Properties of an environmental lightweight concrete formulated with solid industrial waste

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ABSTRACT: Exploitation of aggregate quarries in Brittany (west of France) generates important quantities of solid wastes which have been tipped out in the nature for a long time and constitute now a serious environmental problem. The choice has been made to transform them into insulating lightweight concrete. The lightening has been achieved by adding treated wood aggregates of dimensions 3 to 8 mm. In this paper, authors give results of an experimental work using five types of mineral wastes as raw materials in manufacture of a lightweight concrete. They differ in their mineral compositions, densities, extracting process and their colors. The physical, mechanical, and thermal properties have been studied. The elaborated concretes ranged in class II or class III in the RILEM functional classification. Their thermal conductivities have been found to depend of the water content and agree well with the recommended relationship of the ACI. In addition to that, the microstructure examined by electron microscopy has shown a very good adhesion matrix-wooden aggregate. The experimental results of the investigation show that the performances acquired by these environmental concretes are similar to the ones of the usual lightweight materials with satisfactory compressive strengths (in hydrous equilibrium state). The ensuing analysis serves to suggest the possibility of manufacturing insulating and load-bearing concretes using little energy (no burning and no autoclaving).

1- INTRODUCTION

The rock aggregates industry in the western part of France generates large quantities of wastes in the form of mud or powder materials. These by-products presenting different mineralogical nature and aesthetic colours are dumped in huge mounds in the vicinity the producing industries and thereby creating a serious problem of disposal and environmental pollution. The need has been felt to use these wastes as a source of raw materials in order to replace traditional sand, which is lacking in this part of France, in the producing of various types of building materials. The choice has been made to transform these wastes into lightweight composites with minimum environmental impact. The elaboration's process must require lower quantity of energy and must be simple to implement in developing countries: coolly stabilisation, no burning and no autoclaving. The lightening process is carried out by means of wood aggregates 3-8 mm in size. The option of using this vegetable material is to promote its application as local and renewable resource.

Five solid mineral wastes, which will be described herein, have been treated and transformed into solid waste-based wood composites. The new lightweight materials represents valuable additions both to the range of traditional lightweight concretes which contain expanded clay, expanded shale, vermiculite, perlite or fly ash and to the recent studied lightweight concretes which contain cork granules (Aziz 1979), rice husk (Salas 1986), rice husk ash (Rahman 1988) or wood shavings (Al Rim 1999), etc. The technology employed to develop these new building composites is relatively inexpensive. The quantity of stabiliser required remains low and the finished materials do not undergo any thermal treatment.

The designed lightweight composites are destined for use as insulating or insulating and bearing building units according to their performances. Therefore the measurement of the mechanical and thermal characteristics is necessary.

The porosity of wood composites is generally the result of three phenomenons: The no used water in cement hydration, the moisture exchanges between the matrix and the wood aggregates, or from the wood which is structurally macroporous. However in certain compositions it could be either the bad interface matrix/wood aggregates. Therefore the microstructural analysis is another useful aspect to examine; the porous structure of the elaborated composites must be accurately identified since the macroscopic properties are linked to the microscopic ones.

The present study focuses on the characterisation of the lightweight elaborated composites, with and without wood aggregates. The mechanical behaviour will be described by measurement of compressive and tensile strengths. The thermal conductivity, λ; for describing the thermal behaviour will be also measured. The microstructural aspect will be examined by measuring the pore size distribution and the total porosity of the tested composites. The adherence matrix/wood aggregate will be verified by a scanning electronic microscope. The performances of the tested composites will be compared to those of several lightweight materials.

