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Development of an Eco-material Based on Palmyra Aggregates

Valéry K. Doko[1], Edem Chabi[2*], Sena Peace Hounkpè[3] and Edmond C. Adjovi[1,4]

[1]Department of Civil Engineering, Polytechnic School of Abomey-Calavi, University of Abomey-Calavi, 01 BP 2009 Cotonou, Benin.
[2]Laboratory of Rural Engineering, National University of Agriculture, Kétou, Benin.
[3]Laboratory of Water Technical Sciences, University of Abomey-Calavi, Benin.
[4]Department of Civil Engineering, National University of Sciences, Technologies, Engineering and Mathematics, Abomey, Benin.

Authors' contributions

This work was carried out in collaboration among all authors. Author VKD designed the study, carried out the tests and presented the results. Author EC wrote the manuscript, supported by authors VKD and SPH in the discussion of the results. Author ECA provided his expertise and guided the research work. All authors read and approved the final manuscript.

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ABSTRACT

This study is part of a project to develop a bio-based material meeting the criteria of sustainable development in the field of construction. A study was then made on a cement matrix composite reinforced by aggregates of *Borassus aethopium mart* (palmyra).
For this purpose, studies of cement compatibility with this plant aggregate, the physical, mechanical and thermal behavior of the concrete were performed for two granular compositions. The compatibility study revealed that palmyra aggregrates, although not previously treated, are compatible with Portland-limestone cement. The characterization tests focused on the mechanical properties of three-point flexural tensile strength and compressive strength and thermal properties

**Corresponding author: E-mail: edem.chabi@gmail.com;*

such as effusivity, conductivity and diffusivity. The results obtained are promising: they have very good mechanical and thermal characteristics, considering its use in construction. The mechanical strengths reach 16.25 MPa for a density less than 1500 kg / m^3. The thermal conductivity varies between 0.270 and 0.415. They can be used for the manufacture of panels used in the realization of suspended ceilings and tiles for the realization of roofs.

Keywords: Bio-based material; sustainable development; palmyra aggregate; lightweight concrete.

1. INTRODUCTION

The evolution of the current world urges us all to rethink the modes of construction. In fact, today, the construction sector consumes a lot of energy. It is responsible for about a quarter of carbon dioxide emissions, not to mention the depletion of non-renewable resources. This sector must therefore innovate to limit its impact on the environment while ensuring user comfort. The construction materials used will thus play an important role both in the energy consumption during the use of the building (through their thermal performance) and in the CO_2 emissions (with the carbon impact of the raw materials used to manufacture them).

In this context, bio-based materials, materials derived in part from biomass, are increasingly developed and marketed in the building materials market. These materials, by their ecological character, make it possible to improve the environmental balance sheet of the construction process and that of the building in particular. Among the bio-based materials intended to be used in the building sector, vegetable concretes emerged with the objective of exploiting their thermal, acoustic and hygroscopic properties [1–8]. The local character of the plant by-product used is of great importance for the development of an ecomaterial. As part of this study, we used *Borassus aethiopum mart* (palmyra) as a vegetal aggregate.

Borassus aethiopum also known as the African Fan palm, is a species of palm found in much of tropical Africa, classified as a priority plant in sub-Saharan Africa by FAO experts [9]. It is a renewable resource that produces rot service and termite-resistant wood with a low rate of water absorption of aggregates. All parts of the palmyra (stipe, leaves, petiole, terminal bud, fruits, roots etc.) are usable. Its leaves are used to make containers (vans, baskets, bags), furniture (chairs, beds, mats), roofing and various art objects. Sap from *Borassus aethiopum* serves as palm wine, fresh drink, vinegar and sugar. The roots are used in traditional medicine and weaving nets. As for its petioles, they are used for fencing, making hedges, farm building partitions and firewood. The stipe is used as lumber and construction (framework, floors, beams, pillars). Palmyra is also used as reinforcement in concrete beams because it has a high tensile strength and modulus of elasticity close to those of steel with a longitudinal shrinkage rate [10–12] (Fig. 1). As for the use of palmyra aggregates in concrete, no major research has been conducted.

Fig. 1. Palmyra reinforcement for concrete

2. MATERIALS AND METHODS

2.1 Palmyra Aggregates

The aggregates used are obtained from the direct transformation of the stipe (trunk of the rônier) (Fig. 2). To avoid the possible consequences due to the origins of aggregates, those used in this study are all from the same tree.

From these four classes, two types of mixtures were reconstructed: Fine mixture (MF) and coarse mixture (MC). The particle size analysis test was done on both mixtures (Fig. 3).

The physical characteristics of palmyra aggregates are summarized in Table 1.

2.2 Binder

The binder used in this study is a CEM II B-LL 32.5 R.

Table 2 presents the physical and mechanical characteristics of this cement.

2.3 Mix Design

Table 3 shows the proportions of mixtures.

