COMPARISON OF MATERIALS FOR THERMAL ENERGY STORAGE IN LOW ENERGY BUILDINGS

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Abstract – Available materials used for the management of building needs in thermal inertia are compared according to the following criteria: thermal performance, mechanical behavior, cost and embodied energy. The CES Selector software has been used in order to compare new ceramics materials made of vitrified asbestos containing wastes to conventional materials (concrete, terracotta, limestone…). Those new materials present better thermal and mechanical properties than conventional materials for a similar energy payback time.

Keywords – thermal mass, thermal energy storage, energy consumption, embodied energy

Nomenclature

C_m	cost, €/kg
C	cost, €
C_p	specific heat, J/(kgK)
E_e	embodied energy, MJ/kg
ρC_p	storage capacity, kJ/(m³K)
x	thickness, m
Q	received energy, J/m³
a	thermal diffusivity, m²/s
v	heat transfer speed, m/h
M	molar mass, g/mol
L_f	latent heat, kJ/mol
P	net radiated power, J/s
S	surface, m²
E_{CO2}	CO_2 emission, kg_{CO2}/m^3
E	Young's modulus, GPa
T	temperature, K
m	mass, kg
D	thermal delay, h
V	volume, m³
Greek symbols	
ρ	density, kg/m³
ΔT	temperature difference
σ	Stefan-Boltzmann constant W/(m²K⁴)
ε	emissivity
λ	conductivity, W/(mK)
τ	diffusion time, s
Φ	thermal flux, W/m²
α	thermal expansion coefficient, K^{-1}

1. Introduction

Recent worldwide concerns on environmental and energy issues have led to a whole trend to decrease energy consumption and greenhouse gas releases in the construction area. This can be achieved by improvements of insulation and energy equipments implemented on already existing buildings.

In France, building energy needs is the largest energy consumer. It represents 45% of primary energy consumption compared to 28% for transport and 26% for industry. Building needs is responsible of 25% of greenhouse gas emissions, with 120 billions of tons of CO_2 emit every year [1].

The annual average energy consumption of buildings is about 400 kWh of primary energy per m² per year ($kWh_{pe}/(m^2.year)$), obviously an inacceptable score demonstrating the huge potential of improvement [1]. Within this context, the French government has announced its will to decrease the CO_2 emissions by 75% before 2050, leading necessarily to a corresponding effort in building area. Consequently, since the 1st June 2001, national programs have reinforced progressively (every 5 years) regulations for new buildings. The need to innovate in this field has lead to the creation of different labels related to the levels of building energy consumption. As a result, 5 different labels are under current use today in France [2]:

- RT2005 – for a maximum consumption of 130 $kWh_{pe}/(m^2.year)$
- THPE (very high energy performance) - 100 $kWh_{pe}/(m^2.year)$
- BBC (low-energy building) - 40 $kWh_{pe}/(m^2.year)$
- BEPAS (passive house) - heating consumption < 15 $kWh_{pe}/(m^2.year)$
- BEPOS (positive energy house) - building producing more energy than its own consumption.

In the case of new buildings, this leads to a necessary increase of the energy efficiency of the envelope itself before any energetic equipment concern. This approach requires controlling of two key parameters: on one side insulation, which can considerably reduce thermal losses. The use of insulation in a building allows to decrease the energy demand and the CO_2 emissions [3]; and on the other side, thermal inertia which reduces extreme temperature variations during a day. The latter can also store heat in the winter and limit overheating in the summer. So thermal mass incorporated in a building gives more stable indoor temperature and allow energy saving when heating or cooling is supplied [4 – 7].
Therefore the materials selection for thermal mass and insulation is essential for energy efficient buildings.

According to simulations made using the TRNSYS software [8], a suitable wall has to match specific characteristics in order to discharge in a short time a sufficient amount of heat or coldness. Already well-known materials such as concrete and terracotta present such properties gathered in Table 1.