2. RAW MATERIALS

2.1 The mineral solid wastes

The mineral solid wastes studied have all been collected in the region of Brittany (western France). Apart from the schistose waste, extracted by a dry process in powder form, the solid wastes were selected from decanting basins in the form of mud. They were submitted to a preliminary treatment consisting of reduction into powdered materials after drying at 105°C for 24 hours in a drying oven. These powders were then stored in a dry cell. Their origins and physical characteristics are presented below:

Granite waste: mud resulting from sawing operations on massive granite rocks in Baillé quarry (Morbihan). It has a greyish colour and its main minerals components are sillimanite, orthoclase and quartz. A qualitative x-ray analysis has been used for its identification. Its dry density, as measured by water picnometry, is 2610 kg/m^3.
Sandstone waste: mud resulting from the extraction of sandstone at the Frehell quarry (côte d'Armor) by washing aggregates obtained by crushing. It is pinkish in colour and is primarily composed of quartz. Its dry density is equal to 2640 kg/m^3.
Schist waste: powder collected from the Lacs quarry (Ille et Vilaine). It is greenish in colour; quartz is its main components. Its dry density is 2800 kg/m^3.
Clay 1 waste: clayey waste resulting from the extraction of fossil marine sand and deposits in the Rheu (Ille et Vilaine). The waste is brown in colour and consists mainly of kaolinite. Its dry density is 2600 kg/m^3.
Clay 2 waste: clayey waste resulting from the extraction of a sand-gravely soil by intensive washing at the Mohan quarry (Morbihan). The waste consists of a rough mud with yellowish colour; quartz and halloysite are the main mineral components. The illite mineral is present in small quantities. Its dry density is 2620 kg/m^3.

The chemical composition of the selected solid wastes is presented in table 1. Their grain size distribution obtained by use of the laser granulometer technique is presented in figure 1.

Table 1: Chemical composition of the selected solid wastes

	Granite	Sandstone	Schist	Clay 1	Clay 2
SiO_2	63.78	75.88	58.34	50.94	68.15
Al_2O_3	15.11	13.64	18.69	19.87	18.42
Fe_2O_3	4.13	1.30	7.61	12.01	2.71
CaO	3.45	0.07	1.31	0.47	0.01
MgO	2.34	0.40	3.15	0.77	0.19
Na_2O	3.66	0.59	1.80	0.32	0.10
K_2O	3.54	5.73	3.35	2.73	0.79
TiO_2	0.53	0.14	0.81	0.52	2.01
Mn_2O_3	0.07	-	0.10	0.07	0.02
Loss on Ignition	3.05	2.09	4.30	11.96	7.18
Total	99.94	99.94	99.59	99.94	99.63

2.2 The other components

The cement used to ensure the chemical stabilisation is CPA CEM I 52.5, in accordance with the European standard EN 196-1. The weight reduction of the concretes has been achieved by including 3-8 mm wood aggregates into the cement-mineral fine matrix. They have been undergone by both thermal and physical – chemical treatments and are commercialised under the name "Agrelith C". The mixing water added to react with cement is normal tap water with pH ~ 7.5.

