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Valorization of *Posidonia oceanica* Balls for the Manufacture of an Insulating and Ecological Material

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ABSTRACT

To combat overconsumption of energy in buildings for residential or industrial use, it's necessary to use materials that provide good thermal insulation. In this context, an experimental study was carried out to assess the mechanical and thermophysical properties of a mixture of plaster and fibers of *Posidonia* oceanica. For this purpose, three series of parallelepipedic specimens of dimensions 270 mm x 270 mm x 40 mm and three series of prismatic specimens of dimensions 40 mm x 40 mm x 160 mm were prepared by varying the percentage of fibers from 0% to 20%. Mechanical and physical properties, such as: compressive strength, flexual strength, thermal conductivity and thermal diffusivity, were investigated. Density of different test samples was determined for percentages of fibers ranging from 0% to 20%. The results have shown that fiber-reinforced mixtures have a better resistance to compression and bending. The addition of *Posidonia oceanica* fibers considerably reduces thermal conductivity and thermal diffusivity of the various mixtures. Optimal mechanical properties are reached when the fibers of *Posidonia oceanica* represent a percentage ranging from to 10% by volume.

KEYWORDS: Valorization, Thermal insulation, *Posidonia oceanica* fibers, Plaster, Ecology.

INTRODUCTION

Endemic to the Mediterranean Sea, *Posidonia oceanica*, the most widespread aquatic plant in its waters, represents a main marine constituent of this sea. It occupies between 25,000 and 50,000 km^2 of the coastal areas of the Mediterranean, corresponding to 25% of the seabed. It grows from the first meter up to 40 m deep (Borum et al., 2004).

The fibers of *Posidonia oceanica* leaves, which are difficult to degrade, are brought together by the movements of the sea in felted balls, called aegagropiles, often rejected on the beaches of the Mediterranean, of which they constitute an endemic species. Dried *Posidonia oceanica* leaves have traditionally been used in Mediterranean countries as a packaging material for transporting fragile glassware and pottery, as well as for shipping fresh fish from the coast to cities. Natural fibers are used as reinforcement in composite materials using a cement matrix. Previous research tended to determine the mechanical, thermal and acoustic properties of cements reinforced with natural fibers, such as hemp (Zhijian et al., 2006 ; Sedan et al., 2008), flax (Coutts, 1983), coconut fiber (Cook et al., 1978), sisal (Savastano et al., 2003; Toledo Filho et al., 1999). The effect of using natural kenaf fibers on the strength behavior of weak subgrade soils was studied by Mittal and Shukla (2020). The fibers are mixed in various percentages by weight of soil and a series of heavy compaction, soaked California Bearing Ratio (CBR) and unconfined compressive strength (UCS) tests were conducted.

The energy performance of buildings is directly linked to the construction materials used. Therefore, better thermal insulation materials, made with a low-energy process and renewable resources are needed. The use of insulation materials in the construction sector can be divided into three areas: thermal insulation, sound

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insulation and fire protection (Varun Teja and Meena, 2020). Distinction can be made between insulation material properties in blow-in materials and panel insulation materials. The use of products made from Posidonia fibers is conceivable in all areas (Aditya et al., 2017).

In the field of thermal insulation, there are global producers of foams made from petroleum derivatives (polystyrene particle foam EPS, extruded polystyrene foam XPS), isocyanates (rigid polyurethane foam or foam glass) and manufacturers of mats made of glass or mineral wool dominate (Yang, 2015). Due to environmental aspects, such as high energy consumption during production and sometimes finite resources, many insulating materials made from renewable raw materials have recently established themselves on the European market. The following insulating materials have a similar profile to *Posidonia* fibers: hemp, wood fiber and cellulose flakes, each in loose form for blowing-in or as a mat/plate. There are also niche products made of cotton, sheep wool, coconut fibers, cork, grass and seaweed.

The valorization of *Posidonia oceanica* fibers in insulating construction materials could be interesting for economic and durability reasons because of their availability, renewability and low cost. The fibers of *Posidonia oceanica* have been studied by many authors in order to investigate the mechanical properties of reinforced cement using different ratios of fibers (Allegue et al., 2014). The mechanical and insulating properties have been studied by other authors with the aim of producing bioplastics and other composites (Ferrero et al., 2013; Puglia et al., 2014; Garcia et al., 2017).

Many researchers have studied the effect of the incorporation of *Posidonia oceanica* fibers on the variation of density, compressive strength, flexural strength and thermal conductivity of the mixtures obtained. Hamdaoui et al. (2018) have studied the thermophysical properties of *Posidonia oceanica* natural fibers in order to investigate the potential of their use as loose-fill thermal insulation material in the Mediterranean construction. They showed that the fibers could be a promising ecological loose-fill insulation material in the building field because of their renewability and availability. They have also found that *Posidonia ocenica* fibers have thermal properties comparable to those of industrial insulation materials, mainly high mass heat capacity.

Kuqo et al. (2018) have experimentally investigated the influence of *Posidonia oceanica* fibers in the preparation of lightweight concrete. They found that fibers possess very interesting properties, such as fire resistance, moisture resistance and thermal resistance and can serve as a raw material for the production of composites at a very low cost.

Allegue et al. (2014) have experimentally investigated the influence of *Posidonia oceanica* fibers on the mechanical properties of cement. The authors confirmed that *Posidonia* fiber-reinforced cementitious composites have better flexural strength, higher ductility and lower density than conventional cementitious materials. They have also found that optimal mechanical properties are achieved when 5-10% volume fraction of *Posidonia* fibers is used at a W/C ratio equal to 0.5.