Fig. 2. Aspect of aggregates

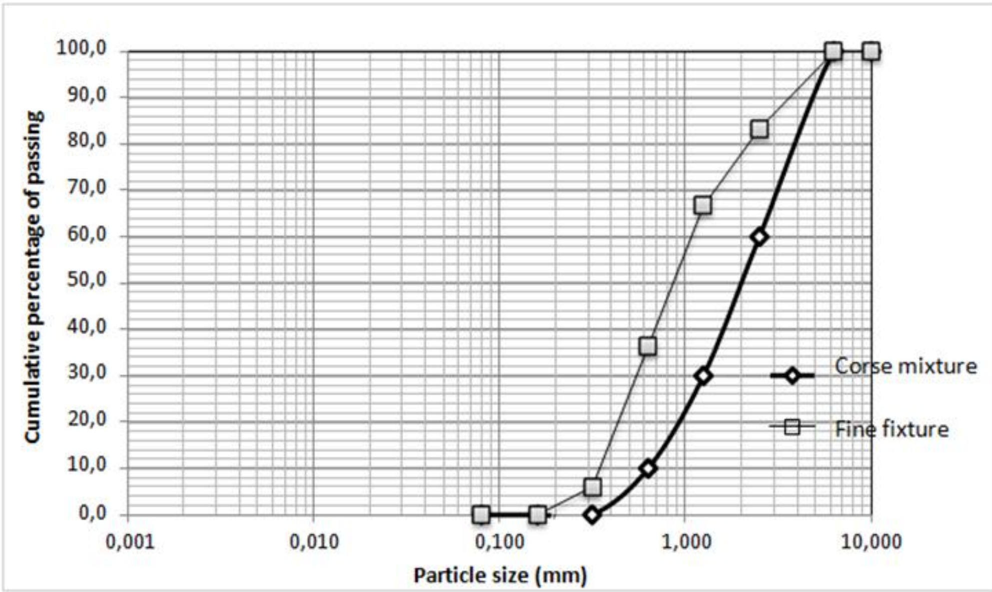

Fig. 3. Particle size curves of fine and coarse mixtures

Table 1. Physical characteristics of palmyra aggregates

Granular compositions	Bulk density (kg/m^3)	True density (kg/m^3)	Absorption rate (%)
Coarse mixture	180	687	10.20
Fine mixture	260	771	10.50

Table 2. Physical and mechanical characteristics of the cement

Density (g/cm^3)	3.01
Blaine value (cm^2/g)	3155
Initial setting time (min)	185
Expansion (mm)	1.5
Compressive strength at 2 days (MPa)	13.2
Compressive strength at 7 days (MPa)	24.2
Compressive strength at 28 days (MPa)	33

3. THEORY/CALCULATION

3.1 Compatibility Study

The problem of compatibility is often mentioned when it comes to composites that combine cement with a material that may contain organic substances. In this study, the method used is the isothermal calorimetry method to evaluate the compatibility between palmyra and cement (Fig. 4). It consists in following the speed of hydration of the cement through the quantity of heat released during the reaction.

The machine used in the study for measuring the heat of hydration of cement is essentially a schematic hydration heat measurement device as shown in Fig. 4. It consists of:

a calorimeter made of a large adiabatic enclosure with three compartments of 25 x 45 x35 cm^3;

three adiabatic enclosures (thermos), placed in each of the compartments, allowing the taking of three simultaneous measurements; three small plastic containers (jars);

three K type thermocouples, immersed in the samples and connected to a data acquisition device that makes it possible to simultaneously take several temperature measurements inside the calorimeter;

Table 3. Mix design parameter

Cement dosage (kg/m^3)	**Granulometry**	**C/PA**	**W/C**	**Nomenclature**
D1 = 400	Fine mixture	2.2	0.50	MF-D1-E0.50
			0.60	MF-D1-E0.60
			0.70	MF-D1-E0.70
	Coarse mixture	1.9	0.50	MC-D1-E0.50
			0.60	MC-D1-E0.60
			0.70	MC-D1-E0.70
D2 = 450	Coarse mixture	3.6	0.40	MF-D2-E0.40
			0.45	MF-D2-E0.45
			0.50	MF-D2-E0.50
	Coarse mixture	3.2	0.40	MC-D2-E0.40
			0.45	MC-D2-E0.45
			0.50	MC-D2-E0.50
D3 = 500	Coarse mixture	4.4	0.35	MF-D3-E0.35
			0.40	MF-D3-E0.40
			0.45	MF-D3-E0.45
	Coarse mixture	4.0	0.30	MC-D3-E0.30
			0.35	MC-D3-E0.35
			0.40	MC-D3-E0.40

C : Cement ; PA : Palmyra aggregate; W : water

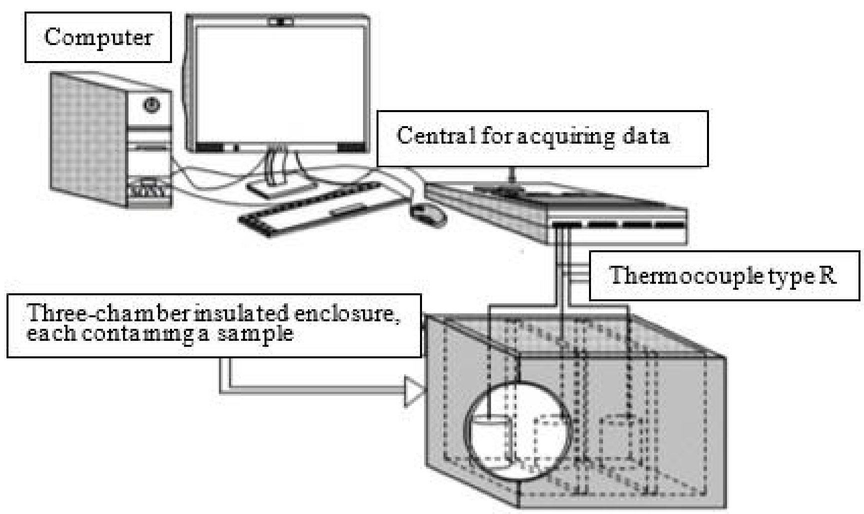

Fig. 4. Device for measuring the heat of hydration of cement

a precision scale weighing up to one gram;

a testo 177-T4 temperature recorder with four outputs.