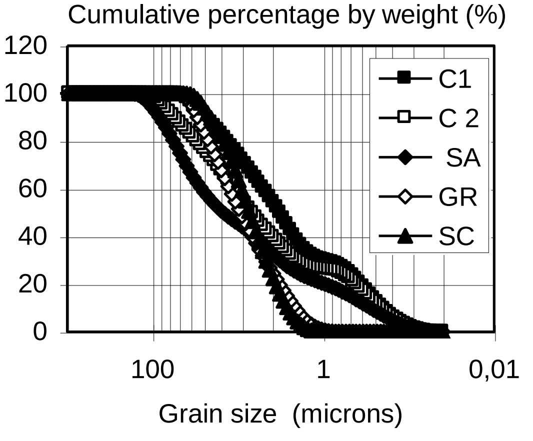


Figure 1: Laser grain size distribution of the mineral solid wastes

3. ELABORATION OF THE COMPOSITE MATERIALS

The influence of the wood aggregates on thermal and mechanical behaviour has already been studied on the Illifault clay waste (Bouguerra 1997); it was concluded that a mixture containing 25% (by weight) wood aggregates yields good thermal conductivity and satisfactory compressive strength. These results have been acknowledged within the scoop of the present study and led to the use of the following proportions of solid phases for all of the composite materials produced: cement 25%, fine mineral waste 50%, and wood aggregates 25%. The materials were initially dried in order to control their moisture content. All five mixtures were prepared by the same process: dry cement and fine mineral waste were mixed in a laboratory mixing machine, in accordance with the French standard NFP 15437, before addition of the wood aggregates. Water was then gradually added once the dry mixture had become homogeneous. To obtain a fresh homogeneous mixture, the mixing machine was turned at low speed for 3 min, followed by high speed for 1 min. The quantity of water, *W*, required to achieve the same level of workability for all mixtures was determined by the use of the following empirical relationship (Al Rim 1995):

$$W\ (litres) = 0.35C + W_f F + 0.80 W_A \quad (1)$$

In equation (1): W_f is an experimental coefficient we have determined such that the mixture water-mineral fine exhibits a normal consistency. W_f = 0.45 for granite, schist and sandstone solid fines, and W_f = 0.70 for the clayey mineral fines. *C*, *F*, and W_A are, respectively, the weight of cement, mineral fine, and wooden aggregates.

The tested materials displayed low dry density, ranging between 810 kg/m^3 for the clayey concretes and 960 kg/m^3 for the schistose concrete. Intermediate values were obtained for sandstone and granite concretes: 860 and 960 kg/m^3, respectively. In view of their densities and the nature of their matrices, these materials are considered as lightweight composites.

To complete the analysis, samples without wood aggregates (matrices) were also produced in order to evaluate their effect on the mechanical and thermal properties. Their preparation was the same as that employed for the composites. Only the wood aggregates and their corresponding quantity of mixing water were removed.

4. MEASUREMENT METHODS

The compressive strengths measurements were performed on samples of 10 cm x 10 cm x 10 cm in size, using a 20 KN capacity Walter Baibag press. The loading speed adopted was provided in the French standard NFP 18 406 for traditional concretes. The tensile strengths were measured indirectly by flexure on prismatic samples 4 cm x 4 cm x 16 cm in accordance with NFP 18 407 French standard.
The thermal conductivity measurements were carried out by the use of a transient method: the thermal shock probe method (Perrin 1987) developed by (Laurent 1989). This method is based on the study of the thermal flux propagation produced by the Joule effect from a cylindrical heating probe. By means of this method, the water migration effects in moist concretes are reduced during the thermal tests. The thermal conductivity was computed from the equation (2) by applying the least-squares approach to the data acquired between 220 and 400 seconds. These limits were established in order to avoid any error due to nonlinearity of the temperature variation, ΔT, with respect to ln(t) during the period of self-heating.

$$\Delta T = \frac{Q}{4\pi\lambda}\left[Ln(t) + C\right] \quad (2)$$

Where Q = the constant power per unit length supplied to the thermal probe (W/m),
ΔT= the temperature rise measured at time t (°C) and C is a constant.

To determine the thermal conductivity, running a linear regression on the ΔT = f[ln (t)] curve is sufficient. Figure 2 provides an example of experimental data pertaining to the granite-wood concrete. The estimate error (due to the contact resistance between the heat probe and the specimens) in the measurements is approximately 5% (Laurent 1989). The samples tested were 10x10x10 cm^3 in size.

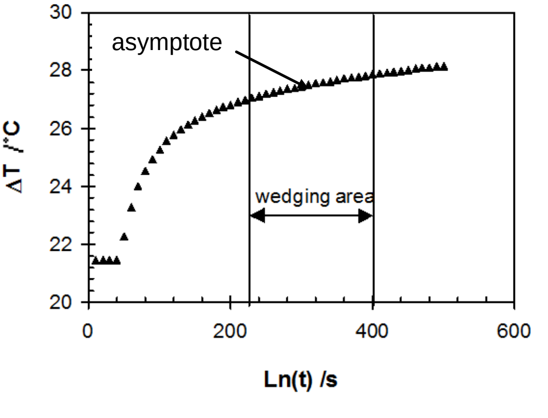


Figure 2: Example of experimental data relative to granite wood composite

The total porosity and pore size distribution of the tested composites were determined by means of the mercury porosimetry technique. An autopore 9400, manufactured by Micrometrics, was employed. Its characteristics are: Hg contact angle, 142 degrees; Hg surface tension, 0.485 N/m, and maximal penetration pressure, 400 MPa. The specimens used, at first dried under vacuum, were 10 x 10 x 20 mm^3 in size. A Philips LX30 SEM 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.