In the study of Khiari et al. (2011), new lignocellulosic particles obtained from *Posidonia oceanica* were studied to reinforce a commercial biodegradable thermoplastic matrix. These reinforcing fillers were used to prepare several composite films using BIOPLAST GF 106 matrix. Different *Posidonia oceanica* fragment loadings; namely, 0%, 10%, 20% and 30% were investigated. The authors showed that *Posidonia oceanica* -based particles enhanced the thermo-mechanical properties of the thermoplastic matrix.

Manjit et al. (1992) studied the strengthening of plasterboard with sisal fibers to replace wooden panels on doors. Plates are made by a sandwich mixture of a layer of short sisal fibers, 5 cm long, not oriented, between two layers of 66% tempered plaster. The results showed that the panels exhibit good resistance after 28 days of exposure to humidity, which they holding in water for the same time without being eroded. The flexural strength obtained after 28 days of exposure is higher than those of plasterboard and fibrous plasterboard and is comparable to that of glued cement boards and other particle boards. Boustingorry et al. (2005) studied the resistance to screwing of plasterboards reinforced with wood fibers. They mixed the wood fragments and the semihydrate powder manually in water. Their work revealed that plaster reinforced with wood fibers reacts differently to bending stress compared to unreinforced plaster. The presence of wood fibers gives it appreciable resistance to the propagation of the crack. The reinforced defibrated wood plate offers better resistance to tearing off a screw than the unreinforced one. In the experimental study of Eve et al. (2007), the plaster was reinforced by adding polymer fibers. The results revealed that the plaster mixture of polymer fibers (polyamide, polypropylene) confers an increase in the porosity of the composite and leads to a reduction of stresses at the break in bending as well as in compression.

This paper presents a new idea for formulating mixtures composed of plaster and fibers of *Posidonia oceanica* in order to manufacture an insulating and ecological material. Mechanical compression and bending tests were carried out as well as thermal tests to assess thermal conductivity and thermal diffusivity of the mixtures.

The Construction Industry and Environmental Sustainability

In 2005, around 25 million m^3 of insulating materials with a natural insulation content of around 5% were consumed in the construction area, while the consumption of European insulation was 77 million m^3. In the automotive industry, approximately 91,000 tons of natural fibers are used each year. Due to the environmental benefits (CO_2 neutrality, renewable energy, potential circulation), the use of biogenic fibers is expected to increase in both areas. In the construction sector, unlike the downward trend in construction activity, more insulation materials are used for insulation in the existing building sector. On the other hand, the proportion of fiber biogens is increasing. For these fibers, annual growth rates of up to 15% are expected by 2025 in the coming years, then around 5% by Fraunhofer ISI. Higher raw material and energy prices also supported the entry of other materials into the automotive sector, where additional potential is expected to be at least 100,000 tons/year of natural fiber inputs.

The fibers of *Posidonia oceanica* occupy a special position compared to other natural fibers, because they are not produced by agricultural or forestry processes. As a marine product, fiber in no way competes for land or use in food production, so it has better environmental performance than any other previous natural fiber. However, this singularity is currently not used due to the absence of techniques for producing new materials from these fibers. Research and development steps are therefore necessary to support the growing market for natural fiber applications.

EXPERIMENTAL STUDY

Materials Used

Plaster

The plaster used is semi-hydrate β "β-HH" of formula ($CaSO_4$, $\frac{1}{2}H_2O$) pure, white in color. It is produced according to an indirect cooking process from natural gypsum with a title greater than 94%, resulting from the formation of MESTAOUA gypsum in the south of Tunisia according to standard NF EN 13279-1 (EN 13279-1, 2008). The physical and mechanical characteristics of the plaster used are given in Table 1.

Table 1. Physical and mechanical characteristics of the plaster used

Properties	Values	
Purity	> 94%	
Density	1.05 g cm^{-3}	
Thermal conductivity	0.35 (W m^{-1} K^{-1}) (Aditya et al., 2017)	
Slump test	180 ± 10 (mm)	
Beginning of setting	7- 8 (mn)	
End of setting (Shore 40)	20 - 22 (mn)	
End of setting (Shore 60)	22 - 26 (mn)	
Mass heat capacity	1000 (J kg^{-1} K^{-1})	
Flexural strength (N/mm²)	2h	7days
	> 1.5	> 3
Surface hardness (N/mm²)	2h	7days
	> 4	> 10
Sieve size	Refusal at 200µm	Refusal at 100µm
	≤ 1%	≤ 10%

Hemi-hydrate gypsum plaster β has a porous structure. Its microstructure consists of crystals in the form of tangled needles or platelets as observed with a scanning electron microscope (SEM). The presence of voids is observable in the images, indicating its high porosity (Fig. 1).

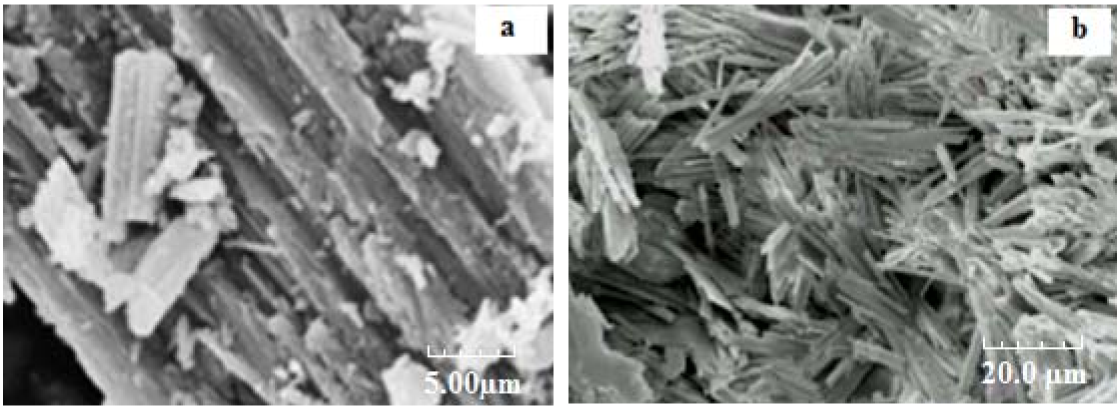

Figure (1) (a) SEM image of hemi-hydrate plaster β and (b) SEM image of a tangle of plaster crystals

Posidonia oceanica **Fibers**

Posidonia oceanica is an underwater plant found on beaches in the form of balls, which are agglomerates of fibers (Fig. 2 (a)). *Posidonia* balls were collected in the fall from Monastir Bay (Tunisia). They were mechanically ground to extract the fibers (Fig. 2 (b)). Then, these fibers were thoroughly washed with water to remove sand and other impurities. Finally, they were dried in an oven at a temperature of 30 °C for 48 hours and stored under normal conditions (temperature: 20 °C ± 5 °C, relative humidity RH: 60% ± 5%).