The recorder is programmed to take temperatures every 15 minutes. The main hydration characteristics obtained after the test are: The maximum temperature (Tmax) reached during the hydration, the time (tm) set to reach this maximum temperature, the rate of hydration or kinetics (R) temperature rise (equation 1), the area (A) under the hydration curve and the degree of compatibility (CA) (equation 2). The area makes it possible to estimate the amount of heat released during the hydration of the cement of a mixture (cement-water) given over a period of 24 hours considered sufficiently long to take into account all the phenomena of hydration. This area under the curve of temperature evolution as a function of time, is evaluated by the trapezoidal method.

$$R\ (°C/h) = \frac{T_{max}-T_{min}}{T_m} \quad (1)$$

$$C_A = \frac{A}{A_t} \times 100 \quad (2)$$

With A and At connoting the respective areas under the time-heat curves in the composite and in the control. From the equation (2), the following comparison scale is proposed [13].

incompatible material: C_A < 28%;

moderately compatible material: 28% < C_A< 68%;

compatible material: C_A > 68%.

3.2 Implementation of Test Specimens and Characterization

For the preparation of the test pieces, metal molds measuring 4 cm x 4 cm x16 cm for the mechanical tests and 10 cm x 10 cm x 3 cm for the thermal tests were used.

The hot ribbon method was used for thermal characterization (Fig. 5). It is a device which has a rectangular-shaped electrical resistance is inserted between two identical samples of the material to be characterized. This is a technique that aims at measuring the conductivity and thermal effusivity of a material in its transient state.

4. RESULTS AND DISCUSSION

4.1 Compatibility Study

Fig. 6 shows the hydration curves of the pure cement paste as well as that of the mixture to which the palmyra was added. The amount of heat produced during the hydration of the cement of a mixture is equivalent to the area under the hydration curve of this mixture.

An analysis of the hydration curves makes it possible to identify three delimited zones. In the first zone which starts from zero to five hours, the speed of hydration of the cement in the mixture containing the palmyra is higher than that of the control. In the second zone between five hours and twenty-three hours, the rate of hydration returns to normal. Finally, the third zone, which starts from twenty-three hours to thirty-six hours, the speed of hydration is again reversed.

These variations, far from creating controversy as to the influence of biomass on the hydration of cement, only confirm the inhibition described by Hachmi [13].

The high speed observed in the first zone can be attributed to the amount of water in the cement-aggregate mixture greater than that of the control. Indeed, the water supplement favors the hydration reactions of the cement phases before they are slowed down by the chemical constituents of the aggregates. This zone also informs on the time necessary to trigger the extraction of biomass inhibiting substances in the cement matrix.

In the second zone, the two hydration curves evolve in the same way and the inhibitory effect of the presence of the biomass is clearly revealed. In addition, the amount of heat released peaks at 10 hours at the control mix and the palmyra-cement mix.

The slight increase in the hydration kinetics of the cement in the mixing of the aggregate in the third zone reflects a greater presence of the unreacted phases in the first two zones. This evolution of the curves thus confirms that the control mixture was better hydrated than those including the aggregate.

