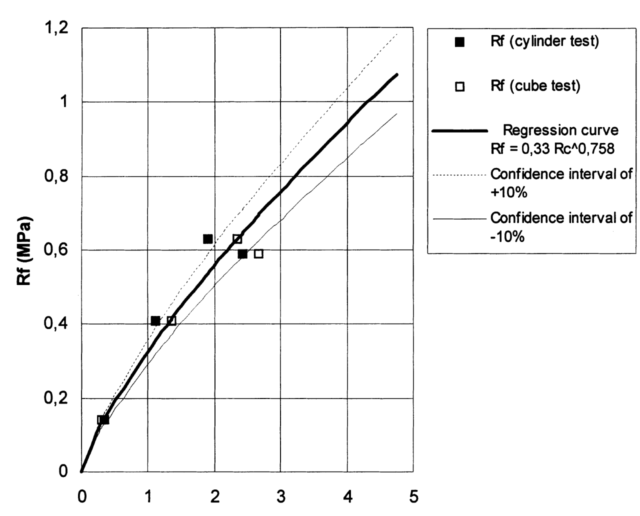


Fig. 6. Relationship between the compressive and flexural strengths.

mechanical behaviour of wood aggregate-clay-cement composite conforms to this expression.

The failure strengths in simple compression reveal that up to approximately 35% wood aggregate content, (equivalent to an apparent dry density of about 600 kg/m^3), these materials satisfy the criteria for Class III of the RILEM [32] functional classification (insulating light concrete), i.e. the compressive strength $R_c > 0.5$ MPa and the thermal conductivity $\lambda < 0.3$ W/m K.

3.3.2. Deformability

The static moduli are initial tangent moduli determined from the diagrammatic representations of the stress–strain relations registered in compression and flexure as explained in the section on operating techniques. These results are presented in Table 2. Fig. 7 shows that a similar relationship exists for static elastic modulus versus density where modulus values are obtained both from compressive strength tests and those given by the flexure studies. It is usually accepted that the modulus of elasticity increases when the compressive strength increases. Empirical expressions have been proposed, in particular, in the case of lightweight aggregate concretes, for example: $E = 1600R^{0.5}d^{1.5}$, where E and R are expressed in MPa and d without units [33]. A numerical analysis of the current data gives a correlation coefficient $r = 0.96$, and the relationship: $E = 1600R^{0.5}d^{1.7}$, where R has the same index as for the lightweight aggregate concretes in general.

The Poisson's ratio calculated for a proportion of stress equal to 33% changes slightly in the studied density range.

The dynamic modulus of elasticity (see Table 2) is higher than the static modulus but, as expected, also decreases when the aggregate content increases. Thus the modulus of elasticity decreases with decrease in the density. Although the elasticity decreases as the

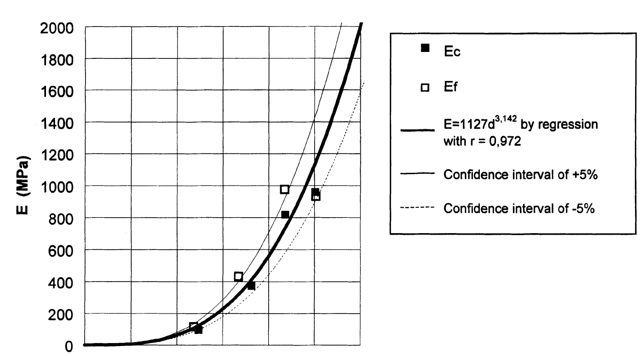


Fig. 7. Evolution of the static elasticity modulus as a function of the density.