Figure 2: (a) Bundles of *Posidonia oceanica* leaves, (b) *Posidonia oceanica* balls and (c) *Posidonia oceanica* fibers

The moisture content related to the mass of *Posidonia oceanica* fibers was determined in accordance with the standard EN ISO 12570 (EN ISO 12570, 2000), from the mass of the specimen before and after drying at 105°C. According to this calculation, the moisture content was just under 10%. This value is similar to that of other natural fibers, such as cotton or hemp.

The density of *Posidonia oceanica* fibers has been determined. The physical characteristics of the fibers used are given in Table 2.

Table 2. Physical characteristics of *Posidonia oceanica* fibers (Kudo et al., 2018)

Properties	Values
Thermal conductivity λ ($W.m^{-1}.K^{-1}$)	0.04 - 0.07
Mass heat capacity C_P ($J.kg^{-1}.K^{-1}$)	2500
Density ρ ($g.cm^{-3}$)	0.35

Posidonia Oceanica fibers can be considered as natural composites consisting essentially of cellulose fibrils (48.40%), held together by a matrix composed mainly of lignin (23.12%) and hemicellulose (18.90%).

Raw *Posidonia* fiber is composed of several fibrils or technical fibers partially linked together by a weak pectin and lignin interphase. Cross sections made on a number of fibrils indicate the existence of empty, hollow spaces.

Experimental Program

Fibers of *Posidonia oceanica* were mixed with plaster with fiber volume fractions ranging from 0 to 20%. The physical and mechanical characteristics of the mixtures obtained were determined. Table 3 shows the shapes and dimensions of the test specimens as well as the adopted standard test methods.

Table 3. Shapes and dimensions of tested specimens

Test	Shape of specimens	Number	Dimensions of specimens	Standard
Compressive strength	Prismatic	30	40 x 40 x 160 mm^3	EN 13279-2
flexural strength	Prismatic	30	40 x 40 x 160 mm^3	NF P 18-433
Thermal conductivity	Parallelepipedic	15	270 x 270 x 40 mm^3	EN ISO 8990
Thermal diffusivity	Parallelepipedic	15	270 x 270 x 40 mm^3	EN ISO 8990

The amount of water used is not constant for all mixtures. It essentially depends on the amount of fiber added. In fact, the addition of fibers considerably modified the workability of the mixture, because they have the capacity of water absorption.

The various mixtures for the preparation of the various parallelepiped and prismatic specimens were prepared by varying the percentage of fiber with percentages of 0%, 2%, 5%, 10%, 15% and 20%.

Mixing was carried out mechanically at low speed with clean equipment. The plaster was slowly sprinkled with water and let to sit for a minute. Then, the mixture was kneaded with beating for two minutes. Finally, the fibers of *Posidonia oceanica* were poured into the mixture and kneaded for two minutes until a homogeneous mixture was obtained.

The molds were carefully cleaned of all impurities. A layer of liquid soap was applied to the interior surfaces of the molds to facilitate demolding. The mixture obtained was poured into the molds before the flow time limit (7 minutes). Demolding was carried out 15 minutes after pouring and the test pieces were kept in the laboratory until the date of testing.

The plaster bags were kept away from moisture in a dry place and stored without direct contact with the ground. Open or partially used plaster bags have been carefully folded and closed. The density of the samples was determined from the measurement of their dimensions and weights. A Sartorius TM precision balance with a resolution of 10^{-5} g was used for the determination of weights.

The water/plaster ratio (noted R) was determined according to the standard EN 13279-2 (EN 13279-2, 2014) by the sprinkling method. This involves pouring 100ml of water into a 250 ml beaker, then taring it on a technical scale. The plaster is sprinkled in the beaker for 30 seconds until the plaster level is 50 ml and during the second 30 seconds reaches 100 ml. The operation is continued until the amount of water is absorbed by plaster for the second minute. The R ratio was determined by the following formula (Eq. 1):

$$R = \frac{M_0}{M_1} \qquad (1)$$

where: M_0: mass of water (g) and M_1: mass of water and plaster (g).

The production of the plaster is carried out according to the mixing protocol described in the previous paragraph at the rate of mixing with demineralized water W/P equal to 1, without any additive, retarder or setting accelerator. At this mixing rate, the aqueous semi-hydrate solution is fairly fluid and hardens less quickly, which allows a better wettability of the fibers and provides reasonable maneuvering time during the processes. The choice of this ratio is also made mainly to have a product of high porosity in order to meet the objective of thermal comfort.

Porosity φ was determined by the micromeritics device by applying different pressure levels to a plaster sample immersed in mercury. The pressure required for mercury to penetrate the pores of the plaster sample is inversely proportional to the size of the pores.

The measured total porosity rate of plaster is around 62%, an expected increase compared to lower mixing rates, because it is established that the porosity of plaster increases with the mixing rate. The value of porosity as a function of the W/P mixing rate (R) has been theoretically established by the following formula (Eq. 2) (Sanahuja, 2008):

$$\varphi(\%) = \frac{R - 0.186}{R + 0.326} x100 \qquad (2)$$

By applying Eq. 2, the porosity of the plaster, mixed with the mixing ratio R equal to 1, is 61.4%, a value which is very close to the experimental value obtained.

