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Physical Characterization of Raphia Farinifera Nuts, Sand and Formulation for The Elaboration of A Cementitious Matrix Composite Material

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ABSTRACT
Increasing climate variability represents a major global challenge, requiring urgent action to mitigate its harmful effects, such as floods and extreme heat waves, impacting nearly every country. Among these urgent measures is environmental protection for sustainable development in all sectors of human activity, particularly in the building sector, where the use of eco-materials is recommended. The work entitled "Physical Characterization of Raphia Farinifera Nuts, Sand, and Formulation for the Development of a Cementitious Matrix Composite Material" falls squarely within this framework and aims to promote the use of local, natural materials, such as Raphia Farinifera, which are renewable and sustainable, by examining their physical characteristics. An experimental approach based on geotechnical standards was used to conduct the tests carried out in this study. To ensure the validity of the test results, a detailed calculation of uncertainties was performed. The tests were carried out according to the NF EN 933-1 standard for particle size analysis, with uniformity coefficients Cu = (1.191 ± 0.003; 2.950 ± 0.005) and curvature coefficient Cc = (1.012 ± 0.006; 1.114 ± 0.007) conforming to the Caquot and Kérisel criteria. The sand used was fine and very clean, with a sand equivalent Es = (86.35 ± 0.009) > 70%. The bulk densities (NF EN 1097-3) were γb (0.731 ± 0.002; 1.500 ± 0.002) g/cm^3 and the actual density was γs= (1.492 ± 0.001; 2.640 ± 0.001) g/cm^3. Finally, the flattening coefficient of Fl =(99.882 ± 0.001) % is also satisfactory, allowing for its potential use in composite materials. The Dreux-Gorisse method has enabled the optimization of a concrete reinforced with raffia farinifera, and future research is planned.

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Introduction

In recent years, the use of composite materials has seen considerable growth in various fields, including construction, aerospace, automotive, and packaging. A composite material can be defined as an assembly of several materials of different natures. Composites most often consist of a matrix in which reinforcements (fibers) are dispersed in a controlled or uncontrolled manner. The matrix holds the reinforcements in place and ensures load transfer, while the reinforcements primarily contribute their high mechanical characteristics (modulus and yield strength, mechanical resistance, etc.) and improve control of concrete cracking by limiting crack width, transforming the brittle behavior of concrete into a ductile one [1]. This combination aims to obtain a material whose specific properties are superior to those of the components taken separately. The concept of a composite material, through the choice of constituents and their respective proportions, as well as the choice of the shape, dimensions, and arrangement of the reinforcements, thus makes it possible to design a material with the desired specific characteristics [2] . Several classes of composite materials can be identified based on the nature of their matrix: organic matrix composites (OMCs), ceramic matrix composites (CMCs), and metallic matrix composites (MMCs). OMCs are the most widely used, representing 92% of the global market, followed by CMCs at 7%, and then CMMs at a much smaller 1%.

To this end, the valorization of plant fibers and their integration into the development of sustainable composites, within the framework of green technologies, for various applications, is currently one of the most considered solutions. This approach, already widely adopted and promising, encourages researchers working in the construction and manufacturing sectors to incorporate plant fibers as reinforcing elements in building materials. Such integration not only helps to improve their strength, durability, and thermal insulation properties, but also promotes the valorization of local materials while enabling a reduction in construction costs and the energy consumption required for heating or cooling [3].

This is how the rise of consideration of the environmental impact of construction and more generally of sustainable development policies has led to questioning alternative construction processes and materials [4]. Due to growing global environmental concerns regarding greenhouse gas emissions and the depletion of non-renewable resources,

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there is a marked trend towards promoting the use of materials from renewable resources to replace conventional materials [5, 6]. Ongoing research on concrete reinforced with raffia nuts is fully aligned with this approach. Plant fiber-based construction materials offer promising prospects for achieving these objectives through the use of raffia nuts, which offer numerous environmental benefits [7]. First, raffia nuts are derived from an abundant and renewable plant resource, which also acts as a carbon sink. These products have the ability to capture carbon dioxide from the atmosphere during their growth and store it within their organisms. Furthermore, the use of plant particles in construction materials saves valuable natural resources by utilizing raffia nuts [8]. Moreover, it allows for to address the problems of disappearance of conventional traditional ordinary materials (rolled gravel, etc.) [7].

This article aims, firstly, to determine the size and percentages (particle size analysis tests by sieving the materials) by weight, as well as the fineness modulus of the sand. Secondly, it will examine the physical characteristics, such as the determination of the actual bulk density, the intergranular porosity, and the flatness coefficient. Next, formulate the concrete mix to determine the quantity of raffia, sand, and water per cubic meter of concrete [9] Finally, evaluate the measurement uncertainties using the propagation method based on the results of other researchers [10].

Experimental

Materials

Developing a new composite material requires a well-defined problem, clear objectives, and a rigorous and consistent methodological approach. Understanding the key characteristics of raffia farinifera nuts and sand is essential before incorporating them into the cementitious matrix.

Presentation of Raphia Farinifera (NRF) nuts

The raffia farinifera nuts discussed in this article come from the commune of Adjarra, in the Ouémé department of Benin. After felling the raffia farinifera tree (Figure 1a), its nuts must be harvested and gathered nearby to allow them to ripen (Figure 1b). Once ripe, the nuts are prepared by first removing the outer husks to access the seed, which is covered by a yellow skin. This skin is then removed to produce oil (Figure 1c). This series of steps results in the raffia farinifera nuts, which are the subject of this article (Figure 1d). In addition to being used for oil extraction, the fruits of the raffia palm can be eaten; an article published in 1927 mentions the production of raffia oil as an interesting product that could be advantageously exploited in tropical Africa; a 2005 FAO document on tropical forest management also indicates that the oil palm remains a versatile tree among local populations in Africa [11, 12].

Presentation of the Sand

Sand is a natural material composed of mineral grains that can be easily separated by simple crushing or by the action of a water current. It results from the natural weathering, either physical or chemical, of rocks. The grains can vary considerably in size, ranging from clay to boulders, and are of diverse geological origins, including alluvium, colluvium, unconsolidated sedimentary materials, glacial deposits, and residual soils. The soils contain less than 3% organic matter [13]. The sand used in this research came from the Littoral Department (Cotonou, Benin), specifically from the Dekoungbé quarry (Figure 2).