5. RESULTS AND DISCUSSION

5.1 Mechanical strengths

Figure 3 presents the evolution of compressive strengths of the dry lightweight composites versus the age. It can be observed that the stabilisation seems to be quickly reached. Furthermore, the dependence of compressive strength on dry density has not been well established when the fine minerals are basically different. In spite of its high density, granite composite displays a lower compressive strength at 28 days. For equal density, the compressive strength of sandstone concrete at 28 days is more than twice that of clayey concrete.

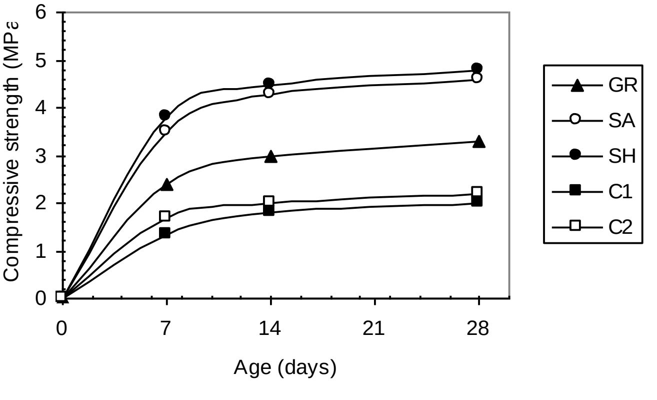


Figure 3: Evolution of compressive strength for the five wood composites

From the point of view of the RILEM functional classification, the produced lightweight concretes are related to the concretes of lightweight aggregates of type II (R_{c28} > 3.5 MPa, for the SA and SH fines) and type III (R_{c28} >0.5 MPa, for the remaining materials) corresponding to load bearing and non load bearing materials. This finding shows the interest of these composites.

The experimental tensile strength at 28 days has been determined by the flexure method. The result values (average of three tests) are collected in table 2. The ratio compressive/tensile strength at 28 days has been calculated for all the composites.

Table 2: Ratio R_{c28}/R_{t28}

Mineral fine employed	R_{c28} (MPa)	R_{t28} (MPa)	R_{c28}/R_{t28}
Granite	3.30	1.46	2.26
Sandstone	4.60	2.33	1.97
Schist	4.80	2.31	2.08
Clay 1	2.00	0.92	2.17
Clay 2	2.20	1.04	2.21

It is useful to note that the mechanical behaviour of the tested lightweight composites is very different of the one of traditional concretes. The ratio R_{c28}/R_{t28} is about 2 for the first materials and about 10 for the second ones. Table 3 presents compressive strength of several lightweight materials. At comparable density, the tested composites are very competitive.

Table 3: Compressive strength of several lightweight materials

Material	Dry density (kg/m^3)	R_{c28} (MPa)
- Plaster	1060	6.40
- Autoclaved aerated concrete	500	2.80
- Wood concrete with clayey matrix	500 - 1000	2.70 – 6.00
- Wood (Agrelith) concrete with cementitious matrix	500 – 700	2.40 – 4.00
- Wood (Granuland) concrete with cementitious matrix	800	3.30
- Wood -shaving concrete with cementitious matrix	1053 – 1096	2.24 – 2.90
- Tested composites	810 - 960	2.00 – 4.80