EXPERIMENTAL TESTS

Three-point Bending Test

Three-point bending test was carried out on prismatic specimens of dimensions 40 x 40 x 160 mm^3 according to the standard NF P 18-433. The test inclues applying an increasing load to the middle of the specimen, simply supported at two points, until breaking to determine the maximum tensile stress at the level of the lower fiber. For each mixture, three specimens were made and tested at the age of 7 and 28 days. The flexural strength was calculated using the following formula (Eq. 3) :

$$R_f = \frac{3F_{max}L}{2bh^2} \qquad (3)$$

where: F_{max}: maximum bending force (N), L: distance between supports (cm) and b, h: width and height of the specimen (cm).

Compression Strength Test

Compressive strength test was carried out on the two halves of the prismatic specimen of dimensions 40 x 40 x 160 mm^3 (obtained from the bending test) according to the standard EN 13279-2 (EN 13279-2, 2014). The test consists of placing the test sample between the steel plates of the hydraulic press and applying a continuous load until the sample breaks. For each mixture, three samples were made and tested at the age of 7 and 28 days. Compressive strength was calculated using the following formula (Eq. 4):

$$R_C = \frac{F_C}{S} \qquad (4)$$

where R_C: compressive strength (MPa), F_C: maximum breaking load (kN) and S: sample section (cm^2).

Thermal Conductivity Measurement

Thermal conductivity for the mixtures was determined using parallelepiped specimens of dimensions 270 x 270 x 40 mm in accordance with the requirements of EN ISO 8990 (EN ISO 8990, 1996). The method used is the box method. It is based on using a device used in the laboratory of building physics that is capable of measuring thermal conductivity and thermal diffusivity of a material (Fig.3). The system consists of:

- Boxes B_1 and B_2: these boxes are isolated to prevent heat loss to the outside. A heating resistance is placed inside box B_1 to provide hot atmosphere.
- Enclosure: highly insulated chamber which provides cold atmosphere maintained at a temperature of θ = 4°C by a cooling system.
- Measuring strip: it displays the different values of temperatures sensed by temperature sensors made of platinum.

In steady state, thermal conductivity is calculated by the following formula (Eq. 5) (Kellati et al., 2000) :

$$\lambda_{exp} = \frac{e}{S.(T_1 - T_2)}\left[\frac{V^2}{R} - C.(T_B - T_a)\right] \qquad (5)$$

where T_1-T_2: temperature difference between the hot side and the cold side of the sample (K), T_B-T_a: temperature difference between the inside and the outside of the box (K), S: sample section (m^2), e: sample thickness (m), V: potential difference (V), R: resistance (Ω) and C: coefficient of box losses (W K^{-1}).

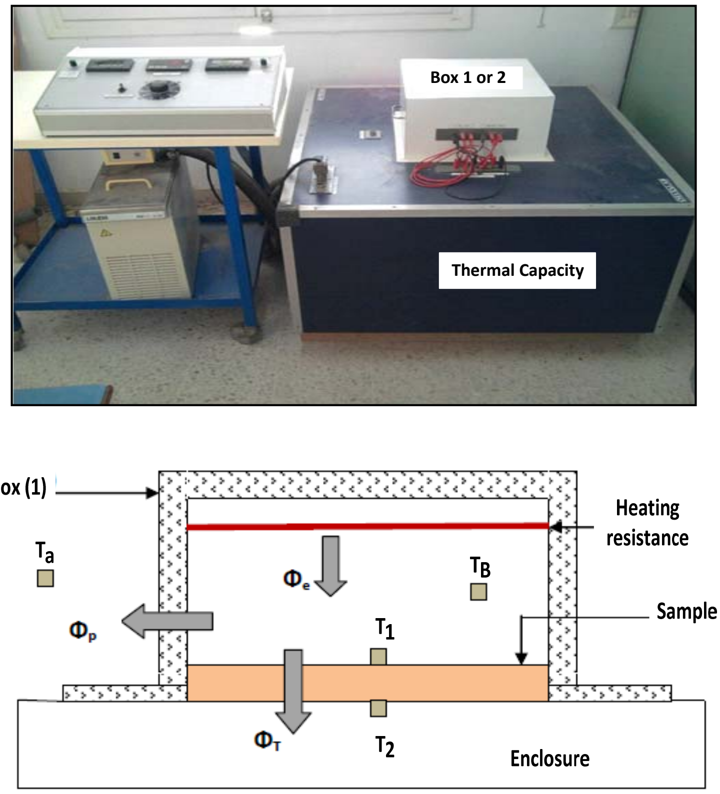

Figure (3): Thermal conductivity testing device

Thermal Diffusivity Measurement

The thermal diffusivity measurement apparatus used in this study is the same as that used for thermal conductivity measurement. In addition, box (2) is fitted with an incandescent lamp of 1000 W at its superior face instead of the heating resistance (Fig. 4). The internal faces of the box are reflective in order to homogenize the flow on the irradiated face of the sample.