Tab. 1: Materials properties for thermal inertia application in buildings

Material thickness (cm)	Storage capacity ($kJ.m^{-3}.K^{-1}$)	Conductivity ($W.m^{-1}.K^{-1}$)	Thermal delay (h)
15 < e < 25	$\rho C_p > 2000$	$1 < \lambda < 2$	6 < D < 8

As a matter of fact, building materials are not selected today on their sole thermo physical properties. For few decades, additional environmental criteria are considered and become even of major interest: embodied energy, embodied green house gas (GHG), availability, conflict of use, eco-toxicity, recycling… According to this modern approach, both concrete and terracotta embodied energy needed for their primary productions are considered today as too important. On the other side, when we look at traditional materials, such as cob/clay, they present a low life-cycle cost and high technical performances which considerably reduce the impact of the building on the environment according to the parameters previously cited [9].
In a more general sustainable approach of development, building needs in materials are huge while much more important amount of various "wastes" have been cumulated during the last century. Most of those materials have been used once, numerous present high hazardous characters. For those latter, energy consuming inertization treatments are necessary, increasing once more their embodied energy and GHG. Therefore, before any possible use of raw natural resource, a particular effort has to be done to recycle those end-of-life inertized wastes.
The aim of the present work is to illustrate this approach through the particular case of new ceramic materials issued of vitrified asbestos wastes (namely COFALIT®). The COFALIT® is presented and then compared to materials from the architecture database in the CES Selector software. Its use in the building field could simultaneously enhance the energy building efficiency and sustainability and add a new highly valuable life of the recycled materials enhancing the industrial treatments of wastes.

2. Available materials for low temperature thermal storage

The suitability of available materials for low temperature thermal energy storage has been evaluated using the CES selector software. The analysis is carried out following the methodology for materials selection developed by Prof. Ashby of Cambridge University. This is of value for designing buildings as many parameters are to be taken into account: thermal properties, mechanical behavior, price, availability, recyclability, CO_2 foot print… The tool has been already used and applied with success to the selection of thermal energy storage materials to be used in energetic industrial processes [10]. Indeed, to find the best way to compare materials, Cabeza et al (2010) have defined criterion of excellence, called material performance index, which combine two or more properties of the material. It enables to maximize the performance for a given application. For example, if the main objective is to minimize cost in the application, *the cheapest solution that meets all constraints is the best choice*. But an application has often many objectives, and when one parameter is minimizing, it does not generally minimize the others. So a multi-objective optimization should be used to obtain a compromise between all the parameters used for the application objectives.
In the paragraph below, thermo physical or other properties are combined and plotted on graphs to enable classification and comparison of conventional materials with respect to the particular application of Thermal

Energy Storage (TES) for buildings. The use of performance index will be more detailed at the beginning of & 3.

2.1. Analysis of conventional materials

2.1.1. Storage capacity and compacity

Traditionally, people are used to take advantage of the heat (solar and internal) stored daily in the wall to get comfort by night during winter and reversibly, to store the available free-cooling during night for use daily in summer.

In buildings, those heat and coldness are traditionally stored by sensible heat in solid or even in liquid media (usually water). For some decades, extensive researches are devoted to integration of latent heat based Thermal Energy Storage Materials (TESM) in walls to increase the storage capacity per unit of volume [11, 12]. Nevertheless, this approach is still under R&D and still suffers of high costs and safety concerns. Consequently, only sensible heat TESM is considered in the present study.

Sensible heat TESM properties are currently restricted, at least as a first step in usual selection procedures, to the storage capacity and the density.

The storage capacity is defined as the ability of a material to store heat or coldness per unit of mass and temperature variation. The density is related to the mass which could be placed in a unitary volume and therefore to the compacity of the material. The highest could be the storage capacity and/or the density; the smallest would be the amount of material needed to store a specific amount of energy.

According to this common approach, a first plot has been realized in terms of storage capacity as function of density for the available materials.

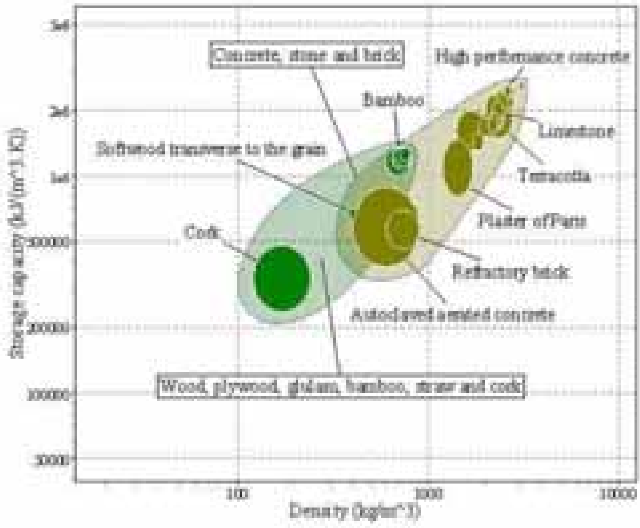

Fig. 1: Storage capacity vs. density

On this diagram illustrated in Fig.1, materials are not spread on the whole surface without coherence but families of materials can be easily identified and attached to a particular area of the plot. Each material is specified by a surface related to its respective variations in the concerned properties. In the present case, concrete, stone and bricks gather within a common domain forming an elongated surface from the center of the diagram to the upper right over wide ranges of values. A second common domain is formed by wood, bamboo and cork within a similar elongated surface mainly at the center of the diagram down to the lower left part. A common surface is also shared by the two families of materials.