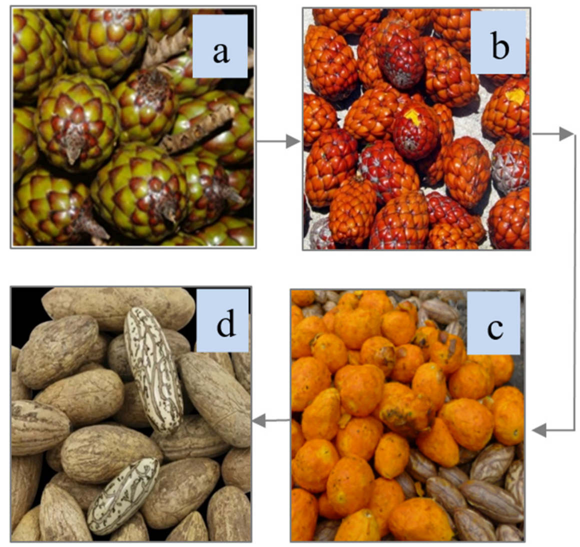

Figure 1: Stages of obtaining Raphia Farinifera nuts, a - after felling the palm tree, b - ripening of the fruit's pods, c - production of Raphia oil, d - obtaining the Raphia Farinifera nuts for our study

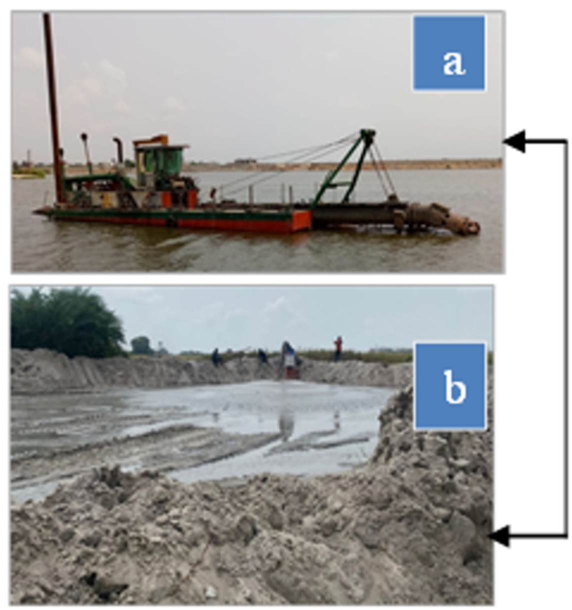

Figure 2: (a) Dredging operation, (b) Extraction of sand used for the preparation of test specimens

Presentation of measuring devices

In accordance with current standards, we will present some measuring devices that enabled the development of this research article.

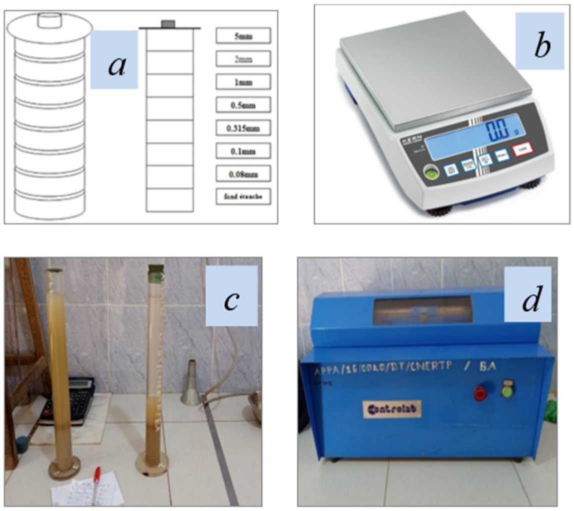

Figure 3: (a) the different series of sieves, (b) the mechanical balance (NF EN 933 -1, of May 2012), (c) Graduated tube, (d) Mechanical agitator in accordance with the standard (NF EN 933 – 8 + A1 of July 2015).

Methods

All scientific knowledge requires rigorous formalization through a precise methodology to ensure that the validity of the results can be established based on experiments and logical arguments. We adopted a sequential strategy, beginning with the collection technique for raffia farinifera nuts and sand, followed by the method for data analysis in the laboratory. This allowed us to identify the standards, equipment, and procedures for conducting the tests, including particle size analysis, fineness modulus, physical properties (sand equivalent), bulk density, actual density, intergranular porosity, and flatness coefficient.

Particle size analysis (LAG)

In accordance with standard NF EN 933-1 (May 2012), particle size analysis determines the size and respective weight percentages of the different grain sizes constituting the samples. It applies to all aggregates with a nominal size less than or equal to 63 mm and greater than 0.08 mm, excluding fillers. The material must be oven-dried to a constant mass at a maximum temperature of 105°C.

Materials used
A standardized series of sieves to be aligned is as follows: For sand or fine aggregates (diameter in mm): 0.063 – 0.080 – 0.16 – 0.315 – 0.630 – 1.25 – 2.5 – 5. For gravel or coarse aggregates (diameter in mm): 6.3 – 8 – 10 – 12.5 – 16 – 20 – 25 – 31.5 – 40 – 50 – 63; an oven with a thermostat from 0 to at least 400°C; scales with capacities up to 30 kg; trays and containers; a wire brush, etc.

Analytical expression
Regarding the uniformity and curvature coefficients, we will note:

$$Cu = \frac{D_{60}}{D_{10}} \quad (1)$$

With: Cu = uniformity coefficient, D60 = particle diameter corresponding to 60% throughput, D10 = particle diameter corresponding to 10% throughput. This coefficient, also called the Hazen coefficient, indicates the spreading of the material on the sieves. The higher it is, the more sieves are used.

$$Cc = \frac{(D_{30})^2}{D_{10} X D_{60}} \quad (2)$$

With Cc = curvature coefficient, D30 = particle diameter corresponding to 30% passing

Fineness modulus (Mf)

In accordance with the standard "(EN 13139)", the fineness modulus (Mf) is an important characteristic, especially with regard to sands. A good concrete sand should have a fineness modulus (Mf) between 2.2 and 2.8

Analytical expression of the fineness modulus "Mf"

$$Mf = \frac{1}{100} \sum_n^i Ri \quad (3)$$

Ri : Represents the cumulative rejections on each sieve, let's say (0.16 — 0.315 — 0.63 — 1.25 — 2.5 — 5)

Sand Equivalent Test (Es)

In accordance with the standard "(NF EN 933 – 8 + A1 of July 2015)", the sand equivalent test is used to determine the quantity of fine impurities contained in a sand.