The principle of the experimental measurement method is to emit a heat flux, for a few seconds, by means of the lamp, on one face of the sample and then, thermal diffusivity is evaluated from the temperature variation of the non-irradiated face of the sample (Degiovanni, 1998). Using Degiovanni model based on the part-time method (Taoukil et al., 2012), thermal diffusivity is given as follows:

$$\alpha = \frac{\alpha_{1/2} + \alpha_{2/3} + \alpha_{1/3}}{3} \qquad (6)$$

where:

$$\alpha_{1/2} = e^2\left[\frac{0.761t_{5/6} - 0.926t_{1/2}}{(t_{5/6})^2}\right] \qquad (7)$$

$$\alpha_{2/3} = e^2\left[\frac{1.150t_{5/6} - 1.250t_{2/3}}{(t_{5/6})^2}\right] \qquad (8)$$

$$\alpha_{1/3} = e^2\left[\frac{0.617t_{5/6} - 0.862t_{1/3}}{(t_{5/6})^2}\right] \qquad (9)$$

[$t_{i/j}$: the time corresponding to the ratio i/j of the maximum temperature (s)]

In the case where there is no generation of energy inside the system, thermal diffusivity is directly linked with other parameters by the following formula (Eq. 10):

$$\alpha = \frac{\lambda}{\rho \, . \, C_p} \qquad (10)$$

where: λ: thermal conductivity (W m^{-1} K^{-1}), ρ: density (kg m^{-3}) and C_p: mass heat capacity (J kg^{-1} K^{-1}).

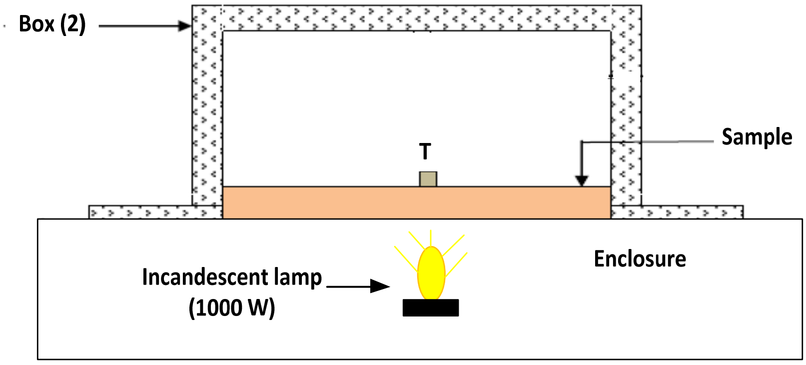

Figure (4): Thermal diffusivity testing device

EXPERIMENTAL RESULTS AND DISCUSSION

Density

Fig. 5 gives the variation of density of the various mixtures as a function of the percentage of fibers measured after 28 days of hardening. It is noted that density decreases for a greater quantity of fibers of *posidonia* included in the matrix. This is due to the low density of the fibers (0.35g.cm^{-3}) compared to that of plaster and the appearance of air bubbles by the fibers during mixing. The density varies from 1.11 g.cm^{-3} for the mixture containing 0% of the fiber up to 0.66 g.cm^{-3} for the mixture containing 20% of the fiber; a decrease of 40% was noted. In addition, it seems that the addition of fibers increases the number of voids and pores in the mixtures, which has a positive effect on the properties of the materials, as they can now be considered lighter materials.

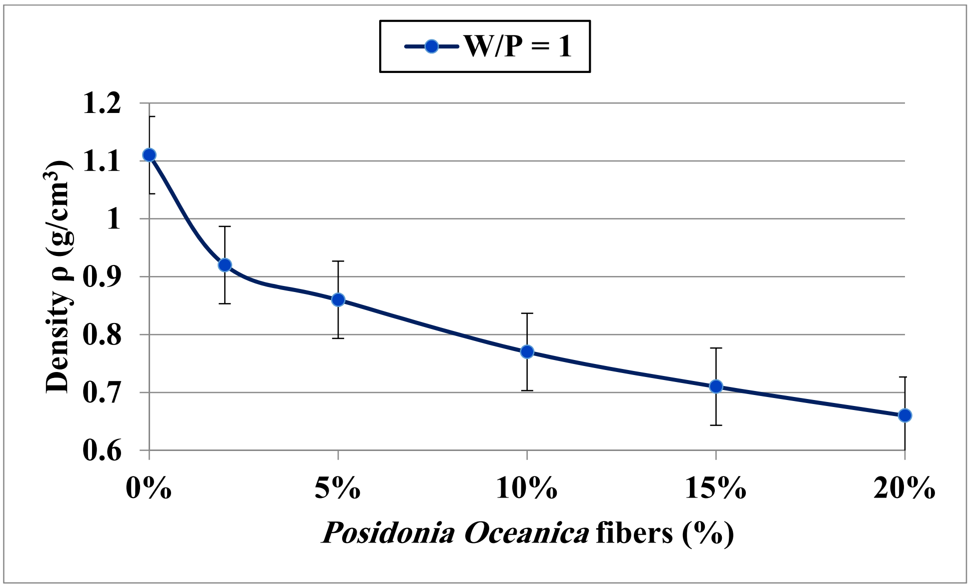

Figure (5): Effect of *Posidonia oceanica* fibers on the density of mixtures for W/P = 1

Flexural Strength

Fig. 6 shows the evolution of flexural strength obtained from three-point flexural test for a fiber content varying from 0 to 20%.

During three-point bending test, a significant difference in the behavior of the samples with and without added fibers was observed. Indeed, the plaster control sample was cracked at the point of maximum stress and then divided into two halves. On the other hand, the sample containing *Posidonia oceanica* fibers exhibited considerably greater flexibility and significantly greater deformation. After the bending test, the specimens containing *Posidonia oceanica* fibers were manually broken into halves. Both sides of the specimen were cleaned of all impurities for further testing.

According to the results, there is a regular increase in flexural strength by the addition of *posidonia* fibers which reaches its maximum for a value of 10% by volume of fibers. This increase can be explained by the increase in the number of fiber -matrix interfaces. Above this value, flexural strength decreases. This property has already been observed for composites with an organic matrix (Lee et al., 2000; Swamy et al., 1974), where flexural strength of fiber-reinforced concrete increases with fiber length and content. Above a certain critical value, flexural strength decreases rapidly. In the study carried out by Allegue et al. (2014), the addition of *posidonia* fibers in the cement composite considerably improves the flexural strength for mixtures containing 20% by volume of fibers. Indeed, flexural strength–strain curves for *Posidonia*–cement composite samples presents two main regions: a linear region, whitch resembles that of the cement sample and a region corresponding the reaching maximal flexural load, where the load gradually decreases with the propagation of the crack.