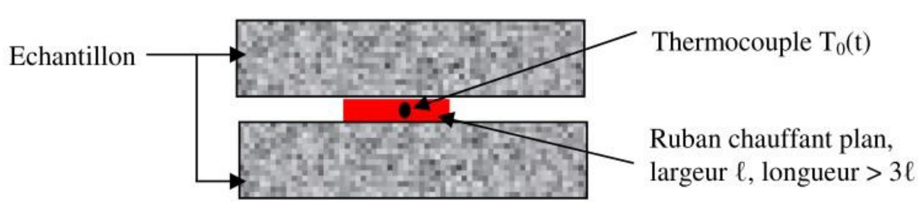

Fig. 5. Diagram of principle of assembly of the hot ribbon

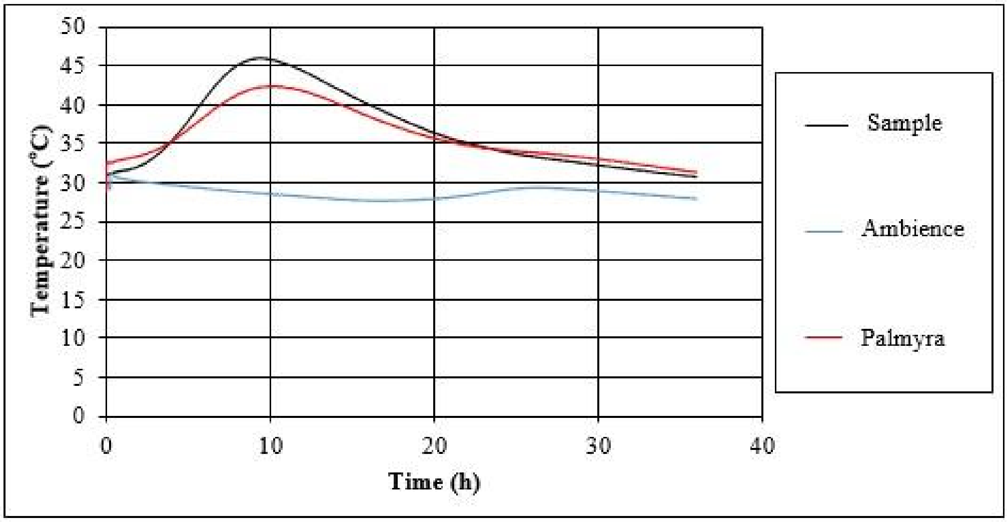

Fig. 6. Cement hydration curves in pure cement paste (sample) and in the presence of palmyra aggregate

Although the palmyra aggregate reduces the degree of hydration of the cement (reduction of the maximum temperature), it does not seem to have any significant effect on the time required to reach the maximum temperature. Table 4 summarizes the various characteristics of the hydration of the cement: The maximum temperature T_m, the time t_m set to reach this temperature, the hydration energy A, and the coefficient of hydration CA.

From the analysis of the table and considering the scales of comparison developed by Hachmi [13], it appears that palmyra aggregate is compatible with the cement (§ 3.1).

4.2 Microstructure of Palmyra Concrete

The figures (L) connote the lateral microscopic views and the figures (T) the transverse views (Fig. 7 and Fig. 8).

In general, two essential parts are observed: a white area that represents the binder (cement matrix) and a second black (palmyra aggregate).

Figures (L) show that the mixture of the binder with the reinforcement is not very homogeneous because of the color concentrations in certain places, which favors zones of weakness in the concrete.

As for the figures (T), the dominance of the white color signifies the strong presence of binder in the side walls of the composites. This phenomenon is explained by the fact that the binder during casting is drained by water to the walls which has also led us to optimize the W / C and not to proceed with a vibration during the implementation specimens, in order to avoid this phenomenon at best.

4.3 Mechanical Properties of Palmyra Concrete

The mechanical properties at 28 days are summarized in Table 5.

4.3.1 Mechanical behavior study

Fig. 9 shows the evolution of the applied loads as a function of the displacement recorded at the crosshead at the center of the specimen subjected to three-point bending.

Table 4. Hydration characteristics of mixtures

Type of mixture	Tm (°C)	tm (h)	A (kCal)	CA(%)
Sample (Cement + water)	46.0	9.38	0.245	100
Cement + water + palmyra	42.6	9.80	0.218	89.11