Analytical expression of sand equivalent "Es"

$$ES = \left(\frac{h2}{h1}\right) X100 \quad (4)$$

Bulk density test (γ_b)

In accordance with the standard "(NF EN 1097 – 6 of June 2016)", the bulk density test is used to determine the water absorption of gravel, sand and other aggregates including voids between particles.

Analytical expression of bulk density " $\boldsymbol{\gamma_b}$"

$$\gamma_b = \frac{M}{V} \quad (5)$$

Test of the Actual Density (γ_S)

In accordance with the standard "(NF EN 1097 – 3)", the density tests the actual mass of a material allows us to determine its mass per unit volume, without the empty spaces between the particles.

$$\gamma_S = \frac{M}{Vréel} \quad (6)$$

Flattening coefficient (Fl)

In accordance with the standard "(NF EN 933 - 3)", the flatness coefficient of an aggregate is defined by three geometric quantities: L: minimum distance from the two parallel planes tangent to the ends of the aggregate, E: minimum distance from the two parallel planes tangent to the aggregate and G: dimension of the minimum square mesh of the sieve which allows the aggregate to pass through.

$$\frac{G}{E} > 1.58 \quad (7)$$

Analytical expression of the flatness coefficient "Fl"

$$Fl = \frac{M_2}{M_1} X100 \quad (8)$$

Intergranular Porosity (η)

In accordance with the standard "(NF EN 1097 – 3, of August 1998)", the intergranular porosity test η corresponds to the percentage of intergranular voids in the container.

Analytical expression for the Intergranular Porosity test "η"

$$\eta = \frac{\gamma_S - \gamma_b}{\gamma_S} \quad (9)$$

CONCRETE MIXING METHOD BY DREUX GORISSE

The methodology developed by Dreux is more complete. It takes into account many factors: the influence of the dimensions of the mold and its reinforcement on the maximum diameter of the aggregates; the influence of the slump on the cement/water mass ratio (C/W) for a cement dosage; the quantity of water is corrected according to the size of the grains, therefore their specific surface area and their water requirement; the final compactness of the dry material is calculated knowing the shape of the aggregates, the fineness modulus, the power of the vibration and the cement dosage. The different proportions of the raw materials are determined from a formula simulating the compressive strength, the use of a nomogram linking the C/E ratio, the slump and its associated cement dosage and a reference curve for the skeleton of the granular mixture (without cement) [14].

Determination of the granular composition of materials

On the particle size analysis graph conforming to standard NF-EN-933-1, a particle size distribution OAB is plotted. Point O is placed at the origin of the graph, point B corresponds to the maximum size (Dmax) of the largest aggregates at the 100% y-axis, and point A is determined by the following relationship:

$$\boldsymbol{Y_A = 50 - \sqrt{D} + K + K_S + K_P} \quad (10)$$

With D = 31.5 mm (largest aggregate diameter); $K_S =$ 2,52and $K_P = 0$. However, the K corresponds to the cement dosage, which is 340 kg/m^3. This is determined through interpolation, since 300 ≤ 340 ≤ 350 kg/m^3.

$$\begin{cases} \boldsymbol{350\frac{kg}{m3}} \longrightarrow \boldsymbol{K_1 = 0} \\ \boldsymbol{340\frac{kg}{m3}} \longrightarrow \boldsymbol{K} = ? \\ \boldsymbol{300\frac{kg}{m3}} \longrightarrow \boldsymbol{K_2 = 2} \end{cases}$$

Hence $\boldsymbol{K = 0,40}$

$$\boldsymbol{X_A = 38 + \frac{|D_{max}|}{2}} \quad (11)$$

Determination of the volume composition of materials

The volumetric composition of the materials is the sum of the volume of the matrix (cement), the volume of the fibers (raffia) and the volume of the sand grains.

$$\boldsymbol{V_{Abs} = V_C + V_R + V_S} \quad (12)$$

Theoretical density of concrete

The theoretical density of concrete corresponds to the sum of the mass of cement, water, sand and the mass of raffia.

$$\boldsymbol{\rho_{Théo} = m_C + m_E + m_S + m_R} \quad (13)$$

Theoretical density of concrete (Δ°)

The theoretical density of concrete is the ratio between the theoretical mass of the granular composition and the mass of water.

$$\Delta° = \frac{\boldsymbol{\rho_{Théo}}}{\boldsymbol{\rho_{Eau}}} \quad (14)$$

ESTIMATING UNCERTAINTIES ABOUT THE MEASURES

In a situation where all influencing quantities vary randomly in time and space, a sufficiently large series of repeated observations should allow us to determine with a very high level of certainty the distribution of values that can reasonably be attributed to the measurand. By statistical analysis of the series of observations in accordance with standard NF 13005 [15], we can thus distinguish :

- Type A uncertainty assessment, where the standard uncertainty is assessed from the statistical analysis of a series of repeated observations of the measurand, and

- type B uncertainty assessment, where the standard uncertainty is assessed by any other means.

Estimation by statistical analysis of a series of measurements

Type A measurement

When we have a series of repeated and independent observations xi of the same quantity X, we can use statistical methods to obtain a measurement result combining all the observations and estimate the standard uncertainty on this result from the standard deviation of the series of measurements.

We define the experimental mean of the measurement series as follows:

$$\bar{X} = \frac{1}{N}\sum_{i=1}^{n} xi \quad (15)$$

This mean $\boldsymbol{\bar{X}}$serves as an estimate of the value of the measurand. The experimental standard deviation of the measurement series is defined by:

$$S(X) = \sqrt{\frac{1}{N-1}\sum_{i=1}^{N}(xi - \bar{x})^2} \quad (16)$$

This is an estimate of the standard deviation of the distribution law of X, that is, of the variability of the measurand.

The mean $\bar{X}$, associated with a finite number of samples (xi), is itself a random variable, which has a mean value coinciding with that of X. We can therefore approximate the standard uncertainty as ($\bar{X}$), which can be estimated from the experimental standard deviation as:

$$u(\bar{X}) = \frac{S(X)}{\sqrt{N}} \quad (17)$$

Thus, the standard uncertainty is reduced by a factor $\sqrt{N}$relative to the dispersion s $(\bar{X})$of the measured results.

Measurement type B

In this case, the uncertainty must be estimated from all available information about the possible variability of the input quantity, and in particular the accuracy indications provided by manufacturers, calibration certificates, measuring instruments, different measuring devices, evaluation methods available in literature, standards, etc.

