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RESEARCH ARTICLE

THERMOPHYSICAL CHARACTERIZATION OF ECO-PLASTER MADE FROM GIANT SNAIL SHELLS

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ABSTRACT

The main objective of this work is to carry out the thermophysical characterization of an eco-plaster made from giant snails shells *Achatina Achatina*. To achieve this, it was first synthesized eco-plaster from snail shells collected in nature. Thermal effusivity and conductivity measurements in transient mode and according to mixing rate $\frac{m_e}{m_p}$, were then carried out with hot strip method. Finally, a thermal behavior study face to surface heating and cooling of specimens was carried out. The results obtained showed on one hand that thermal effusivity and conductivity respectively decrease from 555.386 $J.m^{-2}.K^{-1}.s^{-0.5}$ to 377.736 $J.m^{-2}.K^{-1}.s^{-0.5}$ and from 0.159 $W.m^{-1}.K^{-1}$ to 0.104 $W.m^{-1}.K^{-1}$, when mixing rate increases from 1.8 to 2.7. In the same range of mixing rate, a comparative study showed on other hand, that density, thermal effusivity and conductivity of synthesized eco-plaster are lower than those of imported plaster. Surface heating tests with a constant heat flow for 180 s have shown that temperature rise is the same for both types of plaster up to 15 s in mixing rate range from 1.8 - 2.7 and; up to 30 s for mixing rate of 3.6. Beyond 15 s and 30 s respectively for rates of 1.8 - 2.7 and 3.6, we note that eco-plaster heats up faster than imported plaster. When heat flow is eliminated, we notice that the two plasters are cooled in same way.

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INTRODUCTION

Faced with the energy poverty situation and while building impact in terms of greenhouse gas emissions is very heavy, eco-materials choice is crucial. These judiciously produced materials like plaster and many others, can indeed limit the building negative environmental impacts. Evrard *et al.* (2010) cited by Kabore [2] showed that a plaster board with a density of 900 $kg.m^{-3}$ has a gray energy of 5.8 $MJ.kg^{-1}$ and emits 0.22 $kg_{CO2}.kg^{-1}$, which is relatively low compared to other building materials. Plaster uses are multiple. Plaster is used in building (wall and floor cladding, partition walls, ceilings, decoration, fire protection, hygrometric regulation, sound insulation) and also in artistic field for shapes molding during production and works restoration [3]. It is also used as in buildind sector as insulating material considering its thermal conductivity less than 2 $W.m^{-1}.K^{-1}$ (Langlais *et al.,* 2004). In Benin, there is no gypsum deposit for plaster production; as a result, plaster supply for these applications is based exclusively on imports. However, there is a biomaterial available at lower cost which can be used as raw material for plaster local production : snail shells. According to Sodjinou *et al.* [5], a large quantity of snails (about 62.5 tons) are delivered every year on Cotonou market, which corresponds to about 216 shells tons. This estimated quantity comes, not from a formal purchase iniculture but, from collection of snails developing in wild. This collection is favored by two rainy seasons recorded in Benin. Snail consumption increase in Benin without purchase iniculture promotion strengthens snails collection and is a threat to biodiversity. Adherence to valorization vision of uneaten parts of snails can encourage purchaseiniculture in Benin. This work is therefore part of energy saving in housing, environment protection and snail shells valorization in thermal insulation field.

MATERIALS TESTED

Basic raw material : Acclimated giant snail shells *achatina achatina* from Benin are the basic raw material used in this study (Figure 1).

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Figure 1. Giant snail shells *achatina achatina*

Eco-plaster synthesis from snail shells : Procedure is summarized in Figure 2 After collection, snail shells were reduced to powder in an oven at 900 °C. Powder thus obtained was treated with excess sulfuric acid. After total decarbonation, white paste obtained was separated from supernatant and then rinsed with distilled water and neutralized with an aqueous solution of calcium hydroxide. Calcium sulfate paste thus obtained was filtered and rinsed with distilled water. Hydrated calcium sulfate obtained was heated in a muffle furnace at (200 ± 5) °C for two hours in open air, in order to obtain hemi-hydrated calcium sulfate which is plaster (Karim *et al,* 2013).