Such a diagram is of high interest at different levels: (1) it highlights the areas of what is achievable with current materials, (2) helps any user to choose the proper one for particular need and (3) it helps to identify clearly potential zones of interest for which no current material is available and therefore for which new materials could be designed.

2.1.2. Thermal delay

The well known traditional thermal management cited above (beginning of & 2.1.1) supposes not only a proper storage capacity but also the property of the material to induce a suitable delay, a shift in time, between the storage and the discharge steps. As a practical example, overheat available at mid-day can be stored in the wall and released indoors 10 hours later during the night. Obviously, there is no interest to release this heat after 3 or 22 hours. This delay can be controlled by both a pertinent choice of the TESM with respect to its related properties. So when storage capacity is associated with thermal conductivity, diffusivity and thermal delay can be considered. Diffusivity is the ability of a material to transfer quickly a temperature variation. It is defined as:

$$\alpha = \frac{\lambda}{\rho C_p} \qquad \text{(eq. 1)}$$

Thermal delay is the time lag needed to transfer the heat through the wall side to side. It is defined as [13]:

$$D = \frac{x}{v} \qquad \text{(eq. 2)}$$

with $v = 72.5\sqrt{a}$ the heat transfer speed

$$D = \frac{1}{72.5} x \sqrt{\frac{1}{3600a}} \qquad \text{(eq. 3)}$$

with 3600a being the diffusivity in m²/h.

$$D = 1.38x\sqrt{\frac{1}{3600a}} \qquad \text{(eq. 4)}$$

According to those parameters, a second plot has been realized on Fig. 2 with thermal delay of a 0.2 m thick wall function of thermal diffusivity.

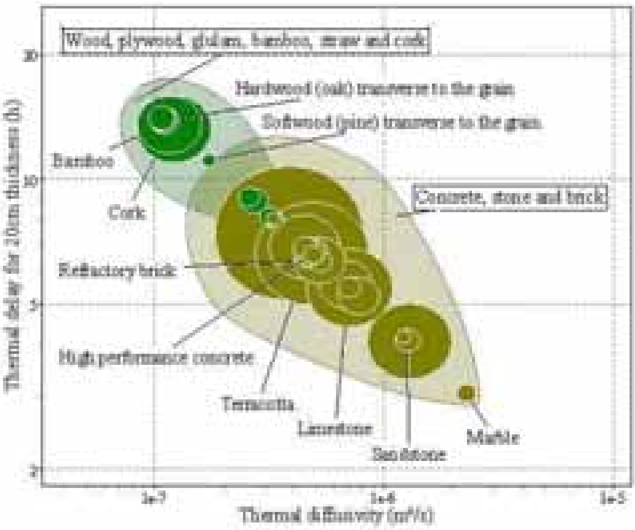

Fig. 2: Thermal delay vs. diffusivity

At the upper left corner, materials such as bamboo and wood, can store the heat longer than concrete or brick for a same thickness. For example, bamboo presents a 15 hours thermal delay whereas high performance concrete only 7 hours for a thickness of 20 centimeters. Globally, this graph highlights the fact that materials from the wood family present a high storage capacity and a low conductivity leading to low diffusivity and so an important thermal delay. Therefore, such approach allows fast and efficient comparisons of materials properties. In France, a wall of 20 centimeters in thickness is usually built with materials within concrete, stone and brick families whereas wood or bamboos which are more used in other countries like in Asia.

2.1.3. Embodied energy

For the past decades, many researches have been done on the relationship between building materials, construction processes and their environmental impacts. Every material needs energy during its whole life, from its primary production, including raw primary constitutive materials extraction, processing, to manufacturing, transport, maintenance… until its end of life from dismantlement to recycling. The sum of all the corresponding needed energies is called embodied energy, and is typically measured as a quantity of non-renewable energy content per unit of building material, component or system. For example, it can be expressed as mega Joules (MJ) or kilo watt hour (kWh) per unit of weight (kg or ton) or volume (m^3).