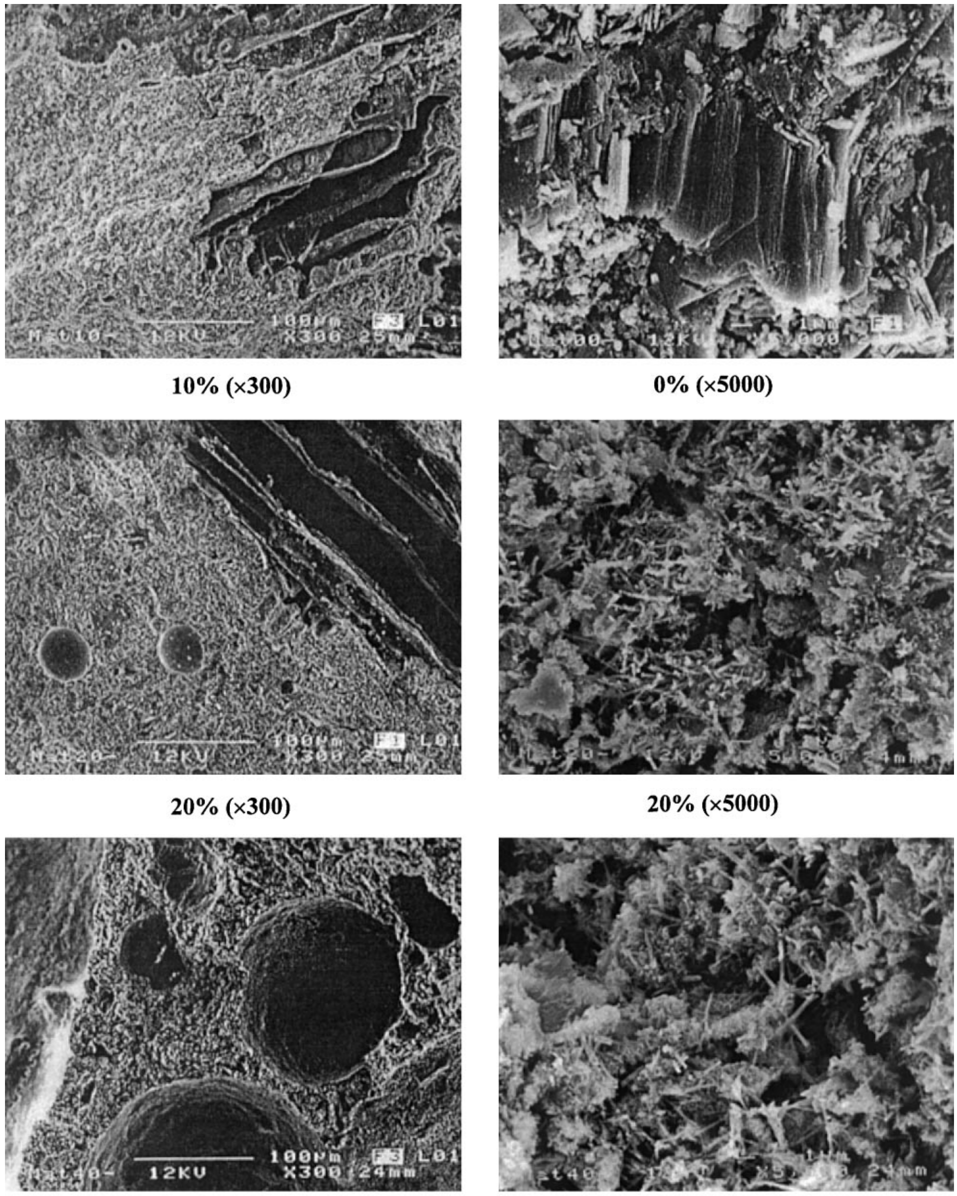
wood aggregate content rises, the zone of plasticity increases.

The material with a high wood aggregate content is therefore weaker but is less brittle, i.e. its capacity in terms of deformation increases. As an example, if we were to compare the performances obtained for a density of about 1000 kg/m^3 (10% wood aggregate content) to those of a plaster with a similar density, the resultant deformability either in flexure or in compression is twice as high for a clay-cement-wood composite [12].

3.4. Relationship of physical properties with the microstructure

The increase in deformability with rising wood content can be explained by the fibrous nature of the wood, which allows it to accommodate the deformations and provides good adherence to the matrix (Fig. 8). The decrease in thermal conductivity and mechanical strength with rising wood content is linked to the increase in porosity imparted by the wood. Nevertheless, this phenomenon remains very complex.