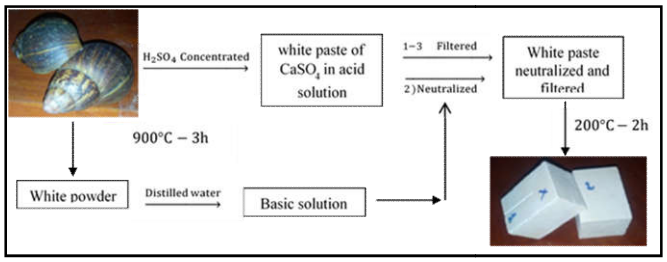

Figure 2. Eco-plaster synthesis from snail shells

Plaster mixing :Mixing rate $\frac{m_e}{m_p}$ is water mass ratio to plaster powder mass put into play to manufacture set plaster. In β-hemihydrates case, this ratio varies between 0.5-1.2 and makes β-hemihydrates commonly used as construction material. In α-type hydrates case used in ceramics manufacture or in dental industry, this ratio varies between 0.3 - 0.5 (Coquard, 1992 ; Eve, 2003). When plaster setting, only a small fraction 18.6 % mixing water participates in chemical reaction (Coquard, 1992). Additional water quantity provides a good paste fluidity and determines material porosity after setting. In this work, plasters were wasted at different ratios $\frac{m_e}{m_p} =$ 1.8 ; 2.3 ; 2.7 and 3.6 (Table 1). Specimens densities were determined. Indeed, preliminary mixing tests showed that is impossible to dissolve plaster powder synthesized with snail shells with a mixing ratio $\frac{m_e}{m_p} < 1$ whereas it was possible for commercial plaster used as reference. Indeed, during dissolution experiments, water quantity corresponding to $\frac{m_e}{m_p} < 1$ were insufficient to dissolve powder; which obliges to supplement water quantity initially taken. These preliminary tests led us to increase water quantities provided for mixing. Plasters are finally elaborated with $\frac{m_e}{m_p}$ mixing ratios greater than 1 and between 1.5 - 4. Plaster set results from rehydration of semi hydrate in water during mixing operation. Mixing protocol used is that described by Coquard (1992). Semi hydrate powder was poured into water and stirred for about 30 seconds. Then it was left to rest for 30 seconds followed by mixture agitation for 30 seconds. This agitation was followed by another rest of 30 seconds and then a final agitation of 30 seconds until homogenization. Plaster setting was carried out according to Equation (1):

$$(CaSO_{4,1}/\rightarrow (CaSO_4 2H_2O) + 1/2H_2O, 2H_2O) \quad (1)$$

To obtain plaster taken, it was proceeded to mix at different ratios $\frac{m_e}{m_p} = 1.8\,;2.3\,;2.7$ **and** 3.6.

Table 1. Plaster mixing ratios $\frac{m_e}{m_p}$

Water mass m_e (g)	67	83.7	100.5	134
Powder masse m_p (g)	37	37	37	37
Mixing ratio $\frac{m_e}{m_p}$	1.8	2.3	2.7	3.6

Samples manufacture: For test pieces manufacture, powder mass equal to 37 g was retained after several tests. Indeed, it represents the maximum powder mass that allows after mixing with a water volume of 67 ml, to completely fill, without material loss, the mold of (5 × 3.5 × 3) cm^3 size used for production of specimens intented for thermal measurements (Figure 3). At the end of setting, samples ground in molds of same volume have different densities. This shows that water quantity used had acted on particles dispersion when plaster setting.

Figure 3. Plaster specimens

Plaster density variation according to mixing rate $\frac{m_e}{m_p}$ ***:*** The plot of density curve as a function of ratio $\frac{m_e}{m_p}$ shows a good correlation (Figure 4) for the samples wasted with the ratios $\frac{m_e}{m_p} = 1.8\,;\ 2.3$ **and** 2.7, for both imported and elaborated plaster. With the samples obtained with ratio $\frac{m_e}{m_p} = 3.6$, it is noticed a defect of setting and a very bad cohesion of particles ; which causes them to crumble at touch. Therefore, it is retained that ratio $\frac{m_e}{m_p} = 3.6$ is too high to make plasters set with powders used. The comparison of specimens densities for the same mixing rate shows that the plaster made from snail shells is less dense than the commercial plaster. This mass difference for same volume indicates that when plaster is set, its bassanite particles are more dispersed in mixing water than in commercial plaster case. Thus, elaborated plaster samples imprison a greater water quantity than those of commercial plaster. Therefore, after water removal by microwave heating, these samples become more porous and have a lower density. This density difference will certainly lead to differences in thermal properties between the two plaster types. These results agree well with those of Jaffel (2006), which shows that porosity increases with mixing rate; which consequently leads to density reduction of material.