The process of calculating embodied energy is complex and involves numerous sources of data. The measure of embodied energy enables to evaluate the associated environmental implications of resources depletion, greenhouse gases, environmental degradation and reduction of biodiversity. As a rule of thumb, embodied energy is a reasonable indicator of the overall environmental impact of building materials or systems. However, it must be carefully used against performance and durability since these last ones can have a compensatory effect on the initial environmental impacts associated with embodied energy.

In the present study, the embodied energy of primary production is compared for previously cited materials. Obviously, a too high embodied energy cannot be compatible with an approach of bioclimatic conception. So as shown in Fig.3, in which embodied energy is plotted as a function of price.

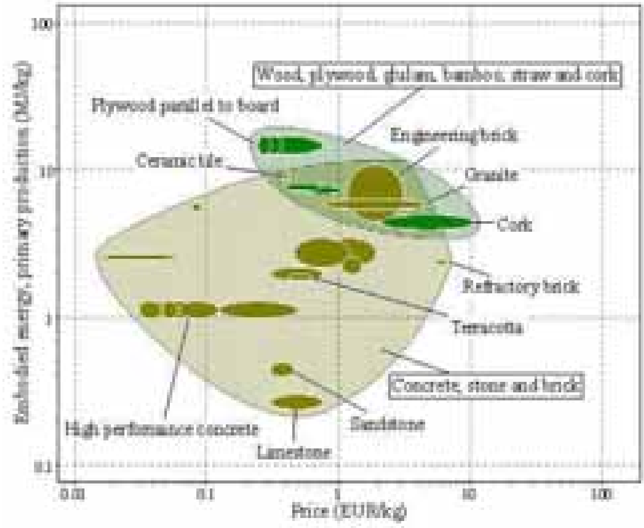

Fig. 3: Embodied energy vs. price

According to this graph, materials from the wood family need generally more energy than materials from the rocks family and so on for the cost. Generally for those materials, all the processes of forming, manufacturing, and extraction of raw materials are the most energy intensive. So "wood materials" use more energy than concrete to be made and are usually more expensive.

2.1.4. Emissivity and thermal expansion coefficient

The emissivity is an important parameter for a material used as a thermal mass. Indeed if the material doesn't emit properly, it will not discharge correctly the stored heat or coldness. The emissivity coefficient ε indicates in fact the ability of a material to transfer heat by radiation as a "grey body" according the Stefan-Boltzmann law cited below, compared to an ideal "black body" for which the emissivity coefficient is taken as reference, $\varepsilon = 1$.

$$P = \sigma \varepsilon S (T^4 - T_c^4) \quad \text{(eq. 5)}$$

where T_c is the temperature of surroundings.

Moreover and independently, thermal charge and discharge of sensible heat suppose corresponding temperature changes. Those changes in temperature are always associated to thermal expansion effects highlighted by changes in material dimensions. This effect can induce critical mechanical consequences if materials of very different expansion coefficient are associated together.

Emissivity and thermal expansion coefficient are independent parameters in terms of both physical and use concerns. Anyway, a corresponding graph using those two parameters can lead potentially to a general trend and then to useful materials classification.

Moreover, in the case of building construction (as for other kind of applications), the choice of materials could concern simultaneous parameters which could present absolutely no physical fundamental relationship. Nevertheless, for the builder, the same material has to minimize and maximize simultaneously selected parameters to fulfill the whole functionality.

This approach is illustrated in Fig. 4 in which emissivity is plotted as function of the thermal expansion coefficient.