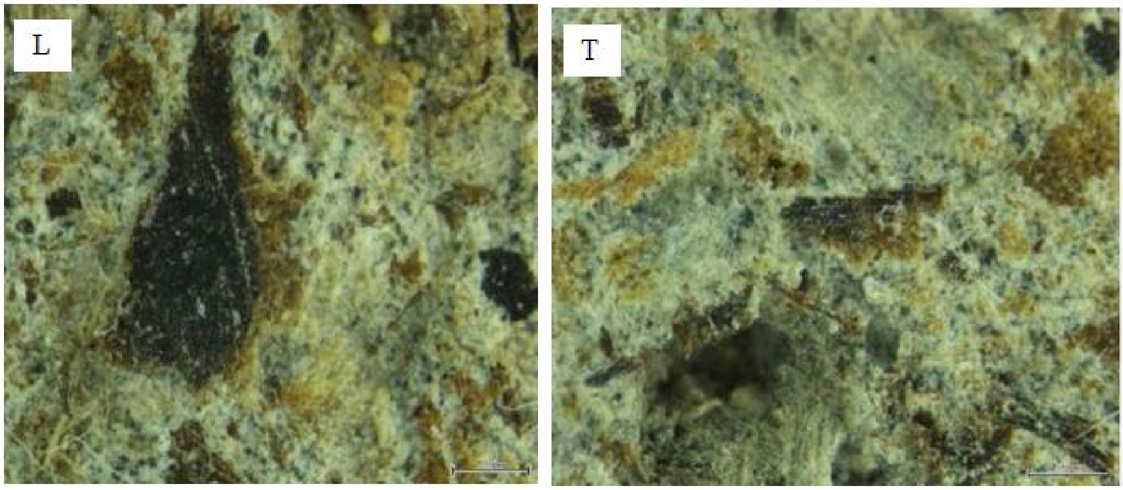

Fig. 7. Microstructure of palmyra aggregate concrete for fine mixture

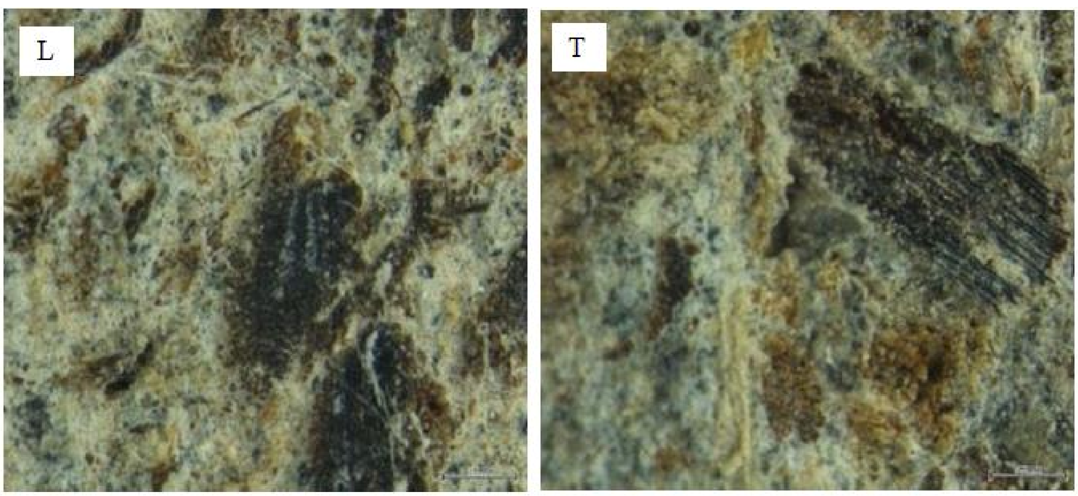

Fig. 8. Microstructure of the palmyra aggregate concrete for coarse mix

The behaviour presented by the palmyra concrete can be subdivided into two phases.

The first phase, characterized by a quasi-linear variation, precedes the peak of the curve. In this phase, the forces applied to the composite are taken up by the matrix before being transmitted to the palmyra. This load recovery also reflects a good adhesion to the cement-palmyra interface.

The second phase, post-peak, is characterized by a controlled and progressive fall of the load while the warp continues to increase. This area illustrates the ductility gain of the composite over the pure matrix. In fact, the comparison of the failure modes of the cement paste and the composite subjected to bending shows a total difference. It is noted that unlike the pure matrix, the cracking in the composites is slowed down by the presence of the palmyra. The behaviour of palmyra concrete stress in compression is similar to that of conventional concrete; however, the recorded deformations are higher. Fig. 10 shows the evolution of the compressive stress as a function of the relative strain.

The curve thus obtained (Fig. 10) can be subdivided into three zones representing the different phases characteristic of the behaviour of this type of concrete.

The first zone exhibits an almost linear variation of the stress as a function of the deformation.

The deformations recorded in this zone are weak; it can be assimilated to the linear phase of the behaviour of the composite. Its extent depends on the quality of the cement matrix.

In the second zone, there is a sudden increase in the deformation announcing the beginning of rupture of the matrix and the recovery of efforts by the palmyra until the complete rupture.

The last zone is characterized by a very high deformability of the composite. After the rupture of the matrix, the charges, even if weak, have the effect of driving out the voids present in the material; it therefore behaves like a cluster of particles.

4.4 Thermal Properties of Palmyra Aggregate Concrete

The thermal properties are directly related to the constituents, to the morphology of the environment (solid matrix and porous network) and to the interactions between the different types of transfers existing in the material. The insulating properties of building materials are quantified through three usual parameters: effusivity (E), thermal conductivity (λ) and diffusivity (a) (Table 6). These depend on the intrinsic characteristics of the constituents and the microstructure of the material.

4.4.1 Influence of cement dosage and granular composition on thermal effusivity

The thermal effusivity of a material characterizes its ability to exchange thermal energy with its environment. It characterizes the sensation of hot or cold that gives a material. If the effusivity value is high, the material quickly absorbs a lot of energy without noticeably heating up on the surface. Conversely, a low effusivity value indicates that the material heats up quickly on the surface, absorbing little heat.

Fig. 11 shows variations in thermal effusivity as a function of cement dosage and granular composition.

By focusing only on the effect of binder dosing, there is an increase in effusivity when the cement dosage increases in both types of mix. This can be interpreted by the fact that an increase in the cement dosage reduces the porosity of the materials, in other words the volume of air. However, still air has a low thermal effusivity. Thus reducing the pores in the material increases the thermal effusivity of this material.

