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Determination of physical parameters of lightweight concrete based on pozzolana and palm nut shells in Cameroon

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Abstract
This study is part of a sustainable innovation dynamic in the field of construction materials, focusing on the physical properties of lightweight concretes formulated with class II cement (42.5 MPa strength), natural pozzolan, and palm kernel shells. The main objective is to assess the balance between structural lightness and physical parameters, in order to identify the formulations best suited to sustainable construction requirements. In this context, several formulations were developed by partially substituting conventional lightweight aggregates with natural lightweight aggregates, namely pozzolan and palm kernel shells, used separately. Experimental results highlight a strong correlation between the type of lightweight aggregate and the overall performance of the concrete. The concrete containing 34% palm kernel shells achieved a dry density of 1850 kg/m³ and a bulk density of 2100 kg/m³. This opens concrete perspectives for integrating these sustainable concretes into smart construction systems.

Keywords: Lightweight concrete, pozzolan, shell, physical parameter

Introduction

In the current context marked by the search for sustainable construction materials with low environmental impact and high technical performance, lightweight concrete represents a central research focus. By reducing density, lightweight concrete offers improved workability on site, a reduction in permanent loads, and, above all, enhanced thermal insulation capacity. In this perspective, several studies have demonstrated the relevance of substituting conventional aggregates with local or recycled materials, notably palm kernel shells and pozzolan. Recent research has emphasized the thermal and mechanical benefits of alternative aggregates. Real showed that the use of special aggregates in lightweight concrete formulations can significantly reduce thermal conductivity while maintaining sufficient mechanical strength for lightweight structural applications. Aggregates refer to the set of granular materials, natural or artificial, used as the mineral skeleton of concrete. According to NF EN 12620, they are divided into two main categories: fine aggregates (sand), with dimensions between 0 and 5 mm, and coarse aggregates (gravel), with dimensions greater than 5 mm. In conventional concrete, aggregates account for 60–80% of the total volume. Their role is fundamental, as they determine the mechanical strength, compactness, workability, and durability of the material. By comparison, the density of conventional natural aggregates is often higher than 2400 kg/m³, whereas that of lightweight aggregates is generally below 1400 kg/m³, due to their high porosity. This porosity, while beneficial for thermal performance, also impacts the mechanical strength of concrete, hence the need for careful selection of their use. The specific behavior of aggregates in the cementitious matrix influences bonding, water absorption, mixture compactness, and overall concrete performance.

Literature Review

Koti (2022) [10] demonstrated that agricultural by-products such as fibers or shells can be used as aggregates in the production of lightweight concretes for road construction. These experimental results from Europe reinforce the relevance of a local approach aiming to valorize materials such as palm kernel shells in the African context.

In Algeria, Dhikra (2024) [2] carried out a study on ultra-lightweight concretes based on This aligns with the approach of the present study, which leverages the fine particle size

distribution of pozzolan to reduce compactness and thereby improve thermal insulation.
Similarly, BILLAMI (2020) [1] tested recycled polystyrene in lightweight concretes, demonstrating a significant reduction in density and interesting insulating capacity. Although the material differs, the principle of waste valorization and thermal optimization is fully consistent with our approach.
Moreover, Habert (2020) [5] showed that cement production is responsible for approximately 7 to 8% of global CO_2 emissions, which drives researchers to explore more sustainable solutions. By integrating natural pozzolan at 5% in our formulation, this study aligns with the trend of reducing clinker content through partial substitution of cement.
From a methodological standpoint, the Dreux-Gorisse method is widely used in concrete formulation studies. However, this method must be adapted when dealing with lightweight or plant-based aggregates, due to their porous structure and particular water absorption behavior. This is precisely the adaptation applied in the present research, by setting a high water-to-cement ratio (1.9) and a cement content of 385 kg/m³.

Materials and Methods
Since the properties of a concrete depend on its composition, we first present the different materials used for the preparation of our concrete, the tests applied for their characterization, the formulation process, and the properties of the materials obtained after preparation.

Acquisition of Materials
Materials used
1. Sand 0/5
2. Gravel 5/15
3. Pozzolan
4. Palm kernel shells
5. CPJ CEM II /B 42.5R cement
6. Portable water

Nature and Origin
To promote local resources, all materials used in this study were locally sourced (Cameroon).