5.2 Thermal conductivity

Table 4 presents all the experimental results obtained at room temperature (~20°C) on the matrices and composites in both at the dry and saturated states. It can be observed each of the solid waste-based wood concrete specimens exhibits a high level of thermal insulating power. The thermal conductivity value, in every case, is less than 0.2 W/mK, regardless of the solid waste used. From this standpoint, the studied composites could be considered as type II lightweight insulating materials in the RILEM functional classification (RILEM 1978). The non-clayey materials proved to be best relative thermal conductors, which suggest that the laminar morphology of the kaolinite plays an important role in the low thermal conductivity of clayey composites. Moreover, it can be noted that the wood aggregates reduce the thermal conductivity in the dry state more than twofold in all cases, from 2.02 for granite composite to 2.61 for sandstone composite; this feature is a result of the macroporosity generated by the inclusion of wood aggregates. In the saturated state, the mean reduction is 1.55, resulting from the high thermal conductivity (λ_w = 0.55 W/mK at 20°C) of the liquid phase.

A close examination of the dry density data, d_{dry}, and the experimental values of thermal conductivity in the dry state, λ_d , (see table 4) allows us to observe an obvious correlation between these two parameters. The small number of samples tested does not enable us to derive a strict law or a strict analysis; however, it is easy to note that the thermal conductivity of matrices and composites increases as the dry density increases. The type of solid mineral waste therefore seems to exert little influence on this correlation.

Table 4: Experimental data on thermal conductivity
(Subscripts: m, matrix; c, composite; d, in dry state; s, in saturated state)

Solid waste	*Matrix*				*Composite*			$\lambda_{md}/\lambda_{cd}$	$\lambda_{ms}/\lambda_{ms}$
	d_{dry} (kg/m^3)	λ_{md} (W/mK)	λ_{ms} (W/mK)		d_{dry} (kg/m^3)	λ_{cd} (W/mK)	λ_{cs} (W/mK)		
Granite	1460	0.359	0.860		900	0.178	0.611	2.02	1.41
Sandstone	1590	0.457	0.950		860	0.175	0.556	2.61	1.71
Schist	1500	0.366	0.894		960	0.190	0.570	2.03	1.57
Clay 1	1270	0.189	0.786		810	0.117	0.529	2.08	1.49
Clay 2	1290	0.252	0.833		810	0.117	0.532	2.15	1.57

In order to compare these test composites with traditional insulating wood concretes and typical lightweight materials, several values of thermal conductivity have been combined in table 5. The "Agrelith" used in this work has previously been described, the "Granuland" is manufactured from treated sawdust, and the "Isochanvre" consists of mineralised paper industry waste.

By inspection of the λ values listed in table 5, it can readily be observed that the tested wood composites display high thermal efficiency and present distinct competitive advantages by virtue of their low energy requirements during manufacturing (no burning and no autoclaving).

Table 5: Thermal conductivity of some lightweight materials

Material	Wood aggregate	Matrix	d_{dry} (kg/m^3)	λ_{dry} (W/mK)
Usual wood concretes	Agrelith (Pimienta 1994)	Cement	500 – 700	0.11 – 0.16
	Granuland (Pimienta 1994)	Cement Cement + sand	800 700	0.22 0.15
	Isochanvre (Sionneau 1994)	Lime	800	0.27
Clayey wood concretes (Bouguerra 1997)	Agrelith	Cement + clay	500 1000	0.13 0.29
Perlite or vermiculite concretes (DTU 1977)	-	-	400 – 600 600 – 1000	0.24 0.31
Expanded clay concrete (DTU 1977)	-	-	600 – 800 800 – 1000	0.25 0.33
Plaster	-	-	1060	0.38
Autoclaved aerated concrete	-	-	500	0.18
Solid waste-based wood concretes (Present work)	Agrelith	Cement + solid mineral waste	810 - 960	0.117 – 0.19

It must be noted that a previous work on the effect of moisture content and temperature on thermal conductivity of the tested composites (Benmalek 1999), has shown that the increase in temperature reduces the thermal conductivity at every moisture content. However above 40°C, the phenomenon of evaporation-condensation, described by many authors (Krischer 1978), (Boris 1980), (Nir 1983), appears and the thermal conductivity becomes constant.