Flexural strength generally increases with fiber content to a state in which mixing becomes difficult. Thus, homogenization of this mixture becomes difficult, as the fibers cannot be bound by the matrix and shrink. This results in an increase in the porosity of the composite and less fiber-matrix cohesion.

In the experimental study conducted by Kuqo et al. (2018), flexural strength varied from 9.41 MPa for the sample without fibers to 4.14 MPa for the sample with the maximum amount of fibers. Flexural strength decreases exponentially with the volume fraction of fibers.

In a study conducted by Hamza et al. (2013) on Tunisian plant fibers and its utilization as reinforcement for plaster-based composites, the authors observed a drop in flexual strength for high reinforcing fiber amounts. This could be explained by the creation of porosity in the material due to an intra-and extra-fiber emptiness, which reduces the composite compactness and cohesion. Flexural strength shows a modest improvement in the strength of the fiber-reinforced samples for additions between 5% and 7% by volume. The fibers have brought lightness to the plaster and changes in behavior even if they are added in small quantities.

Several parameters can influence flexural strength, such as quality, length and orientation of the fibers. According to Morlier and Khenfer (1991), the flexural strength considerably increases with the growth of the length of the fibers, which influences the mode of rupture of the test pieces. Indeed, for fibers of great lengths, the break is ductile and stable. On the contrary, for fibers of short lengths, the break is weak and unstable with a sudden drop in value. According to the experimental study conducted by Djoudi et al. (2012), flexural strength considerably increases with length of the fibers. A maximal increase was achieved for different lengths and for a dosage of 1.5% of fiber, especially for 30 mm fiber length. A loss of flexural strength was recorded for a 2% fiber dosage due to excess fiber and poor distribution of the fibers in the matrix. Flexural strength increases with increasing fiber length.

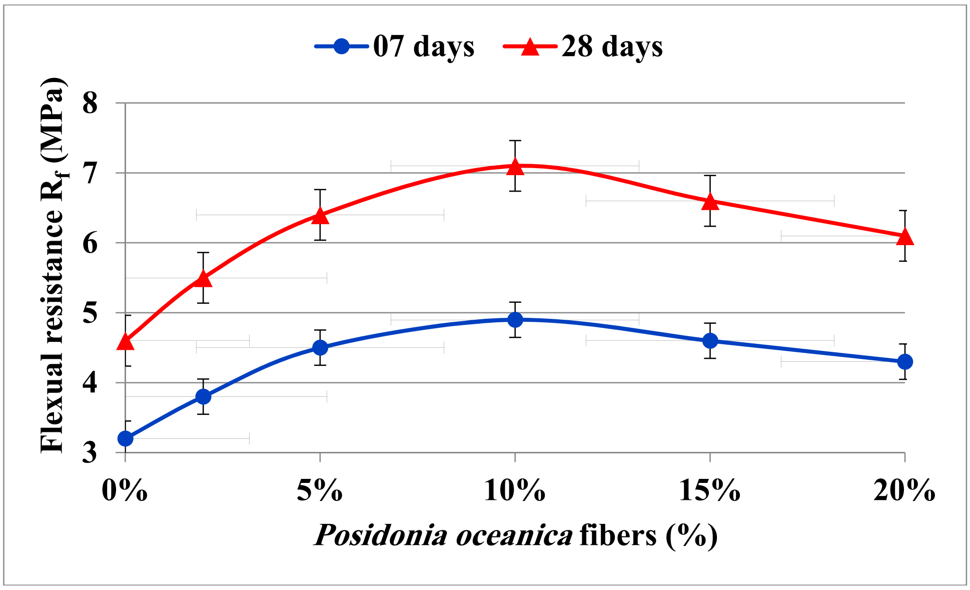

Figure (6): Effect of *Posidonia oceanica* fibers on the flexual strength of mixtures at the age of 7 and 28 days

Compressive Strength

Fig. 7 presents the results of the mean values of compressive strength at the ages of 7 and 28 days using compression tests for a fiber content ranging from 0 to 20% by volume. Compression tests show that the compressive strength at 28 days can reach a value of around 14.80 MPa for a W/P ratio equal to 1. Compressive strength was significantly improved by the addition of *posidonia* fibers and reached a maximum for the addition of 5% by volume of fibers. Above this value, compressive strength decreases slightly as the fiber content increases. This is due to the higher porosity of the mixture and therefore the reduction in fiber-matrix cohesion. The compressive strength reached 70% of its final value at the age of 07 days, then it increased slowly until the age of 28 days.

According to Djoudi et al. (2012), the increase in fiber mass dosage increases the compressive strength of fibrous plaster concrete, which reaches its maximum for the value of 1.5% of fibers. Then, compressive strength gradually decreases because of the decrease in the workability of the mixtures and the excess of fibers in the matrix. The same results were found in the experimental study of Rachedi et al. (2017) carried out on plaster mortar samples reinforced with date palm fibers. A slight increase in compressive strength was noticed for a dosage between 0% and 1% of fibers. Then, compressive strength increases rapidly to its maximum for a dosage of 1.5% in fibers. Thereafter, compressive strength gradually decreases for a fiber dosage greater than 1.5%. According to the same authors, this decrease in compressive strength can be explained by the addition of a large amount of fiber, which disturbs the mineral mortar skeleton by creating voids inside the dough and increasing its porosity. Mangat and Azari (1984) have shown that the orientation of the fibers and their correct arrangement in relation to the applied force considerably influence the values of compressive strength.