Fig 1: Images of the different components used

Laboratory Work
The Materials and Geotechnics Laboratory of the Fotso Victor University Institute of Technology in Bandjoun was the facility where the tests on our different materials (sand, gravel, and cement) were carried out.

Characterization test of the concrete constituents
The physical characterization tests of the concrete constituents represent a fundamental step in any rigorous experimental methodology within materials science. Their main objective is to determine all measurable and observable properties of solid and fluid materials, without altering their chemical structure. In the context of lightweight concrete, this step is all the more critical as it allows researchers to anticipate how each material will affect the final properties of the concrete both in its fresh and hardened states.

Particle size distribution
Particle size distribution, regarded as an essential component of aggregate geometry, refers to the analysis of the size distribution of solid particles in a granular material- such as sand, gravel, pozzolan, or PKS. It involves measuring, classifying, and interpreting grain size to characterize the granular structure of a material through standardized quantitative parameters. The recorded masses are used to compute the retained (R_i) and the cumulative passing percentage (P) for each sieve, using the formulas below:
Retained percentage on sieve i (R_i)

$$R_i = \frac{M_i}{M_0} \times 100$$

Cumulative Passing Percentage P

$$P = 100 - \sum_{i=1}^{j} R_i$$

Fineness modulus is defined as the sum of cumulative retained percentages on a series of standardized sieves, divided by 100.

$$FM = \frac{\%R_5 + \%R_{2.5} + \%R_{1.25} + \%R_{0.63} + \%R_{0.32} + \%R_{0.16}}{100}$$

Particle size distribution curves are plotted with grain diameter on the x-axis and cumulative passing percentage on the y-axis. These curves help evaluate the spread and uniformity of aggregate grading.

Bulk Density

- In this study, the bulk density of dry aggregates is determined according to standard NF P18-554. The method involves filling a container of known volume without compaction to assess the loose bulk density, simulating a natural state. the bulk density ρ_{bulk} is calculated as follows:

$$\rho_{bulk} = \frac{M}{V} \text{ with } M = M_1 - M_0$$

ρ_{bulk} bulk density, M mass of the dry aggregate sample, V known volume of the container, M_0 mass of the empty container, M_1 mass of the filled container.

- The test is repeated three times and average taken to minimize errors.
- No vibration or compaction is applied during the filling process.

True density is typically measured using the pycnometer method, in accordance with standard NF EN 1097-6. This method is based on the principle of volume displacement by a liquid, usually water. Materials used: a glass pycnometer of known volume, an electronic balance of accuracy ±5 g, an oven, distilled water, a pen, a funnel.

$$\rho_{abs} = \frac{M}{M + M_w - M_2} \times \rho_w$$

$$M = M_1 - M_0$$

M_0 mass of empty pycnometer, M_1 mass of pycnometer + dry aggregate, M_2 mass of pycnometer + water + aggregate.

Moisture content

The moisture content is determined according to EN 1097-5, by measuring the mass of a sample before and after drying at 105 °C until constant weight.

Calculation of moisture content W

$$W(\%) = \frac{M_w - M_d}{M_d} \times 100$$

Where: M_w wet mass of the aggregate, M_d dry mass of the aggregate, W moisture content.

Water absorption coefficient

The water absorption coefficient of an aggregate is a key property that quantifies the material's ability to absorb water into its accessible pores after prolonged immersion

Absorption coefficient calculation:

$$A(\%) = \frac{M_{sat} - M_d}{M_d} \times 100$$

Where:

M_{sat} saturated mass of the aggregate, M_d dry mass of the aggregate, a water absorption coefficient

Results

At the end of this study, it appears that the values of the physico-mechanical parameters of concrete vary significantly depending on the type of the aggregates used. In this section, we will analyze and compare the test results of ordinary concretes samples with those in which part of the aggregates was replaced by pozzolan and palm kernel shell.