To compare the thermal performance of the solid mineral waste-based wood composites tested with that of other lightweight materials, several characteristics have been listed in table 6. It can be observed that at comparable dry densities, the test materials are indeed competitive.

Table 6: Thermal parameters of some lightweight materials

Materials	d (kg/m^3)	λ(W/mK)
Aerated autoclaved concrete	500	0.18
Dry plaster	1060	0.35
Saturated plaster	1440	-
Clayey wood shaving concrete (Al Rim 1995)	1054	0.24
Aerated non autoclaved concrete (Marmoret 1998)	700-1500	0.16-0.58
Expanded clay concrete (Morabito 1989)	1520	0.64
Clayey wood aggregate concrete (Bouguerra 1997)		
Matrice	1280	0.45
30% wood aggregates	820	0.20

5.3. Microstructural analysis

5.3.1. Total porosity

Table 7 shows, in addition to dry densities, the total porosity of the tested matrices and composites. To correct the sample's representativity problem, in view of the dimensions of wood aggregates, each presented value constitutes the average of measurements made on randomly-chosen samples.

Table 7: Total porosity of the tested composites

Solid waste	Matrices		Composites	
	Dry density	Total porosity (%)	Dry density	Total porosity (%)
Granite	1.46	40.10	0.90	58.34
Sandstone	1.59	34.77	0.86	61.68
Schist	1.50	38.93	0.96	57.64
Clay 1	1.27	47.30	0.81	63.51
Clay 2	1.29	47.03	0.81	64.35

It can be observed that the matrices's total porosity seems to be linked to the quantity of the mixing water; this explains its higher values for the clayey matrices. Furthermore total porosity of the wood composites is more important due to the contribution of the wood aggregates porosity themselves.

The dry density is another parameter which is linked to the total porosity. Figure 4 illustrates this relation for the matrices as well as the composites. This relation can be represented by a single linear equation: p (%) = -35d + 92.26 with a correlation coefficient of 0.99 where d is dry density expressed without unit.

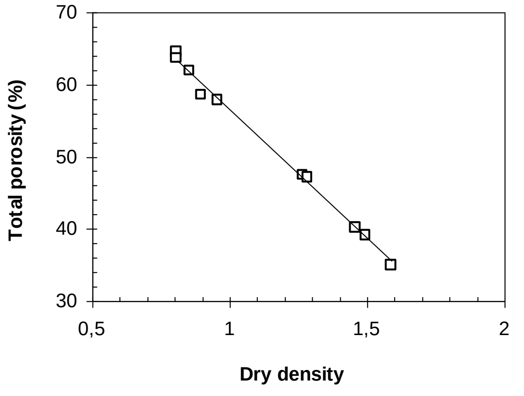


Figure 4: Relation dry density - total porosity

5.3.2. Pore size distribution

The accumulated normalised volume, i.e., the ratio of the cumulative volume to the total porosity as a function of the average diameter of the pores, is presented in the figure 5, for both matrices and composites.