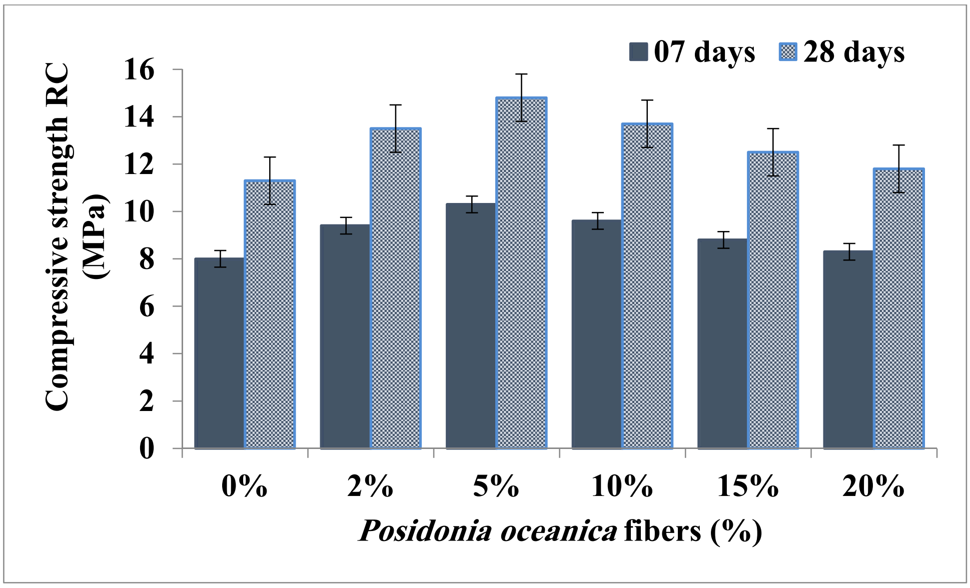

Figure (7): Effect of *Posidonia oceanica* fibers on the compressive strength of mixtures at the age of 7 and 28 days

Thermal Conductivity

A thermal insulator is a material with low thermal conductivity. This type of material has the characteristic of slowing down heat exchange between the interior and the exterior of a building. The characterization of a thermal insulator therefore amounts to measuring one of the thermal properties listed on the material. Thermal conductivity λ is the most measured property.

Thermal conductivity was experimentally determined for parallelepipedic specimens of dimensions 270 x 270 x 40 mm^3 at the age of 28 days. The results of thermal measurements obtained experimentally by the box method are presented in Fig. 8.

The results show that the addition of *Posidonia oceanica* fibers considerably reduces thermal conductivity of different mixtures from 0.35 W.m^{-1}.K^{-1} to 0.11 W.m^{-1}.K^{-1}. For the replacement percentages of 2%, 5%, 10%, 15% and 20%, the reductions in thermal conductivity were 9.6%, 17.7%, 43.5%, 67.7% and 79%, respectively, compared to control samples. This decrease can be explained by the microstructure of the mixtures. Indeed, air is trapped between the fibers causing an increase in air content.

As thermal conductivity of air (0.025 W m^{-1} K^{-1}) is lower than that of plaster (0.35 Wm^{-1} K^{-1}), air voids prevent heat transfer through mixtures. In addition, fibers of *Posidonia oceanica* also limit heat flow, because the thermal conductivity of the fibers is much lower than that of plaster. The experimental results also show that heat –insulating efficiency of a material is opposite to its density. Regression results in Fig. 8 and Eq. (11) show that the thermal conductivity λ is exponential correlated with the volume of *Posidonia oceanica* fibers (PF), where k is the rate of change. The correlation coefficient (R^2) is almost 100%.

$$\lambda_{(PF)} = \lambda_{(0)} e^{k.PF} \qquad R^2 = 0.994 \tag{11}$$

Djoudi et al. (2012), have studied the variation in thermal conductivity for concrete plaster reinforced with fiber content (% by mass) and for different fiber lengths. They found that thermal conductivity measured at the age of 28 days decreases with increasing fiber dosage and increases with increasing fiber length. This improvement in thermal insulation is mainly due to the increase in voids generated by the packing of fibers. Indeed, for a given fiber content, the production of voids by short fibers is much higher than that by longer fibers which are more difficult to align and pack densely (Morrissey et al., 1985).

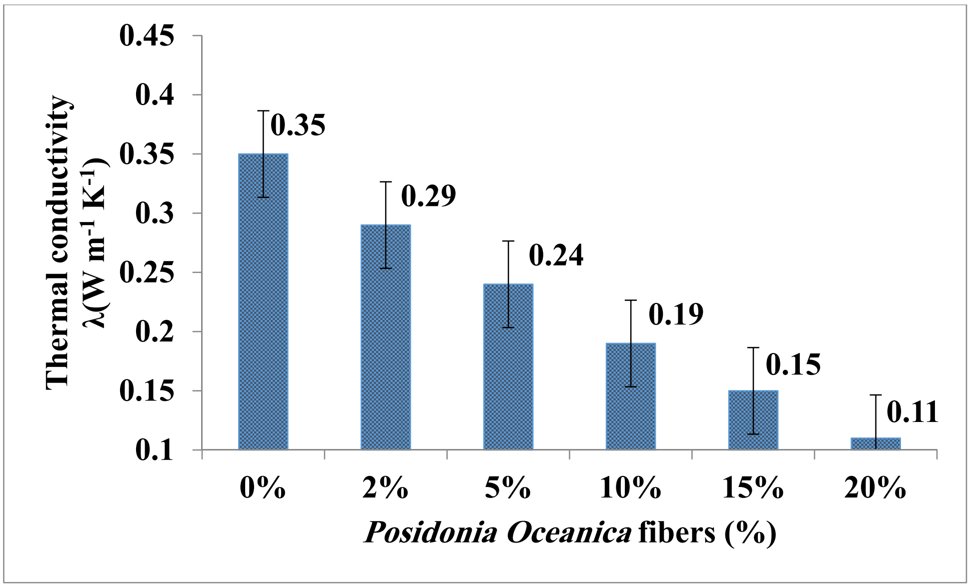

Figure (8): Effect of *Posidonia oceanica* fibers on the thermal conductivity of mixtures at the age of 28 days