Table 1: Real and bulk densities of aggregates

Aggregate	Real density (kg/m³)	Bulk density (kg/m³)
Gravel	2680	1500
Sand	2400	1475
Pozzolan	1750	825
Palm kernel shell	1250	625

Table 2: Density (fresh and dry) of the different formulation

Formulation	Fresh density (kg/m³)	Dry density (kg/m³)
Nor	2372.0	2350.0
23% P	2164.0	2100.0
33% P	2109.5	2025.0
24% PKS	2062.6	1975.0
34% PKS	1974.8	1850.0

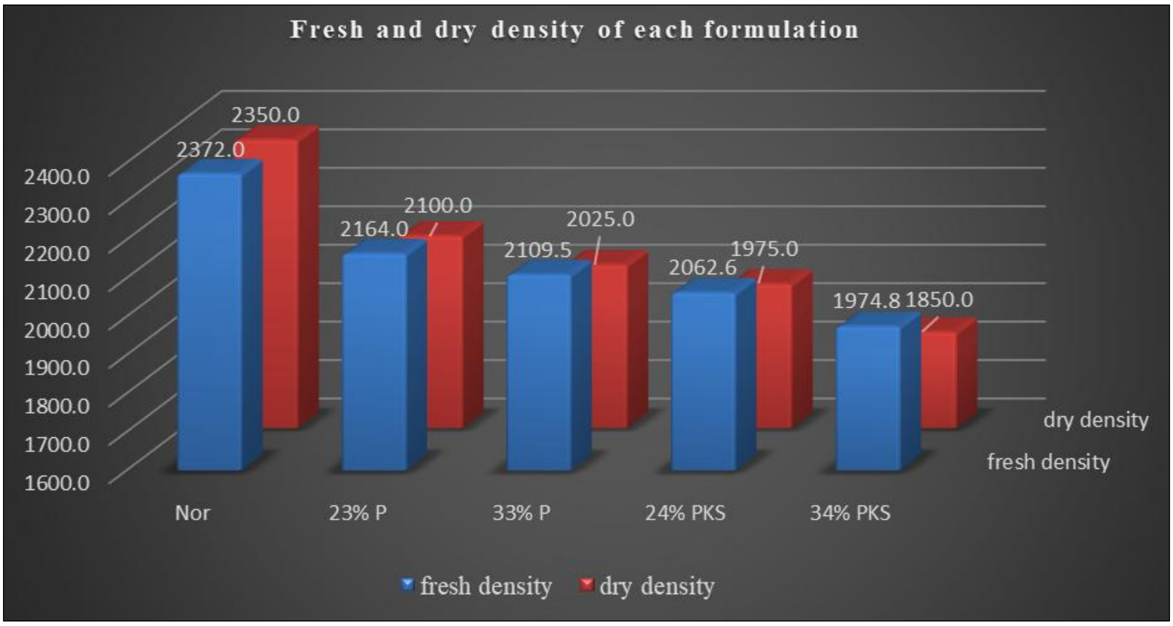

Fig 2: Comparative chat of fresh and dry density of the different formulation

Table 3: Water absorption capacity and moisture content of the constituent aggregates.

Aggregate	Water absorption (%)	Moisture content (%)
Gravel	1.2	1
Sand	1.5	5
Pozzolan	12	8
PKS	16	11