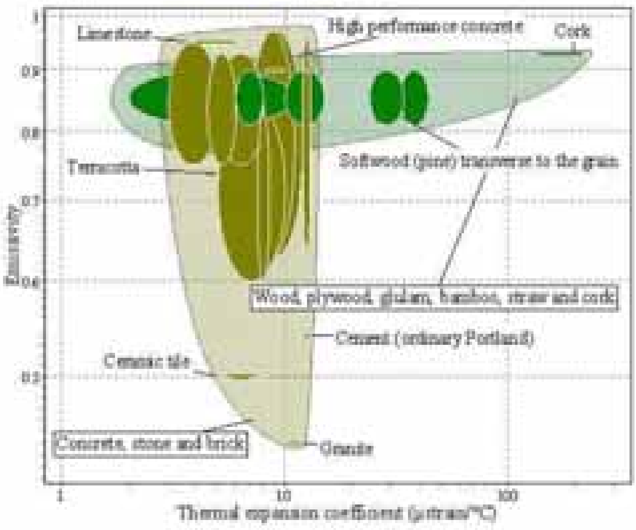

Fig. 4: Emissivity vs. thermal expansion coefficient

Most of the selected materials have an emissivity ranging between 0.8 and 0.9, especially “dark materials” within concrete, brick and stone families, currently named "selective warm materials". These materials are closed to the "black body", which highlights their important ability to store thermal energy. Some materials present also higher emissivity (up to 0.97) or significantly lower ones (down to 0.45). Then, relevant choices would have to be done depending if the material would be used indoors as thermal mass and would preferably present high emissivity or be used outdoors and should present a low emissivity.
The 2nd plotted property, thermal expansion coefficient, is usually ranging within a narrow domain of values (from 3 to 11×10^{-6} K^{-1}) for the construction materials such as concrete, stone and brick. Comparatively, this coefficient presents a wide range of variation (from 2 to 250×10^{-6} K^{-1}) for materials within the wood, bamboo and cork families because of their capacity to absorb water, like cork, mainly used as a hygrometric regulator material.
The Fig. 4 is an illustrative example of classification using two physically independent parameters presenting simultaneous interest for building construction. In current European buildings, high emissivity and simultaneously low thermal expansion are usually preferred leading to a choice of materials gathered within the upper-left quarter of the graph. In areas concerned by earthquakes and typhoons, more flexible materials would be preferred even if they present larger thermal expansion coefficients (which can be balanced by construction techniques anyway).
In areas of very narrow temperature variations, like in Caribbean islands, the practical interest of those two parameters could be really negligible before others more concerned by resistance against sea-shore conditions or storms.

2.2. COFALIT®, material made of vitrified asbestos containing wastes

COFALIT® is made by the INERTAM company [14] located on the Atlantic coast in France. It is obtained by vitrification of asbestos wastes with a plasma torch at 1500°C. At the end of melting, the material is poured into ingot moulds, then removed from the mould and cooled down at air temperature. Dangerousness from the asbestos fibers aspect had then completely disappeared; the material is entirely inert and harmless for humans [15]. After a last crushing step, it is currently used as road ballast (fill), the only current industrial opportunity (Fig.6).
Regarding the limited opportunities of this material, the company processes at the moment only 6000 tons of asbestos wastes of the 250 000 extracted every year in France, the leftovers being stored in big bags waiting for a final treatment in a specialized landfill disposal.
The tables 2 and 3 present some of the major properties of COFALIT®, highlighting specially an important storage capacity (similar to concrete), a good mechanical behavior and a very low cost.

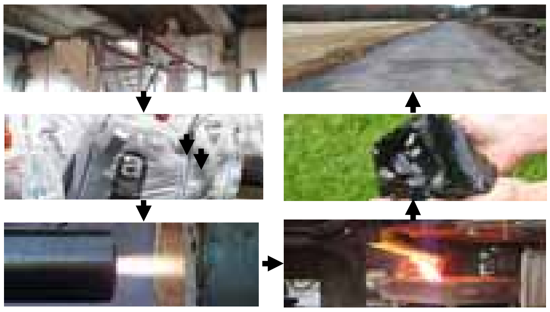

Fig.6: Vitrification treatment steps for asbestos wastes

Tab. 2: Thermal properties of COFALIT®

	ρ	ρC_p	λ	K	D (e=20cm)	ε
	$kg.m^{-3}$	$kJ.m^{-3}.K^{-1}$	$W.m^{-1}.K^{-1}$	K^{-1}	h	/
COFALIT®	3120	2680	2	$8.8*10^{-6}$	6.10	0.96

Tab. 3: Economical, mechanical and environmental properties of COFALIT®

	E	C_m	E_{CO_2}	E_g
	GPa	$€.kg^{-1}$	$kg_{CO_2}.kg^{-1}$	$MJ.kg^{-1}$
COFALIT®	100	0.010	0.06	2.15

The embodied energy is calculated regarding only the energy used for plasma torch to melt asbestos containing wastes. As those wastes are composed of various raw dismantlement materials, the calculation is reduced here to the major concerned compounds CaO-SiO_2.