Thermal Diffusivity

Thermal diffusivity (α) expresses the ability of a material to rapidly transmit a change in temperature. It is the rate at which heat propagates by conduction in a material. Thermal diffusivity was experimentally determined in parallelpipedic specimens of dimensions 270 x 270 x 40 mm^3 at the age of 28 days. The results of thermal measurements experimentally obtained by the box method are presented in Fig. 9. According to the results, it can be seen that the incorporation of *Posidonia oceanica* fibers has considerably reduced thermal diffusivity and therefore improved the thermal insulation of different mixtures. For example, adding 2% and 5% fiber produced a reduction of 8.80% and 20.12%, respectively, in thermal diffusivity.

The lower the value of thermal diffusivity, the longer it will take for heat front to pass through the thickness of the specimen. Therefore, the time between the moment when the heat arrives at a surface and the moment when it reaches the other side is important. The results also show that thermal diffusivity of plaster experimentally obtained is around 3.18 $10^{-7}m^2\ s^{-1}$. This value is consistent with the value calculated from the parameters (thermal conductivity, specific heat and density) of Eq. 10 and with the values reported in the literature (between 3. $10^{-7}m^2\ s^{-1}$ and 3.73 $10^{-7}m^2\ s^{-1}$). Compliance validates the measurement method.

In the experimental study of Elbenda (2012), a reinforced plasterboard sisal fiber oriented [0°/90°/45°/-45°] following four layers was prepared. The measurements of thermal diffusivity of the samples gave an average value of 2.77 $10^{-7}m^2\ s^{-1}$; there is a fall in thermal diffusivity of plaster due to the presence of fibers. This result was already mentioned in a contribution by Thomason et al. (2011), reporting a coefficient of thermal diffusivity of plaster reinforced with tow equal to 2.07 $10^{-7}m^2\ s^{-1}$.

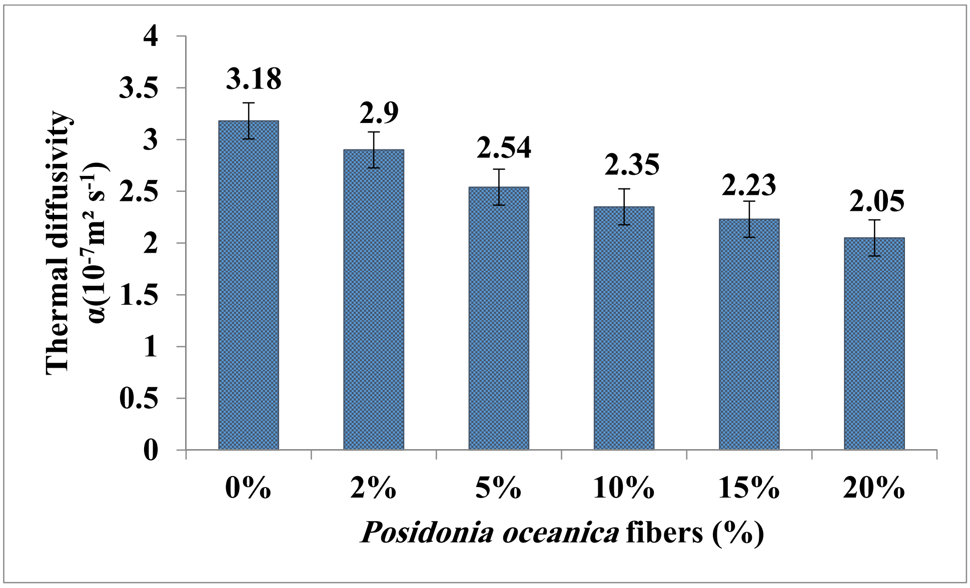

Figure (9): Effect of *Posidonia oceanica* fibers on the thermal diffusivity of mixtures at the age of 28 days

CONCLUSIONS

The current paper presented the results of an experimental study on the effect of *Posidonia oceanica* fibers on the mechanical and thermophysical properties of plaster. Compressive and flexural strengths have been determined. Thereafter, thermal conductivity and thermal diffusivity of the various mixtures were determined by the box method. According to the experimental results, the following conclusions have been drawn :

1. The addition of *Posidonia oceanica* fibers can decrease the density of mixtures up to 40%.
2. A clear improvement in the mechanical properties has been observed, especially for volume replacements between 5% and 10%.
3. Thermal conductivity has been decreased from 0.35 $W.m^{-1}.K^{-1}$ to 0.11 $W.m^{-1}.K^{-1}$. This reduction improves the thermal insulation of the material.
4. In view of the efficiency of interaction between the fibers and the matrix, this new composite formed by *Posidonia oceanica* fibers and plaster could be used as a thermal insulator and to save energy.

In this experimental study, only certain properties of the mixtures of plaster and *Posidonia oceanica* fibers were studied. Further experimental research is recommended in order to study physical properties, such as water absorption and fire resistance. It is also important to study the behavior of mixtures with a pretreatment of *Posidonia oceanica* fibers and deduce the possibility of using the material for sound insulation.

Nomenclature			
λ	Thermal conductivity, W m^{-1} K^{-1}	M_1	Mass of water and plaster, g
α	Thermal diffusivity, m^2 s^{-1}	RH	Relative humidity
C_P	Mass heat capacity, J $kg^{-1}K^{-1}$	R	Water/plaster ratio
ρ	Density, g cm^{-3}	R_f	Flexural strength, MPa
M_0	Mass of water, g	R_C	Compressive srength, MPa

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