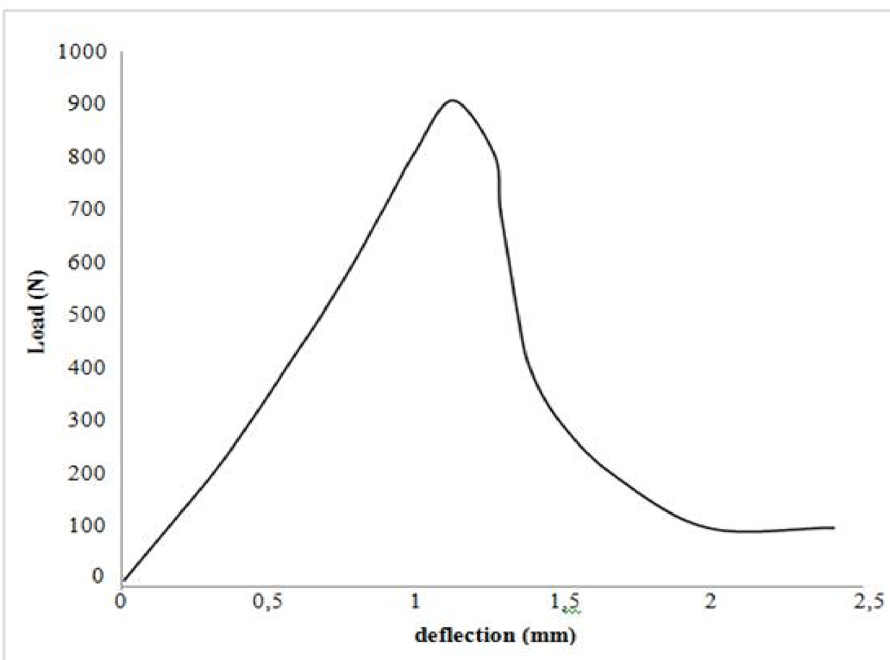

Fig. 9. Typical bending behaviour curve of the palmyra aggregate concrete

Table 5. Synthesis of mechanical characteristics

Cement dosage (kg/m^3)	Granulometry	C/PA	W/C	Density (kg/m^3)	Tensile strength (MPa)	Compressive strength (MPa)
D1 = 400	Fine mixture	2.2	0.50	1180	4.63 ± 0.22	6.18 ± 0.72
			0.60	1080	5.50 ± 0.43	6.84 ± 0.34
			0.70	980	4.00 ± 0.22	4.82 ± 0.30
	Coarse mixture	1.9	0.50	1190	2.38 ± 0.22	1.93 ± 0.12
			0.60	1060	3.63 ± 0.22	3.83 ± 0.14
			0.70	1030	1.75 ± 0.22	1.48 ± 0.14
	Fine mixture	3.6	0.40	1270	7.75±0.57	10.01±0.39
D2 = 450			0.45	1310	6.50±0.43	9.70±0.48
			0.50	1210	3.63±0.57	13.45±1.03
		3.2	0.40	1420	6.75±0.38	11.97±0.28
	Coarse mixture		0.45	1410	6.19±0.80	12.08±0.32
			0.50	1110	4.63±0.57	9.08±0.44
D3 = 500	Fine mixture	4.4	0.35	1420	7.63±0.22	15.52±0.72
			0.40	1380	6.50±0.43	14.09±0.34
			0.45	1290	5.50±0.22	12.23±0.30
	Coarse mixture	4.0	0.30	1470	8.38±0.43	14.43±0.61
			0.35	1440	7.75±0.57	16.26±0.45
			0.40	1380	7.25±0.22	15.13±0.68

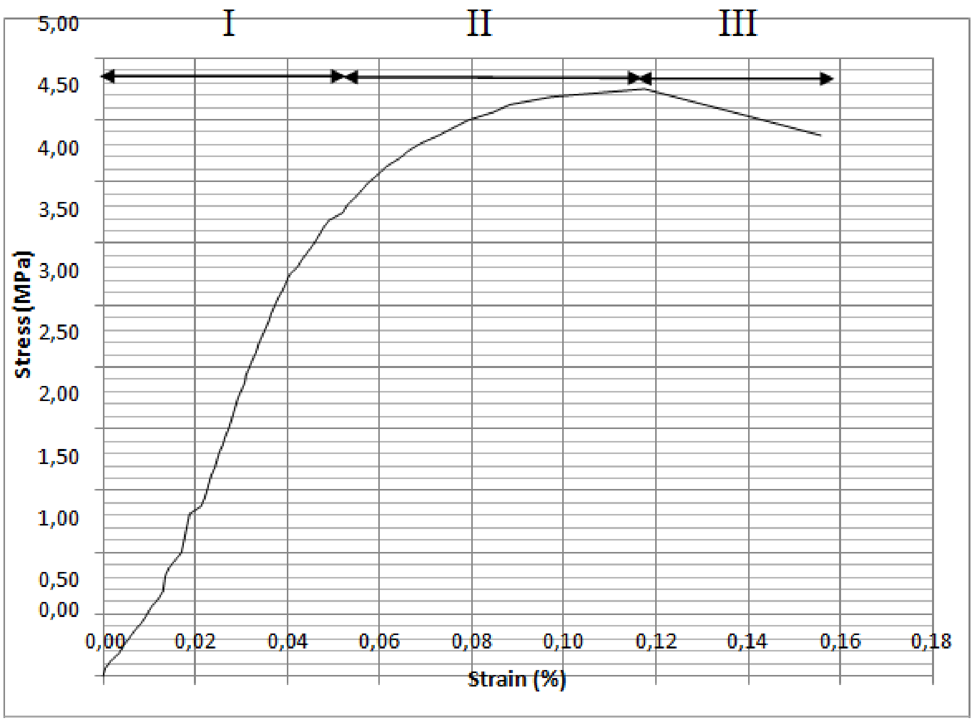

Fig. 10. Stress-strain curve of the palmyra concrete in compression

With regard to the granular composition, the composites made with the fine mixture have a higher effusivity than those made with the coarse mixture with exception of dosage D1 where the effusivity of corse mixture is greater than that of fine mixture. This means that the composite made with aggregates from the fine mixture would quickly absorb a lot of energy without heating up considerably on the surface. This conclusion is also advantageous since the aim is the use of composites as a construction material.