Combined uncertainty or combined type uncertainty $\boldsymbol{u_1(y)}$

When the quantity depends on several independent parameters, whose type uncertainties are such that Y = f(x_1, x_2, x_3, ..., x_n), we used the uncertainty propagation method based on the results of other researchers [7].

$$u_1(y) = \sqrt{\left(\frac{\partial f}{\partial x_1}u(x_1)\right)^2 + \left(\frac{\partial f}{\partial x_2}u(x_2)\right)^2 + \cdots + \left(\frac{\partial f}{\partial x_n}u(x_n)\right)^2} \quad (18)$$

$\boldsymbol{u(x_i)}$is the standard uncertainty on the quantity $\boldsymbol{x_i}$; $\frac{\partial f}{\partial x_i}$is the partial derivative with respect to$\boldsymbol{x_i}$

- For the case of the uniformity coefficient Cu and the curvature coefficient Cc of particle size analysis tests

$$Cu = \frac{D_{60}}{D_{10}} \text{ And } Cc = \frac{(D_{30})^2}{D_{10}XD_{60}}$$

$$\boldsymbol{Cu = f(D_{60}, D_{10}) = \frac{D_{60}}{D_{10}}} \quad (19)$$

- Partial derivatives of the uniformity coefficient:

$$\frac{\partial Cu}{\partial D_{60}} = \frac{1}{D_{10}} \text{ And } \frac{\partial Cu}{\partial D_{10}} = -\frac{D_{60}}{(D_{10})^2} \quad (20)$$

- Uncertainty combined with the uniformity coefficient:

$$u_c(Cu) = \sqrt{\left(\frac{\partial Cu}{\partial D_{60}} \text{x}\, u(D_{60})\right)^2 + \left(\frac{\partial Cu}{\partial D_{10}} \text{x}\, u(D_{10})\right)^2} \quad (21)$$

$$\frac{u_c(Cu)}{Cu} = \sqrt{\left(\frac{u(D_{60})}{D_{60}}\right)^2 + \left(\frac{u(D_{10})}{D_{10}}\right)^2} \quad (22)$$

$$Cc = f(D_{30}, D_{10}, D_{60}) = \frac{(D_{30})^2}{D_{10}XD_{60}} \quad (23)$$

- Partial derivatives of the curvature coefficient:

$$\frac{\partial Cc}{\partial D_{30}} = \frac{2D_{30}}{D_{10}.D_{60}}, \frac{\partial Cu}{\partial D_{10}} = \frac{-(D_{30})^2}{(D_{10})^2.D_{60}} \text{And} \frac{\partial Cu}{\partial D_{60}} = \frac{-(D_{30})^2}{D_{10}.(D_{60})^2} \quad (24)$$

- Combined uncertainty of the curvature coefficient:

$$u_c(Cc) = \sqrt{\left(\frac{\partial Cc}{\partial D_{30}} \text{x}\, u(D_{30})\right)^2 + \left(\frac{\partial Cc}{\partial D_{10}} \text{x}\, u(D_{10})\right)^2 + \left(\frac{\partial Cc}{\partial D_{60}} \text{x}\, u(D_{60})\right)^2} \quad (25)$$

$$\boldsymbol{u_c(Cc) = \sqrt{\left(\frac{2D_{30}}{D_{10}\text{x}D_{60}} \text{x}\, u(D_{30})\right)^2 + \left(\frac{(D_{30})^2}{(D_{10})^2\text{x}D_{30}} \text{x}\, u(D_{10})\right)^2 + \left(\frac{(D_{30})^2}{D_{10}\text{x}(D_{60})^2} \text{x}\, u(D_{60})\right)^2}} \quad (26)$$

$u(D_{10}), u(D_{30})$ *et* $u(D_{60})$, are calculated in resolution of the sieves used of 0.10mm in accordance with standard NF EN 933-1, of May 2012.

Total uncertainty

When it is possible to obtain both type A and type B, the total uncertainty is:

$$u_T{}^2(X) = u_A{}^2(X) + u_B{}^2(X) \quad (27)$$

Results and Discussion

Analysis of the characterization results

Particle size analysis

Table 1: Determination of uniformity coefficients and curvatures of materials

Coefficient	Raphia Farinifera (RF)	Sand
Uniformity coefficient	1.191 ± 0.003	2.950 ± 0.005
Coefficient of curvature	1.012 ± 0.006	1.114 ±0.007

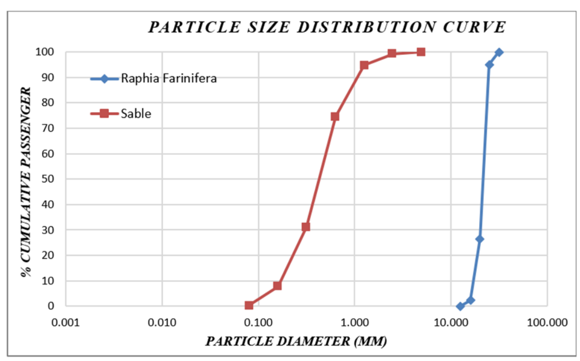

Figure 4: Illustration of the particle size analysis curves of Sand & Raphia farinifera

Table 1 above provides information on the uniformity coefficients (Cu) and curvature coefficients (Cc) of the materials. Raphia farinifera has a uniformity coefficient (Cu = 1.191 < 2). According to Caquot and Kérisel, the particle size distribution is uniform, and the curvature coefficient (Cc = 1.012) is within the range of (1 < Cc = 1.012) < 3, therefore the raffia farinifera nuts are well-graded. Analysis of Table 1 also shows that the curve for raffia farinifera in Figure 3 demonstrates uniformity and good grading according to standard NF EN 933-1, May 2012 [16]. Furthermore, we observe that the sand exhibits a uniformity coefficient (Cu = 2.950), indicating a wide particle size distribution and a well-graded curvature (Cc = 1.114), according to the Coquet and Kérisel intervals. This explains the shape of the sand particle size analysis curve shown in Figure 4. The sand's fineness modulus (Mf = 2.92) falls within the range of (2.8 < Mf < 3.2), meaning the sand is suitable for applications requiring high strength at the expense of workability. However, in such cases, the concrete must be well-fiber-reinforced to avoid segregation, in accordance with standard EN 13139.