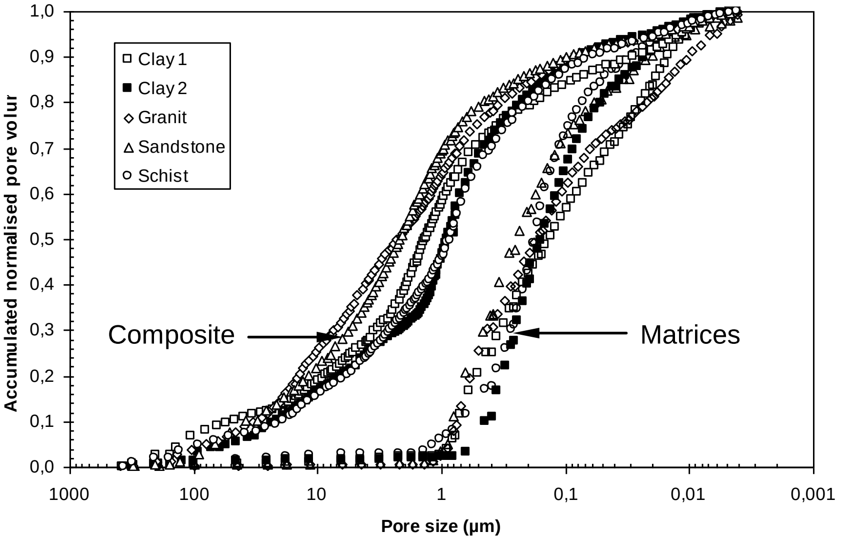
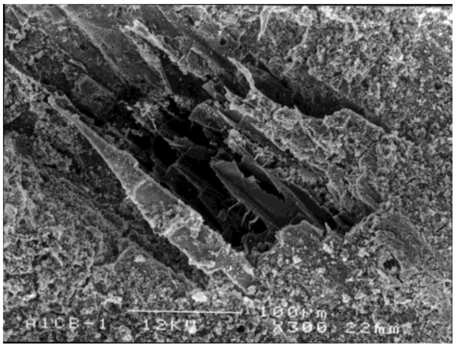


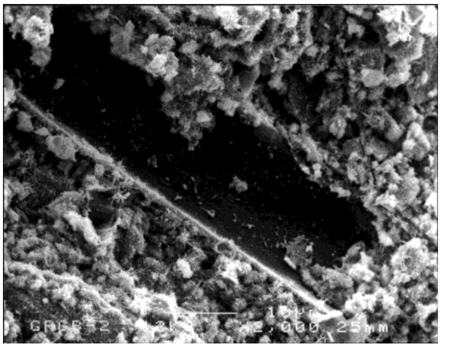
Figure 5: Accumulated normalised pore volume

It can be clearly observed two distinct groups of curves characterising the matrices and the composites. It should be noted that the matrices's microporosity (pore diameter $\varphi \leq 1\mu m$) is generally attributed to the mixing water which is not consumed by the cement hydration. In fact, the part of required mixing water serving for workability, and no used for the cement hydration, disappears by evaporation. It can also be observed on the composites's curves the non existence of "accident"; it is therefore not very probable that the total porosity increase in comparison to the matrix is due to a lack of adherence in matrix/wood aggregate.

To make sure that the possible cracks due to mixing water evaporation or to entraining air during mixing are not the source of macroporosity, a microstructural images from a SEM have been achieved. Figure 6 displays matrix/wood aggregate bond for a clayey and no clayey matrix respectively. The very strong bond is observed.



(a) Clay 1 lightweight composite (x 300)



(b) Sandstone lightweight composite (x 2000)

Figure 6: Matrix/wood aggregate bond

6. CONCLUSION

The potential for recycling mineral industrial wastes as an alternative to natural sand in the production of cementitious lightweight composites materials has been explored. Results have shown the significant qualities of their thermal behaviour. A comparison with other materials, both traditional and new, has proven favourable.

The thermal performance of the lightweight composites tested, associated with satisfactory mechanical characteristics, qualify them for RILEM's type II functional classification. The use of these materials to produce single-layer or multilayer insulating elements and bricks for insulating-bearing materials can now be envisaged, in addition to perfecting partitioned wall units.

The thermal conductivity of the clayey composites has been found to be the lowest, because of the mineralogy of the matrices. This parameter generally increases with higher dry density values and decreases more than twofold when wood aggregates are incorporated into the matrices.

The images from a scanning electron microscope have revealed a very strong matrix/wood aggregate bond. The macroporosity is then generated by the wood aggregates and not from a bad adherence matrix/wood aggregates or by cracks due to several origins.

An in–depth investigation will be devoted to studying the dimensional stability pertaining to the water affinity of wood aggregates.

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