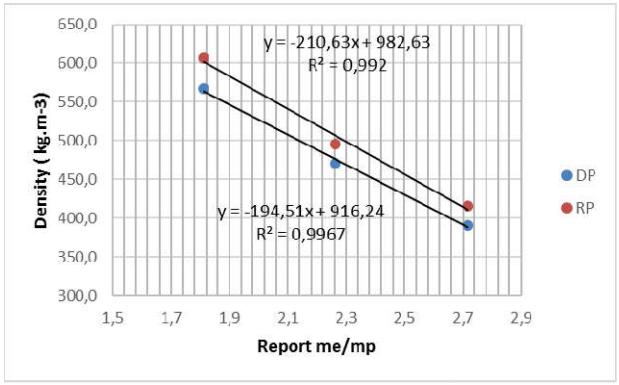

Figure 4. Plaster density variation according to mixing rate $\frac{m_e}{m_p}$ (DP = Developed plaster; RP = Reference plaster)

HOT STRIP METHOD PRINCIPLE

The hot strip was a rectangular-shaped electrical resistance with thin thermocouple wires embedded. Temperatures were measured at resistance center, avoiding thermal losses through the electrical wires at one end of the resistance. The resistors were inserted between two plane surfaces of the test samples of dimensions large for the system to be considered semi infinite medium in all directions during the experiment times (Figure 5). The ratio of length to width of the resistance was chosen so that heat transfer at center was bidirectional during minimum testing time of 180 s (Meukam *et al,* 2004 ; Jannot, 2008). The hot strip method had advantages of simplified data processing based on separated heat transfer models at the hot strip center; unidirectional during time interval t_1 for thermal effusivity estimation by hot plane model, and bidirectional during time interval t_2 for thermal conductivity estimation by hot wire model.

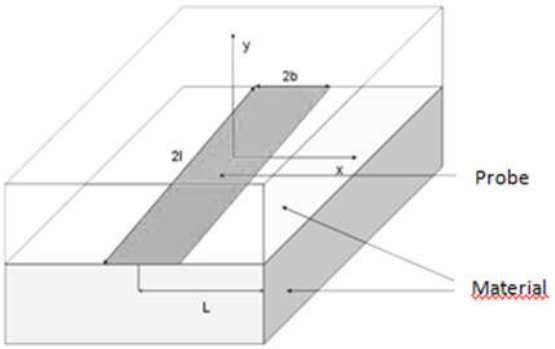

Figure 5. 2D model hot strip

Thermal Effusivity (E): The temperature recorded during time interval t_0 - t_1 for heat transfer at resistance center in unidirectional was used to estimate thermal effusivity of each sample with hot plane model using Equation (2) (Meukam *and al,* 2004; Jannot, 2008):

Thermal Effusivity (E): The temperature recorded during time interval t_0 - t_1 for heat transfer at resistance center in unidirectional was used to estimate thermal effusivity of each sample with hot plane model using Equation (2) [10, 11] :

$$T_s(0,0,t) - T_s(0,0,0) = \frac{2\phi}{EA\sqrt{\pi}}\sqrt{t} + \phi\left[R_c - \frac{m_s c_s}{(EA)^2}\right] \qquad (2)$$

The thermal effusivity was estimated from the mean slope of the experimental curve $\mathbf{T_s(0,0,t) - T_s(0,0,0) = f(\sqrt{t})}$, which was equivalent to $\frac{2\phi}{EA\sqrt{\pi}}$, determined by linear regression between two times t_0 - t_1, when the heating curve was assumed to be linear (steady state conditions) in the time interval.