In accordance with the standard "(NF P 94-056)", particle size analysis makes it possible to determine the size and respective weight percentages of the different grain families constituting the samples. It applies to all aggregates with a nominal size less than or equal to 63 mm and greater than 0.08 mm, excluding fillers. From these four classes [17] constituted two types of mixtures (fine mixture and coarse mixture, designated MF and MG respectively, with fineness moduli of 2.7 and 3.00) used for preparing the test specimens, illustrating the particle size distribution curves of the two mixtures. Furthermore, the particle size distribution analysis curves of the sands and other natural aggregates were carried out according to standard NF EN 933-1, and the fineness modulus was determined [18, 19, 20, 21]. From the analysis of these results, we conclude that the Raphia farinifera nuts, which come from southern Benin, specifically from the commune of Adjarra, and the sand from the Cotonou Benin coastline, from the Dekoungbé quarry, can be used for the formulation of concrete test specimens.

Analysis of Sand Equivalent Results

These results are shown in the table below according to the standard NF EN 933 – 8 + A1 of July 2015 [22].

Table 2 : Determination of Sand Equivalent

Reference	T	E
h(height)	43	43
h'(height under piston)	34.1	34.2
h2(h-h')	8.9	8.8
h1 (direct reading)	10.2	10.3
Es%	87.26	85.44
Es%(average)	$\mathbf{ES} = 0,\mathbf{8635} = \mathbf{86,350\%} \pm \mathbf{0.009}$	

According to Table 2, the sand is fine and very clean, in accordance with current standards, since Es = 86.35% > 70%. Similarly, researchers [23] determined the physical characteristics of the sand, notably the sand equivalent (Es = 92.52% and 87.33%), according to standard NF EN 933-8. Furthermore [22, 23] evaluated the percentage of sand equivalent in several quarries, notably on dune sand in Sali, Bouda and Mansouria , finding (79.51% and 94.4%) respectively.

It should be noted that the NF EN 933-8+A1 standard of July 2015 defines the sand equivalent test as a reference method for evaluating the cleanliness of aggregates, particularly fine fractions (0/2 mm and 0/4 mm). This test is essential for determining the content of clayey, organic, or plant fines that can affect the quality of materials in applications such as concrete or asphalt mixes. Analysis of Table 2 shows that the evaluated percentage is well above 70%, therefore the quarry sand from Dekoungbè Cotonou, Benin, can be used for the production of test specimens of the composite material that is the subject of this study.

Analysis of bulk density results

The physical characteristics, in particular the bulk density, are determined in accordance with the applicable standards (NF EN 1097 - 3) [24], and the test results are presented in Table (3 and 4); as well as in Figures 5 and 6.

Table 3 : Determination of the Bulk Density of Raphia Farinifera

Settings	RF10 Test	RF06 Test	RF03 Test	RF00 Test
Total weight Sample P0	6556	6584	6572	6512
Empty crate weight P1	5020	5020	5020	5020
Net weight Sample P2 = P0 – P1	1536	1564	1552	1492
Cash register volume V	2104	2104	2104	2104
Bulk density $\gamma_b = P^2/V$	0.730	0.743	0.740	0.709
Average :	0.731 ± 0.002			

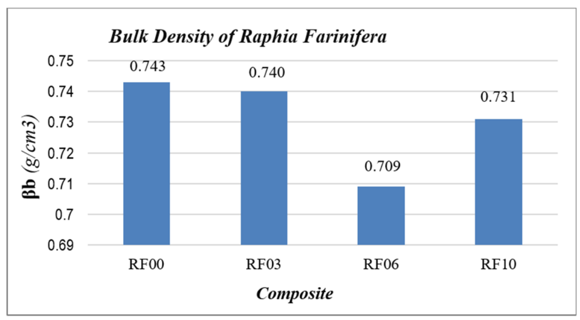

Figure 5 : Illustration of the bulk density of Raphia farinifera

The bulk densities of Raphia farinifera, determined using the pycnometer method and the water-accessible vacuum method, are summarized in Table 3.4. The average bulk density of Raphia farinifera, at 0.731 g/cm^3, is low, indicating the material's lightness according to standard NF EN 1097-3. As illustrated in Figure 5, we observe the decrease in bulk density of the Raphia farinifera nuts. The 6% percentage decreases with increasing particle diameter, with lower values indicating that the Raphia farinifera nuts are lightweight.

Based on the methodology of the characterization of aggregates for the determination of properties in the wet state, considered representative of the state of aggregates in a vibro-compacted plant-based concrete proposed by several including [25]. On the graph represented by [26], the bulk density is compacted dried of plant aggregates such as Vine shoots (SV = 0.319 g/cm3), Corn husks (SM = 0.051 g/cm3), Wheat straw (PB = 0.042 g/cm3), Flax shives (AL = 0.115 g/cm3), Wheat chaff (MP = 0.056 g/cm3), Sunflower hurd (ET = 0.135 g/cm3), Miscanthus stem (TM = 0.119 g/cm3), Coriander straw (PC = 0.074 g/cm3), Hemp shives (CHEN = 0.1 g/cm3) and Sunflower pith (MT = 0.02 g/cm3).

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These values particularly reinforce the results obtained when determining the bulk densities of Raphia farinifera nuts. It appears that plant-based fibers have a low bulk density. Thus, Raphia farinifera nuts from southern Benin, specifically from the commune of Adjarra, can be considered a potential reinforcing material in cementitious matrix composites.

Table 4: Determination of the Bulk Density of Sand

Settings	SB10 Test	SB06 Test	SB03 Test	SB00 Test
Total weight Sample P0	1795	1800	1796	1790
Empty crate weight P1	299	299	299	299
Net weight Sample P2 = P0 – P1	1496	1501	1497	1491
Cash register volume V	1000	1000	1000	1000
Bulk Density γ_b= P2/V	1,500	1,501	1,497	1,491
da (Average):	1.500 ± 0.002			

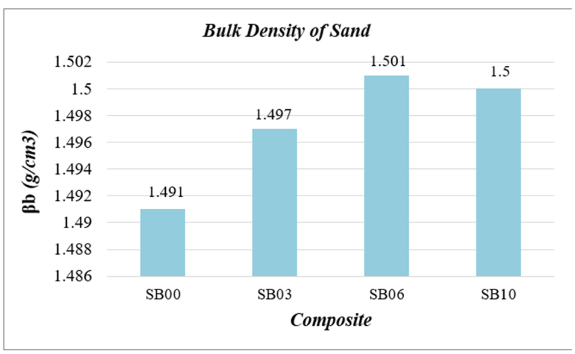

Figure 6: Illustration of the bulk density of sand

The bulk densities of the sand, determined using the pycnometer method and the water-accessible vacuum method, are summarized in Table 3.5. The average bulk density of the sand, at 1.496 g/cm^3, is low, indicating the material's lightness according to standard NF EN 1097-3 . As illustrated (Figure 6), a slight increase in density is observed following the addition of the raffia farinifera nuts.