4.4.2 Influence of cement dosage and granular composition on thermal conductivity

For a better knowledge of the thermophysical properties of the composites studied, the thermal conductivity, amount of heat that passes through the body in the presence of a temperature gradient, was measured under variable conditions. For a given material, the range of variation in conductivity is quite wide and depends on several factors, including temperature, porosity, particle size, dosage, density, and water content. Knowing this property is especially useful for calculating the thermal resistance of building elements. The effects of binder content and particle size are also observed on the thermal conductivity of the test specimens (Fig. 12).

Table 6. Synthesis of thermal characteristics

Cement dosage (kg/m^3)	Granulometry	C/PA	W/C	Density (kg/m^3)	Thermal effusivity (E) W.S^{0,5}.m^{-2}.K^{-1}	Thermal conductivity (λ) W.m^{-1}.K^{-1}	Thermal diffusivity (a× 10^{-7}) m^2.s^{-1}
D1 = 400	Fine mixture	2.1	0.60	1080	700.65±63.41	0.270±0.022	1.59±0.467
	Coarse mixture	1.9	0.50	1270	755.38±8.45	0.283±0.010	1.42±0.136
D2 = 450	Fine mixture	3.6	0.40	1310	832.09±31.12	0.340±0.010	1.67±0.075
	Coarse mixture	3.2	0.40	1.29	748.40±9.60	0.340±0.021	2.09±0.286
D3 = 500	Fine mixture	4.4	0.35	1580	867.80±8.94	0.393±0.007	2.06±0.068
	Coarse mixture	4.0	0.35	1450	811.24±5.55	0.415±0.007	2.62±0.073

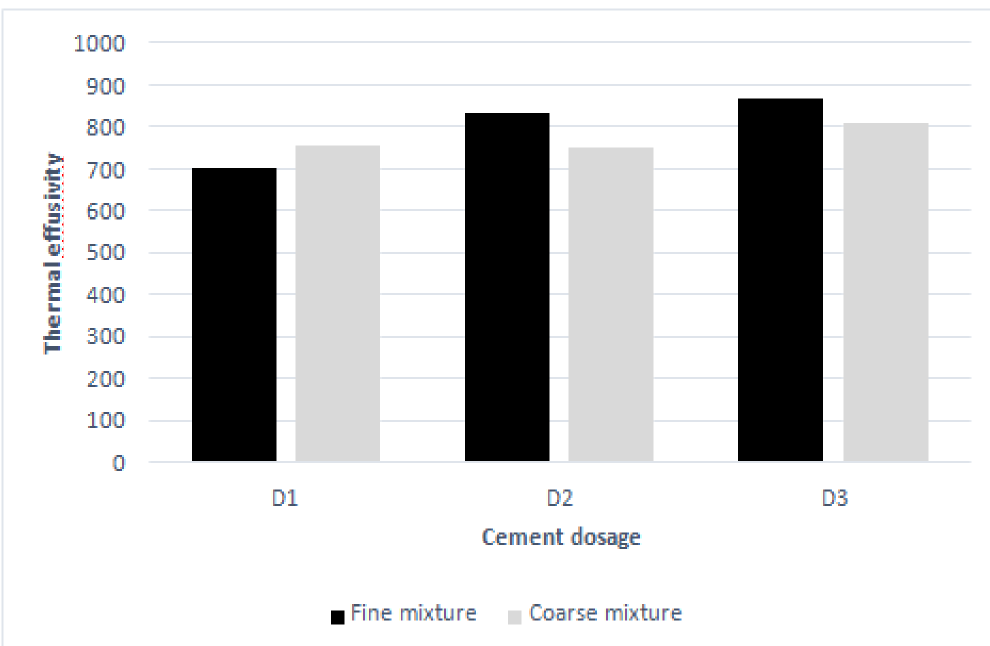

Fig. 11. Variation of the thermal effusivity depending on the cement content for both granular compositions