Thermal conductivity (λ): The bidirectional heat transfer coupled with hot wire method were used to determine the thermal conductivity for entire temperature range recorded using the Equation (3) (Meukam *et al.* 2004; Jannot, 2008) :

$$T_s(0,0,t) - T_s(0,0,0) = \frac{\phi}{4\pi\lambda L_{hw}}\ln(t) + \phi\left[R_c - \frac{\ln\left(\frac{r}{\sqrt{a}}\right)}{2\pi\lambda L_{hw}} + \frac{0.57\ 7}{4\pi\lambda L_{hw}}\right] \quad (3)$$

where $L_{hw} = 2l$ is length, r is radius

However, the hot strip behaved as a hot wire after a very long time interval so that the asymptotic behavior could be used to estimate thermal conductivity in a relatively short time as intended. If the slope of the curve, $\mathbf{T_s(0,0,t) - T_s(0,0,0) = f(\ln(t))}$, varied for hot strip, the variation was sufficiently slow and considered constant on reduced time intervals. The thermal conductivity λ was estimated from slope $\frac{\phi}{4\pi\lambda L_{hw}}$ of the experimental curve determined by linear regression between 100 s and 180 s. Figure 6 shows the experimental hot strip devise used.

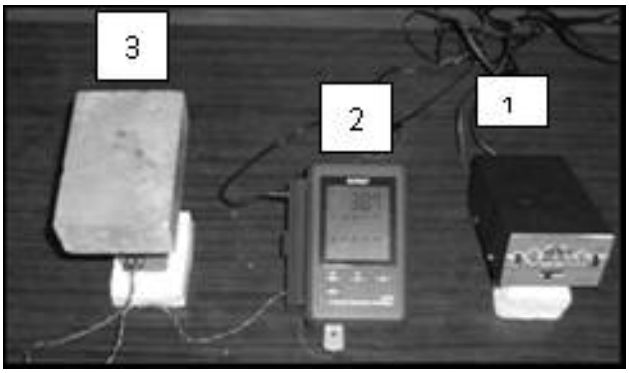

Figure 6. Experimental hot strip device (1. stabilized alimentation, 2. recorder temperature, 3. electrical resistance inserted between two material samples)

RESULTS AND DISCUSSIONS

Eco-plaster thermal conductivity variation according to density: Figure 7 shows that eco-plaster thermal conductivity increases with its density. It indicates that plaster thermal conductivity is an affine function of density. From literature, it is noted that lower is density, lower is useful thermal conductivity of set plaster (Daligang, 2002). Thus, porosity is main parameter favoring insulating nature of material, in order to have low thermal conductivities (< 1 $W.m^{-1}.K^{-1}$ for insulating materials), it would be necessary to formulate rather porous plasters, having low densities (Coquard, 1992; Eve, 2003).

Eco-plaster thermal conductivity according to mixing rate: Figure 8 analysis shows that thermal conductivity of eco-plaster developed based on snail shells are lower than those of reference plaster for the same $\frac{m_e}{m_p}$ ratios. It can be deduced that when shell plaster setting, the junction between crystallites is

such that more pores develop there than commercial plaster case.

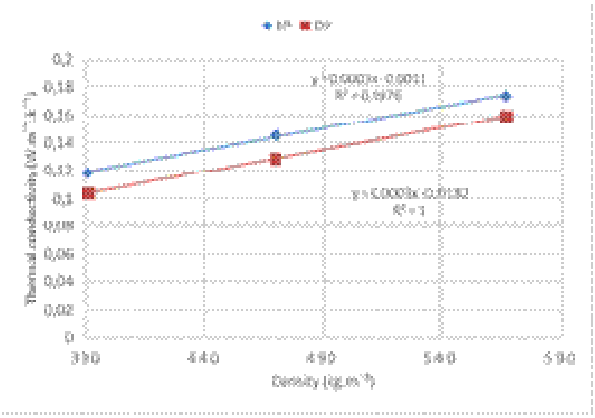

Figure 7. Thermal conductivity variation according to density

Eco-plaster thermal conductivity according to mixing rate: Figure 8 analysis shows that thermal conductivity of eco-plaster developed based on snail shells are lower than those of reference plaster for the same $\frac{m_e}{m_p}$ ratios. It can be deduced that when shell plaster setting, the junction between crystallites is such that more pores develop there than commercial plaster case. This relatively greater porosity would give to developed plaster, the property of better thermal insulating compared to commercial plaster studied.