Based on the results from other researchers [25], which support the results of the present study on the Dekoungbé quarry, the bulk density of dune sand at the Sali, Bouda and Mansouria sites gave the values of (1.57; 1.54 and 1.49) g/cm3 respectively.

Analysis of the results of the Actual Density

The physical characteristics, in particular the actual density, are determined in accordance with the standards in force and the test results are presented in Table (5 and 6) [27].

The actual density values of Raphia farinifera, determined using the pycnometer method and the water-accessible vacuum method, are summarized in Table 5. An average value of 1.203 g/cm^3 is significantly lower than that of conventional natural aggregates recommended by standard NF EN 1097-6 of June 2016, which is around (2.6–2.8) g/cm^3. This indicates that the material is lightweight and suitable for short spans. Based on the results of other researchers, in particular... [25] The actual density of the aggregates is in the range of (2.6 – 2.8) g/cm^3. These values were obtained using the pycnometer method according to standard (NF EN 1097-6) and under vacuum (NF P 18 – 459). These results confirm the low actual density values of the plant fibers.

Table 5 : Determination of the Actual Density of Raphia Farinifera

Testing on Raphia farinifera with Picnometer				
Picnome No.	F1	F2	F3	F4
Mass of Material M	181.20	181.22	184.21	182.23
Material Volume V	150.58	150.59	147.56	149.54
Absolute density Material γs = M/V	1,203	1,203	1,792	1,768
Average (γs)	1.492 ± 0.001			

Table 6: Determination of the Actual Density of Sand

Sand Test with Picnometer				
Picnome No.	B1	B2	B3	B4
Mass of Material M	112.86	123.05	114.97	118.92
Material Volume V	42.71	46.62	42.71	46.62
Absolute density of material γs = M/V	2,642	2,639	2,642	2,639
Average (γs)	2.641 ± 0.001			

The actual density of the sand, determined using the pycnometer method and the water-accessible method under vacuum, is summarized in Table 6. An average value of 2.640 g/cm^3 falls within the range of (2.6–2.8) g/cm^3, indicating good material performance. Based on the results of other researchers, notably [28] , The actual density of dune sand at the Sali, Bouda, and Mansouria sites yielded values of (2.63, 2.64, and 2.64) g/cm^3, respectively. These results confirm the values recorded at the Dekoungbé site, the subject of this study.

Analysis of Intergranular Porosity Results

The physical properties, in particular the determination of intergranular porosity, are determined in accordance with standard NF EN 1097-3, dated August 1998 [29]. These test results are presented in Table 7.

The intergranular porosity (denoted η) is calculated from the bulk density (γb) and the actual density (γs) of the material according to standard NF EN 1097-3, August 1998. Table 7 shows the evaluation of the intergranular porosity of Raphia farinifera and Sand. This proper evaluation of the intergranular porosity is essential to ensure the quality and performance of Raphia farinifera nuts and Sand in construction applications. Within the framework of the work carried out by [30], A three-dimensional (3D) characterization methodology for the microstructure of porous materials for thermal purposes was applied.

Table 7: Determination of the intergranular porosity of Raphia Farinifera and Sand

Raphia Farinifera (RF)		
Composite 1	Actual Density of Raffia	Bulk Density of Raffia
	1,203	0.730
RF00	η_{RF00} = 39.318% ± 0.001	
	1,203	0.743
RF03	η_{RF03} =38.824% ± 0.001	
	1,792	0.740
RF06	η_{RF06} = 57,433%± 0.001	
	1,768	0.709
RF10	η_{RF10} = 59,898%± 0.001	
Sand		
Composite 2	Actual Density of Sand	Bulk Density of Sand
	2,642	1,500
SB00	η_{SB00}= 43.330% ± 0.004	
	2,639	1,501
SB03	η_{SB03}= 43.331% ± 0.004	
	2,642	1,497
SB06	η_{SB06}= 43.329% ± 0.005	
	2,639	1,491
SB10	η_{SB10}= 44.001% ± 0.005	

Correlation between actual bulk density and intergranular porosity

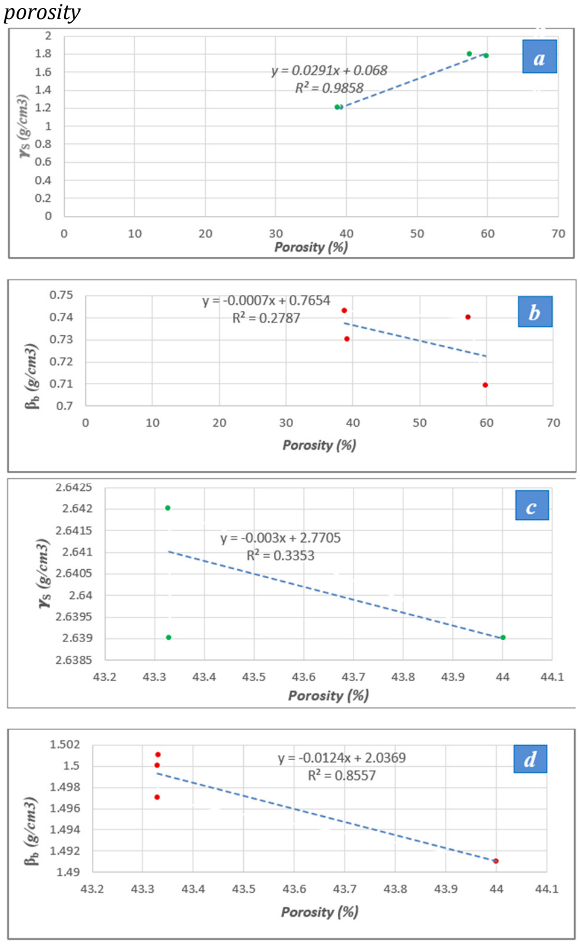

Figure 7: Porosity Correlation, **a** - actual density of raffia, **b** - bulk density of raffia, **c** - actual density of sand, and **d** - bulk density of sand

Figure 7 shows the correlation between intergranular porosity and the actual bulk density of Raphia farinifera nuts and sand. This figure shows that higher porosity leads to lower densities, confirming that the presence of pores reduces the compactness and density of the material, with the exception of Figure a (correlation between porosity and the actual bulk density of Raphia farinifera nuts). The coefficients of determination indicate a strong linear correlation between porosity and densities. Approximately 85 to 99% of the variation in density is explained by the variation in porosity for Figures a and b.