The heat needed for melting the wastes is composed of sensible heat from room temperature to 1500°C which is the melting temperature and the latent heat [16]:

$$E_e = \frac{C_p}{M}\Delta T + \frac{L_F}{M} \quad \text{(eq. 6)}$$

where

$$M(CaO - SiO_2) = 116.14\, g / mol$$

$$C_p (J/(molK)) = 63.58 + 0.05724 \times T(K)$$

$$T = 1821\, K$$

$$\frac{C_p}{M}(J/(gK)) = 1.44$$

$$L_F(1821\, K) = 57.3 kJ / mol$$

$$\frac{L_F}{M}(J/g) = 493.37$$

$$E_e = 1.44 \times (1821 - 293.15) + 493.37$$

$$E_e = 2693.474 J / g \quad \text{(eq. 7)}$$

$$E_e = 2.693 kJ / g$$

$$E_e = 2.7 MJ / kg$$

Then the CO_2 quantity, E_{CO2}, is estimated regarding the quantity of CO_2 emitted per electric kWh (kWh_e), which is equivalent to 60 g per kWh_e [17] for industrial use of electricity:

$$E_e = 2.7 MJ / kg = 0.75 kWh_e / kg \quad \text{(eq. 8)}$$

$$E_{CO_2} = 45 g_{CO_2} / kg = 0.045 kg_{CO_2} / kg \quad \text{(eq. 9)}$$

Its availability and low cost (10€ per ton) have made COFALIT® a potential candidate for sensible heat thermal storage. The first selected potential energetic application for COFALIT® is its use in thermodynamic concentrated solar power plants (CSP) as a sensible heat thermal storage material [18].
As a matter of fact, regarding a sustainable approach, if used as energetic material, the embodied energy and CO_2 of this recycled ceramic could be balanced by its new life. In the particular case of CSP, the embodied energy presents a payback estimated to about one year of use. This is reasonably small before the 35 years of a CSP plant operation and can justify the high energy cost of the thermal waste treatment.
In the case of building construction, the energy and GHG contents of materials should be systematically analyzed in similar way defining the corresponding payback.

3. Comparative study

In order to compare COFALIT® to others available materials previously studied and in order to select the most efficient material for thermal energy storage in buildings, performance index are defined, based on the approach proposed by Cabeza et al (2010) and described at the beginning of paragraph 2.

3.1. Index performance

The needed function here is thermal energy storage with the main objective being to maximize the storage capacity per unit of cost. In terms of performance criteria, it leads to the thermal energy stored per unit of volume (eq. 10) and the cost per unit of mass (eq. 11):

$$Q = \rho C_p \Delta T \quad \text{(eq. 10)}$$

$$C = m C_m \quad \text{(eq. 11)}$$

So stored energy per unit of volume and cost can be written as:

$$Q = \frac{m}{V} C_p \Delta T = \frac{C}{C_m V} C_p \Delta T \quad \text{(eq. 12)}$$

Looking at Eq. (12), it can be seen that the objective to maximize storage per unit of cost depends on different variables, some geometrical such as volume, other operational as the temperature interval and other depending only of the material properties (cost per kg and specific heat capacity). So the material with the highest value of Q is the one with the highest value of C_p/C_m, which is defined as the performance index P1, which is related only on material properties:

$$P1 = C_p / C_m \quad \text{(eq. 13)}$$

As we are looking for thermal mass materials which have to diffuse internally heat or coldness by conduction during the day, which means short term storage, the time dimension has to be included. This task is achieved using thermal diffusivity in the function thermal energy storage. Material thickness can be associated to diffusivity and diffusion time through the eq. 14:

$$x = \sqrt{2 a \tau} \quad \text{(eq. 14)}$$

And so on for the cost:

$$C = m C_m = \rho V C_m = \rho S x C_m = S \sqrt{2\tau} (a^{1/2}) \rho C_m \quad \text{(eq. 15)}$$

So in this case, to reach the objective of minimizing cost without concerns in operating conditions, the material with the intrinsic lowest cost is the one with the highest value of the performance index P2:

$$P2 = 1/(a^{1/2})\rho C_m \qquad \text{(eq. 16)}$$

In the Fig.7, the performance index P1 vs. P2 are plotted together and considered when short term storage is needed. In this case, materials with the highest performance index P1 and P2 are located on the top right of the graph. They present a low cost C_m, an important storage capacity ρC_p and also a high diffusivity a. Materials within the concrete and stone family, especially high performance concrete, and COFALIT® are the most efficient materials, this one being far away with its very low cost and high storage capacity.