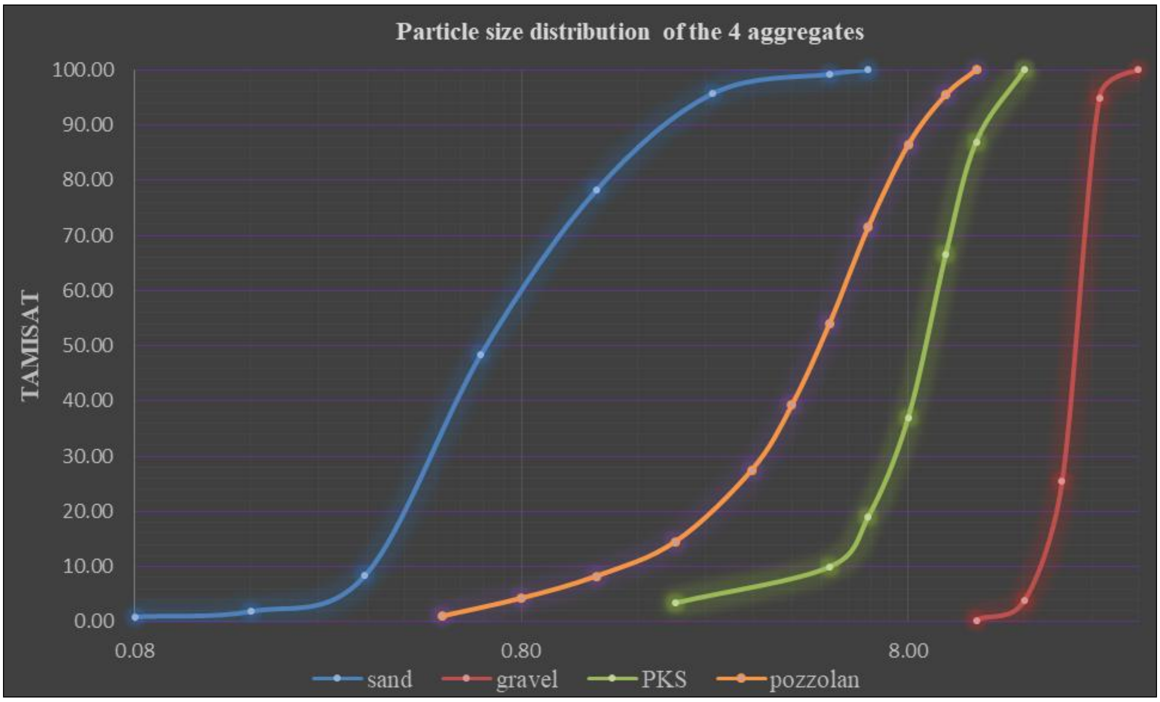

Fig 3: Particle size distribution of the four aggregates (comparative chart showing the grading curves of sand, gravel, palm kernel shell, and pozzolan)