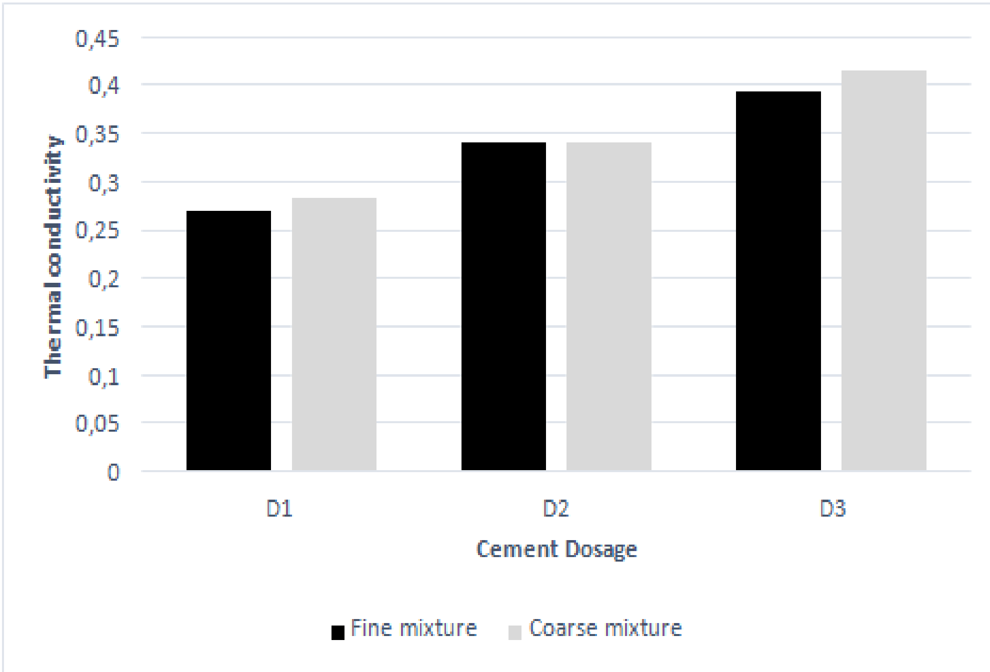

Fig. 12. Variation of thermal conductivity depending on the cement content for both granular compositions

Fig. 12 shows that considering only the influence of cement dosing, the thermal conductivity increases with the cement dosage. This increase is related to the decrease in the volume of voids occupied by air in the specimens, caused by the increase in the cement dosage. However, it is important that air is the most insulating constituent. Since cement is the most conductive component, its increase would certainly increase the thermal conductivity.

As for the effect of particle size, the results obtained show that the conductivity values decrease considerably when passing from the fine mixture to the coarse mixture. Thermal conductivity is a decreasing function of the porosity of the material. Which means the coarse mixture is more porous.

4.4.3 Influence of cement dosage and granular composition on thermal diffusivity

Thermal diffusivity is the rate at which heat propagates by conduction in a material. The lower the value of thermal diffusivity, the more time the heat front will take to traverse the thickness of the material, and therefore the more time between the moment the heat has arrived on a face of a wall and the moment when it will reach the other side is important. In other words, it characterizes the speed of penetration of heat into the material. This parameter varies according to several factors, some of which are, the cement dosage and the granular composition which involves the porosity and the density.

The effects of binder dosing and particle size are also observed on the thermal diffusivity of the test specimens (Fig. 13).

After analysis of Fig. 13, there is generally an increase in the value of the thermal diffusivity when the cement dosage in the mixture increases.

Considering the influence of the granular composition, the test pieces whose formulation includes a dosage D2 or D3, diffuse more heat when they are made with a granular composition corresponding to the coarse mixture. Unlike the dosage D1 it is the fine mixture that prevails over the coarse mixture.

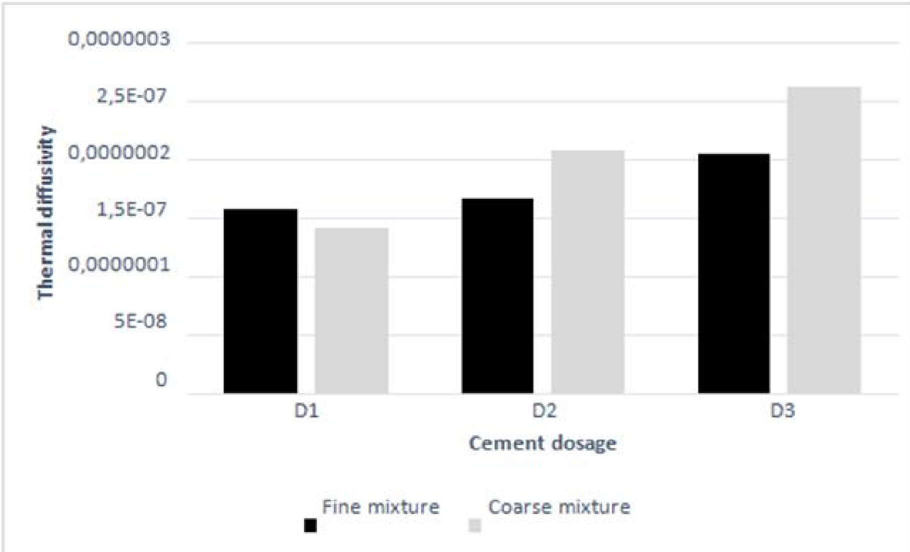

Fig. 13. Variation of thermal diffusivity depending on the cement content for both granular compositions

5. CONCLUSION

This work summarizes the study of the possibility of using the palmyra, as aggregate in concrete.

To ascertain the usability of this type of aggregate in a cement matrix, a compatibility study with cement was studied. Indeed, the biggest enemy of the setting of cement is the extractives (including tannins) although it is possible that the alkalines resulting from the dissolution of the cement can attack the hemicelluloses and convert them into soluble oligosaccharides which could inhibit the hardening of the cement. The compatibility tests gave a hydration coefficient of 89.11% which allows to conclude that the untreated palmyra is really compatible with the cement type CEM II B-LL 32.5 R.

Concrete also offers good mechanical resistance (up to 16.25 MPa), considering its use in construction.

These concretes have advantages from the point of view of thermal performance, compared to conventional building materials.

In conclusion, this bio-sourced material can be used in construction, for example concrete blocks, suspended ceilings or tiles for the realization of roofs (Fig. 14).

Fig. 14. Example of palmyra concrete plate

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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