The porosity comprises both the porosity of the wood and that of the matrix itself [13]. It can be observed from Fig. 9 that the structure of the wood is not or has only been slightly affected by transformations due to the mixing and then to the hardening. In contrast, MEB images (Fig. 8) show that the morphology of the matrix surrounding the wood aggregates changes with the percentage of wood and appears to become more porous as this percentage increases. This finding would imply that the impact of the presence of wood aggregates in the composite is two-fold. Wood aggregates contribute to the lightening process by virtue of their low density and they provide an additional lightening of the composite by inducing a porosity that increases as the percentage of wood rises. The origin of this porosity has not been determined in great detail within the scope of this study. Although we have not been able to observe a supplementary foaming during the mixing process, considering that the pores exhibited a spherical shape, the additional macroporosity would nonetheless seem to be linked to the physical phenomenon of air entrainment. The origin of the excess microporosity would be linked to the exchanges occurring between wood aggregates and the matrix. Studies are presently being conducted in order to better determine the link between wood aggregates and the porosity of the matrix. Some tests [14] have already shown that porosity could be reduced by treating the aggregate with boiling water and hydraulic lime (Fig. 10).



10% (×300) 0% (×5000)

20% (×300) 20% (×5000)

40% (×300) 40% (×5000)

Fig. 8. Images in electronic microscopy of the matrix for different percentages of aggregates.

4. Conclusion

The purpose of adding wood to clayey concrete is to improve the insulation characteristics of these materials. We have shown the variation in the thermal conductivity as a function of the percentage of wood.

The mechanical strength drops with a decrease in density. In contrast, the deformability increases, which could be advantageous during the application of these materials in multi-layered walls.

However, the association of wood with clay could raise some uncertainty with regard to the sensitivity of the composites to humidity. This could entail, in addition, problems of durability and a decrease in insulating capacity. With respect to this topic, it should be noted that a thorough study has already been conducted by Bouguerra [13]. He has demonstrated that the behaviour in contact with moisture under normal conditions of use (i.e. 65% RH and 20°C) is very satisfactory. The entrapment of water in the vapour phase remains weak (less than 2.5%). This value does not affect the thermal performance in any significant way. Moreover, Bouguerra [13] has demonstrated that, when in contact with liquid water, the aggregates tend to slow the progression of the impregnation front. This is attributed to the phenomenon of reducing the capillarity as well as

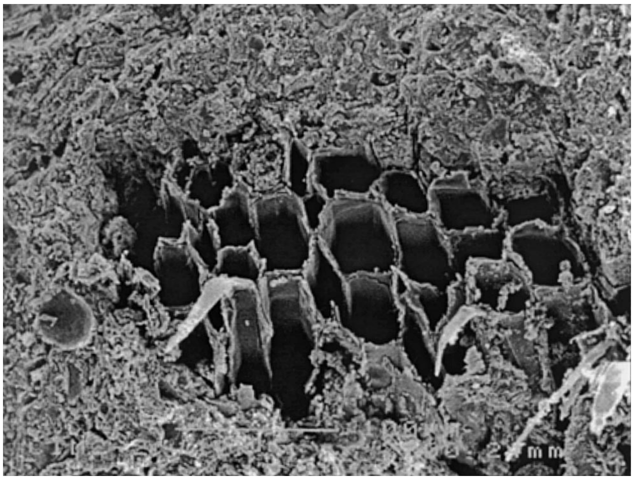


Fig. 9. Composite fines-cement-wood aggregates (300×). Illustration of a wood aggregate inside the matrix.

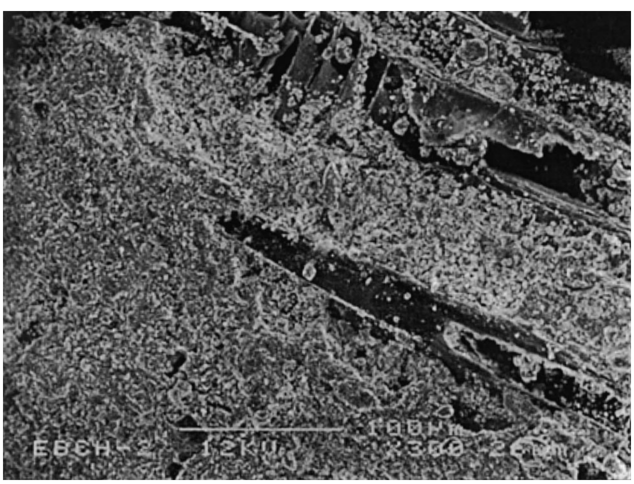


Fig. 10. Influence on the porosity of the matrix of the combined processing of the aggregates with boiling water and hydraulic lime (300×), lime/wood = 0.75, 20% Ag.

decreasing the quantity of water being absorbed by the material.

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