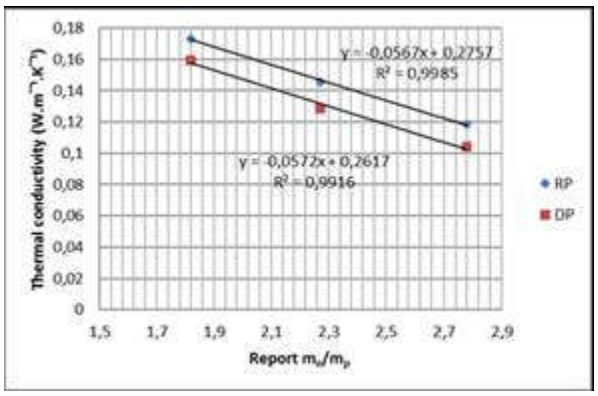

Figure 8. Eco-plaster thermal conductivity according to mixing rate

Eco-plaster thermal effusivity according to mixing rate: Figure 9analysis shows that thermal effusivities values of shell plaster are lower than those of reference plaster. That mean heat flow is less easily propagated from a surface inward of plasters based on snail shells.

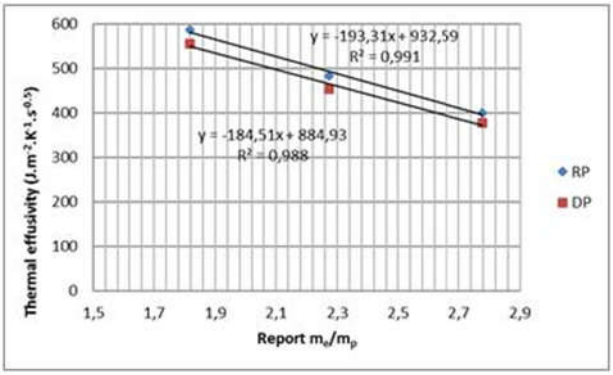

Figure 9. Eco-plaster thermal effusivity according to mixing rate

These results are consistent with the recorded thermograms. Indeed, with a lower effusivity, heat flux at surface has difficulty in circulating in material with lower thermal conductivity. So on this surface, temperature measured will be higher. In total, the low values of effusivity and thermal conductivity recorded, made plaster a relatively higher thermal comfort material than commercial plaster.

Sample heating and cooling thermograms: Figure 10 (10-a – 10-d) thermograms reflect heating and cooling thermal behavior of plaster according to different mixing rate. Indeed, a constant heat flow was imposed for 180 s (heating phase) and then removed (cooling phase). These thermograms show that heat flow propagates more in commercial plaster samples than in developed plaster samples. It is also noted that this propagation decreases as the $\frac{m_e}{m_p}$ratio increases (or specimens density decreases). The air presence in set plaster network would contribute to this behavior. Depending on the $\frac{m_e}{m_p}$ ratios, a temperature difference of 3 °C to 5 °C is recorded after 180 s on the surfaces subjected to constant flow.

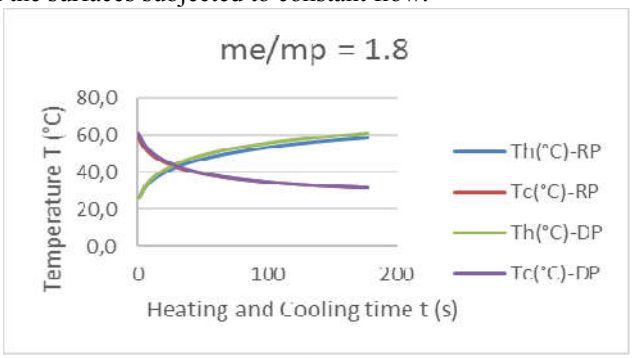

Figure 10 a. Plaster samples heating and cooling thermograms $\frac{m_e}{m_p} = 1.8$