Analysis of the results of the flattening shape coefficient

The physical properties, in particular the determination of the flatness coefficient, are determined in accordance with standard NF EN 933-3 [31]. These test results are presented in Table 8, (M1: Total mass of the sample tested and M2: Total mass of the sieves after the test).

Table 8: Determination of the flattening shape coefficient of Raphia Farinifera

M1 = 2500g	Refusal Sieve (g)	Passing through the gate
31.5 mm	-	20 mm
25 mm	89	16
20 mm	2244	12.5
16 mm	156	10
12.5 mm	8	8
10 mm	-	6.3
8 mm	-	5
6.3 mm	-	4
5 mm	-	3.15
4 mm	-	2.5
Total	M2 = 2497	-

Analysis of Table 8 reveals that Raphia Farinifera has a flatness coefficient of (99.882 ±0.001) %, thus reflecting a potential ability to be integrated into concrete formulations.

Furthermore, the work of [32] enabled the completion of the flatness coefficients of the aggregates from the Harrouchi site (46.74%; 32.57% and 12.01%) and Kadiri (57.74%; 29.47% and 9.84%). At the same time [33] determined the flattening coefficients of the massifs at several sites. It is interesting to note that for the Adrar Madet massif, the flattening coefficient is the lowest, at 6.15, indicating that this obstacle is angular and high. In contrast, the Eglab massif, with a flattening coefficient of 500, a value much higher than the other massifs, represents a low and flat obstacle. The vertical component of wind speed, in addition to the two subdivisions of the current on either side of the massif, is much more pronounced at Eglab than at Adrar Madet. The sheltered area is much larger downstream of the Eglab obstacle than at Adrar Madet. The Tibesti massif can therefore be classified as a flat and low massif. This proportion shows that the raffia farinifera nuts have an ovoid shape, since fl = 99.88%, according to the standard NF EN 933 – 3, we can certify that the raffia nuts can play the role of reinforcement in the development of the cementitious matrix composite material.

ANALYSIS OF THE RESULTS OF THE CONCRETE FORMULATION

Dreux Gorisse Method

Concrete formulation is linked to a construction operation. We will focus on the formulation of a cementitious matrix composite material reinforced with raffia farinifera nuts, intended for use in the manufacture of structural elements for a building, road, etc. To obtain an optimal concrete formulation using raffia farinifera nuts as reinforcement, it is first necessary to have a thorough understanding of the different characteristics of the components (raffia farinifera, sand, cement, and water). In our case, we used raffia farinifera nuts from Adjarra in southern Benin and sand from Cotonou (Dekoungbé). These natural materials were taken into account in the development of the concrete formulation using the method of (Dreux Gorisse, 1998) [9, 34]. This method aims to propose an optimal material composition based on the analysis of granular behavior, represented by the granularity curve resulting from sieving according to the standard (NF EN 933-1, May 2012). It also includes the insertion of the OAB reference coordinates, necessary for the interpretation and adjustment of granular mixtures.

Analysis of the results of the granular behavior of the materials

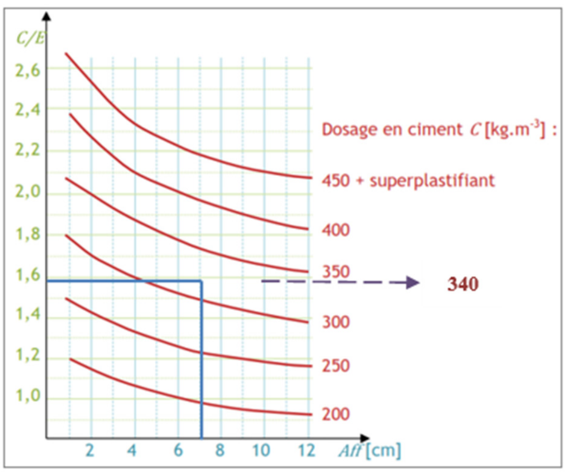

Figure 8 : Nomograph for estimating cement dosage C(kg/m3)

The required quantity of cement (C) is estimated at 340 kg/m^3 of concrete. The NF-EN-206/CN standard recommends a minimum cement content of 260 kg/m^3 for concrete of exposure class XC1, a value significantly exceeded in our formulation with Raphia Farinifera nuts (Figure 8). The required quantity of water (E) is 215.19 L/m^3, calculated as E = C/1.58 = 340/1.58.

Adjustments may be made to the water quantity (E) if the aggregates are damp after outdoor storage or due to their specific surface area. The water dosage should also be adjusted if the maximum aggregate size differs from 25 mm.

In this application, Dmax = 31.5 mm; according to Table 9, the correction to be applied is -1.73% to the water content: E = 215.2 - ((1.73/100) x 215.2) = 211.48 L/m^3. This first part of the concrete mix design provides the quantities and ratios for each constituent: C = 340 kg/m^3, E = 211.48 L/m^3, and C/E = 1.58. However, the concrete consists of sand and raffia farinifera, the proportions of which still need to be determined according to the AOB reference curve.

Table 9: Water percentage correction as a function of the size of the largest aggregates Dmax (correction if Dmax ≠ 25 mm) [9, 34].

Maximum dimension D (mm)	5	10	16	25	40	63	100
Correction in pour-percentage (%)	+15	+9	+4	0	-4	-8	-12

Graphical representation of the reference granular curves (Sand – Raffia)

The graphical representation is made using the coordinates of OAB. The coordinates of the reference curve OAB are: O (0 ; 0); A (42 ; 47) and B (31.5 ; 100).

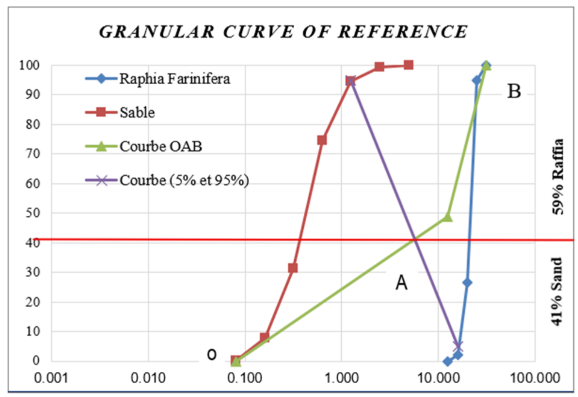

Figure 9 : Illustration of reference granular curves (Sand – Raffia)

This second part of the concrete mix design specifies the aggregate proportions (sand and raffia). The intersection of the OAB curve and the line representing 5% of the raffia nut curve and 95% of the sand curve gives the percentages (sand and raffia) that make up the mix. In this application, this is 41% sand and 59% raffia nuts (Figure 9).