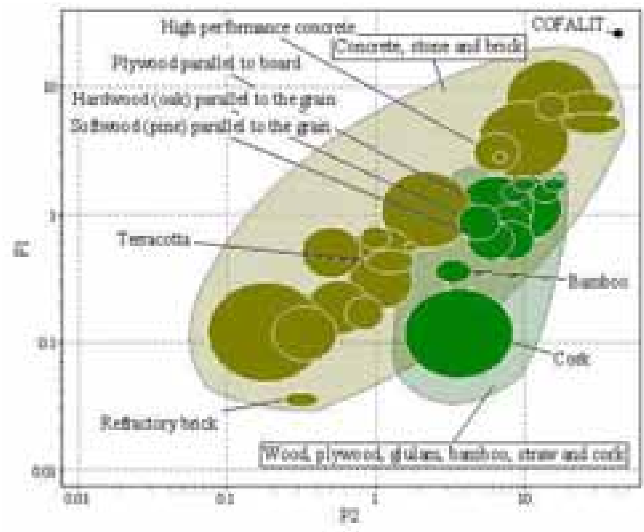

Fig.7. P1 vs. P2

It is also possible to plot a performance index vs. only one property, such as Young's Modulus, which should be maximized for every material. Fig.8 shows P1 as a function of Young's Modulus E. Materials with the highest performance in terms of energy storage and mechanical behavior are located on the top right of the graph. According to those parameters, COFALIT® and materials within the concrete, stone and brick family are again the most efficient ones.

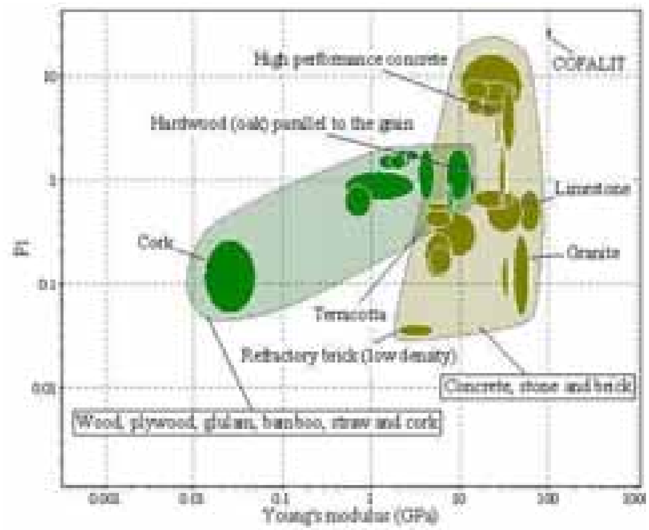

Fig.8: P1 vs. E

Following the same approach, one can consider the storage capacity per unit of embodied energy and the two performance indexes below are calculated. The index P'1 is related to the stored energy per unit of embodied energy while the index P'2 refers to the thermal diffusivity and embodied energy. In this case, materials with the highest performance index present a low embodied energy and thermal diffusivity.

$$P'1 = C_p / E_e \qquad \text{(eq. 17)}$$

$$P'2 = 1/(a^{1/2})\rho E_e \qquad \text{(eq. 18)}$$

Most efficient materials, located on the top right of Fig.9, are stones. They present a low embodied energy needed only for their extraction, so an important performance index P'1. As seen on Fig.2, stones have an important thermal diffusivity, which leads to an average performance index P'2. Materials from the concrete, stone and brick family are generally more efficient in terms of short term storage regarding embodied energy than the "wooden" materials. COFALIT®, with an embodied energy equivalent to 3 MJ/kg, is situated between concrete and bricks. Its fabrication needs high temperature (1500°C) to reach melting point so a high primary energy demand.

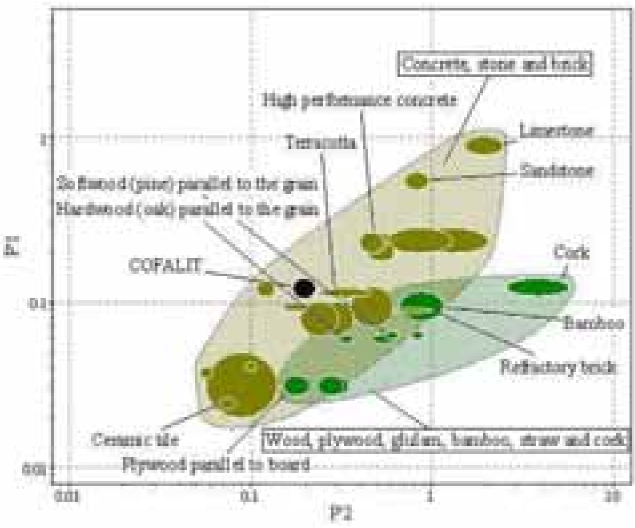

Fig.9: P'1 vs. P'2

3.2. Energy payback time for a passive storage

Regarding the previous figures, it is important to consider the energy payback time of each material. It is defined as the time in years needed for a system to « payback » its energy initial content. For that, the received energy Q by a material needs to be evaluated, during a time t in years, when "one storage cycle" per day is considered:

$$Q = \rho C_p \Delta T \times 365t \qquad \text{(eq. 19)}$$

ΔT is the difference between the material temperature when storage is activated (maximum 60°C) and the material initial temperature (equivalent to 20°C).