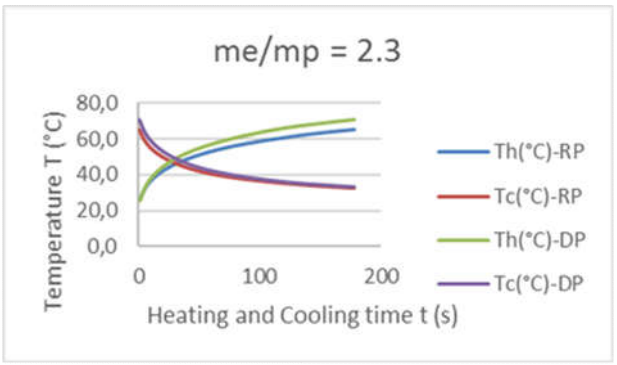

Figure 10-b. Plaster samples heating and cooling thermograms $\frac{m_e}{m_p} = 2.3$

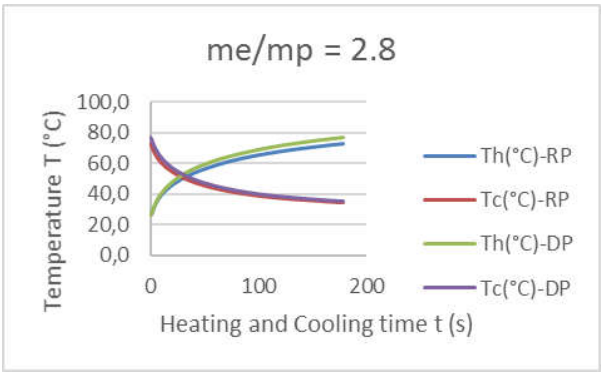

Figure 10-c. Plaster samples heating and cooling thermograms $\frac{m_e}{m_p} = 2.8$

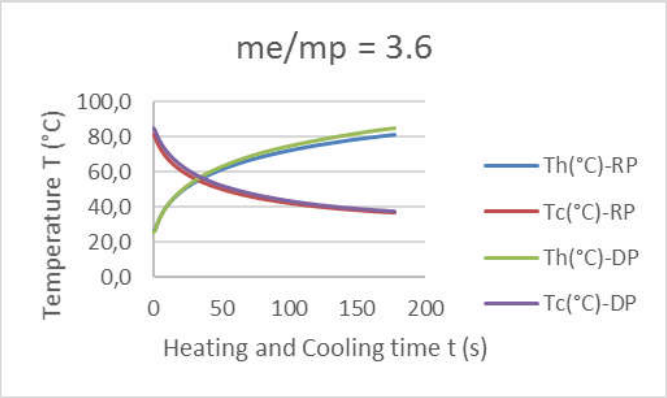

Figure 10-d. Plaster samples heating and cooling thermograms $\frac{m_e}{m_p} = 3.6$

CONCLUSION

The present work shows that it is possible to develop low density plaster from Achatina Achatina snails shells. The elaborated plaster mixing requires a water quantity of water corresponding to $\frac{m_e}{m_p}$> 1 ratios. Thermal measurements show that elaborated plaster has relatively low thermal conductivities and effusivities compared to commercial plaster chosen as reference. These results contribute to snail shells valorisation, which, instead of being considered waste thrown in garbage, can be used as raw material for low density plaster synthesis with interesting thermal characteristics. Synthesized plaster can also better meet the comfort and energy needs in building at low cost.

Conflicts of Interest: Authors declare no interest conflicts regarding the publication of this paper.

NOMENCLATURE

a: Thermal diffusivity, m².s-¹
E : Thermal effusivity, $J.K^{-1}.m^{-2}.s^{-0,5}$
L: Length, m
m: Mass, kg
R: Electrical Resistance, Ω
S: Surface, m²
T: Temperature, K
t: Time, s
w: Water content, %
x, y, z: Space variables, m

Greek letters

ρ : Density, $kg.m^{-3}$
λ: Thermal conductivity, $W.m^{-1}.K^{-1}$
θ_s: Laplace transform of probe temperature
φ: Heat flux, W

Indices / Exhibitors

s: Related to prob

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