Table 10: Summary of concrete formulation

No.	Settings	Unit	Values Obtained
1	Average 28-day strength of concrete	MPa	20
2	Abrams cone subsidence	cm	7
3	Absolute density	g /cm3	1.21
4	C/E ratio	-	1.58
5	Cement dosage per 1m^3 of concrete	kg	340
6	Water dosage	L/m3	215.19
7	Water dosage correction	L/m3	211.48
8	Granular composition (reference curve)	-	O(0 ;0) A(42 ;47) B(31.5 ;100)
9	Volumetric composition	M3	Sand: 248.53 Raphia: 435.79
10	Concrete density	kg/m3	1,726,000 ± 0.002
11	Theoretical density	-	1.726 ± 0.002

Concrete mix design methods vary, most aiming to achieve maximum granular compactness. Some methods measure the compactness of the granular constituents, while others use a reference granular distribution curve assumed to provide the optimal compactness with the granular constituents used. The practical objective is to find an optimal mix of different constituents to obtain concrete that meets technical specifications, has a lower composition cost, and offers improved workability. Table 9, however, presents the different values obtained during concrete mix design. We observe a wide variation in the theoretical densities of the concrete, primarily due to the low density of Raphia farinifera (1,726.00 kg/m^3), which is slightly lower than the recommended value (2,000 kg/m^3) for ordinary concrete. This also results in a low theoretical density of Raphia farinifera (1,726).

In general, an increase in the density of ordinary concrete made from gravel content (2,371 kg/m3) was observed during formulation studies conducted by [9, 34]. Similarly, the Dreux-Gorise composition method was used in determining the actual and calculated densities (2,320.83 and 2,342.10) kg/m3 [23].

The results presented in this study showed that the characteristics of concrete, particularly its bulk density and theoretical density, made with plant-based aggregate (Raffia farinifera nuts), are indeed lower than those of ordinary concrete made with rounded and crushed gravel, but remain acceptable and feasible, especially since they offer several advantages such as minimizing CO2 impact. Following this, several avenues for further investigation are being explored, including determining its mechanical properties (compression and three-point bending tests) and thermal properties.

THE MIXING WATER

Water is necessary for cement hydration and also facilitates the placement of concrete (lubricating effect), provided that this influence is not overused, as excess water reduces the concrete's strength and durability. The water used comes from the laboratory of the National Center for Public Works Testing and Research (CNERTP).

Table 11 : Characteristics of the mixing water

Settings	Units	Precision	Values	Analysis methods
Temperature	°C	± 0.100	-25,000 < T < 65,000	Electrochemical (NF T90-106) with the Oxi 730 WTW inolab oximeter
Oxygen Dissolved	mg /l	± 0.100	3,600	
Potential Hydrogen (pH)	-	± 0.010	4,790	Electrochemical (NF T90-008) with pH 3110 SET 3 (WTW)
Redox potential (eH)	Mv	± 0.100	125,200	
Conductivity	µs /cm	±1,000	463,000	Electrochemical NF EN 27888 with waterproof pH/EC/TDS conductivity meter Family
Total Dissolved Salts (TDS)	mg /l	±1,000	231,000	
Turbidity	NTU	± 0.010	0.110	Nephelometry NF T 90-033 using the MERCK TURBIQUANT 110 IR turbidimeter
Suspended solids (SS)	mg /l	± 0.100	0.000	By EN 872 filtration
Total Organic Carbon (TOC)	mg /l	± 0.100	13,500	
Ammonium	mg /l	± 0.100	0.000	Spectrophotometric analysis using kits
Chloride	mg /l	± 0.100	1,080	
Magnesium	mg /l	± 0.100	24,300	
Sulfate	mg /l	± 0.100	9,300	

CEMENT PRODUCTION

To manufacture Portland cement, a mixture of crushed limestone and clay (or similar materials) is fired at a very high temperature (1450°C) in a rotary kiln. The limestone provides the lime, and the clay primarily provides the silica and alumina. The product obtained from the kiln is called clinker. Portland cement is then manufactured by adding a small amount (5%) of gypsum to the pulverized clinker (particle size varies approximately between 1 and 80 µm). A summary of the cement manufacturing process is illustrated in Figure 10.

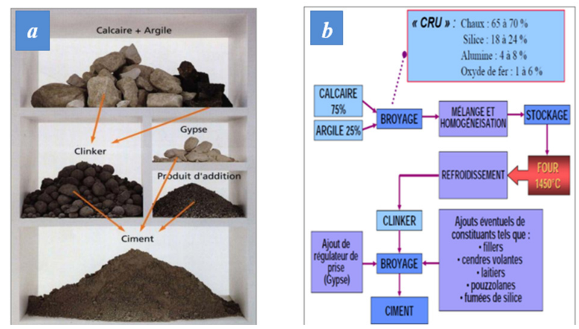

Figure 10 : Illustration of Portland cement manufacturing, a - Raw materials and intermediate products in cement manufacturing and b – Diagram of the cement manufacturing process [35].

The chemical composition of the cement in this study

Portland cement (PC) of CEM I 42.5R grade was used. The characteristics of the cement used are presented in Table 12.

Table 12 : Chemical composition of cement [36].

Composition in Oxides (%)	Composition definitions	OPC
CaO	Lime, Calcium oxide	63.14
SiO2	Silica Oxide	20.23
Al2O3	Aluminum Oxide	5.14
Fe2O3	Ferric Oxide	3.87
MgO	Magnesia	1.25
Na2O	Sodium Oxide	0.26
K2O	Potassium Oxide	0.83
SO3	Sulfur trioxide	2.89
Loss in the fire	-	1.55
Specific weight (g/cm3)	-	3.1
Blaine specific surface area, (cm2/g)	-	3780

Conclusions

This article is part of an effort to contribute to the development of a scientific and normative framework dedicated to the characterization of plant-based aggregates used in construction. The results obtained validate the relevance of the definition and the methodology for measuring physical indicators and uncertainties, which can predict the performance of raffia farinifera nuts and sand for use in cementitious concrete mixes. Regarding their integration into the concrete mix design as a constituent within the cementitious matrix, it is important to formulate the concrete mix to determine the quantities of raffia farinifera, sand, and water per cubic meter of concrete. This allows for the study of the mechanical (flexural strength, compressive strength, etc.) and thermal (thermal conductivity, diffusivity, and effusivity) characteristics of concrete reinforced with raffia farinifera nuts.

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