On Fig.10, the ratio between the received energy Q and the embodied energy E_e of each material is plotted function of time. When this ratio is upper than 1 ($Q/E_e>1$), it means that the received energy during the number of corresponding years balances the material embodied energy leading to an energy payback.

Limestone needing energy only for its extraction has a low energy payback time equivalent to 7 days. Concrete payback its energy content in about 1 month and a half and COFALIT® in about 2 months and a half. The energy payback time of COFALIT® in building construction is five time more important than for CSP. This is due to the respective amount and frequency of thermal storage specific to the applications. The energy payback time of COFALIT® is more important than for the former materials, due to the large energy amount needed for its making. Anyway it enables the reuse of materials in end lifecycle and so a positive life cycle analysis in opposition to conventional materials previously cited. This aspect concerns other important issues which are the availability of materials and the interest to use recycled materials before new ones for which additional extensive exploitations of natural resources are needed. Then, a critical choice appears finally between environmental impact of waste treatments for inertization and recycling (including embodied energy and CO_2) and natural resource depletion and energy needs to manufacture new materials.
Anyway, regarding the energy payback time of about 2 months and a half, the recycled COFALIT® material presents an energy content still significantly lower than the expected time of operation for its new life-cycle

(at least 50 years for a building). Moreover, the Plasma Torch process used today for wastes melting could be potentially significantly improved by combination with concentrated solar heat to reduce the corresponding energy needs and GHG production. This potential is already under study in related laboratories.

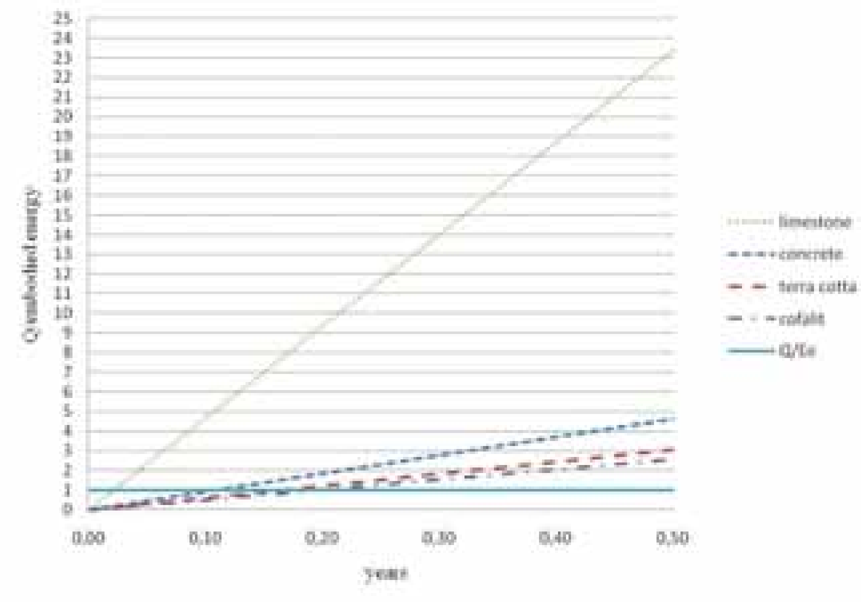

Fig. 10: Materials energy payback time

4. Conclusion and perspectives

COFALIT® is a material with a good prospect. Its use enables asbestos wastes recycling, waiting today for a treatment. Also, with the principle of « who is polluting is paying», person who owns asbestos wastes are compelled to pay for their vitrification, which explains the cheap cost of COFALIT®.
The fact that COFALIT® is molten and then casted enables a complete shaping liberty and so many different use opportunities. It reveals itself to be a potentially multifunctional material, used for thermal mass (Trombe wall for example), as a supporting structure or for its aesthetic quality as a vitrified stone (coatings).
This material could eventually substitute, at least partially, concrete and brick materials in construction. Some pilot test will soon be carried out to evaluate its performance when integrated into low energy buildings.

Acknowledgments

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