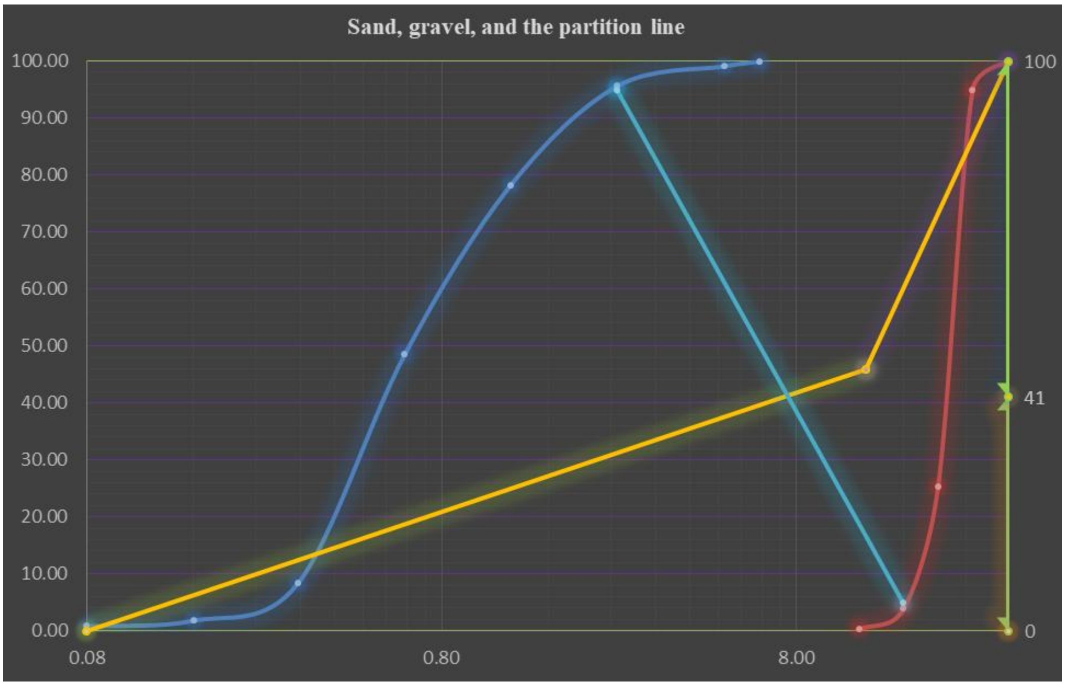

Fig 4: The particle size distribution of sand, gravel, and their partition line

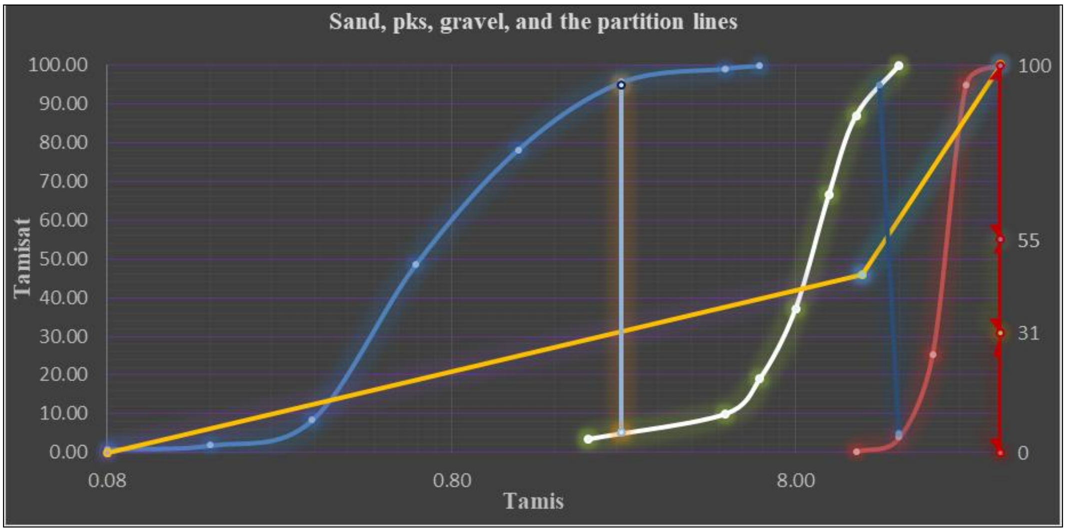

Fig 5: The particle size distribution of sand, gravel, PKS, and their partition lines

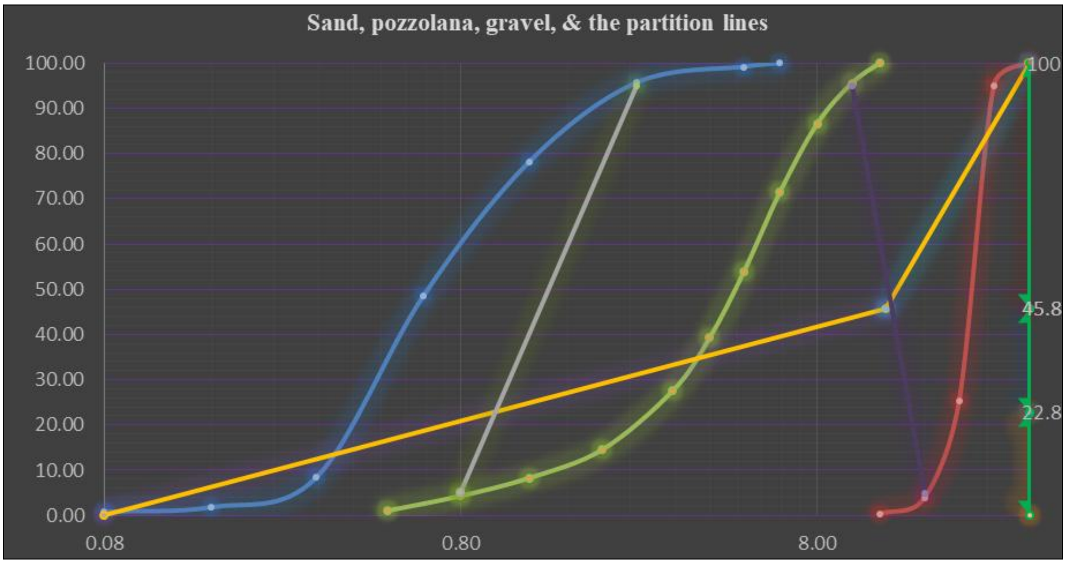

Fig 6: The particle size distribution of sand, gravel, pozzolan & their partition lines

Table 4: Summary of mix design used during casting

Concrete type	classical	With 24% PKS	With 23% pozzolan	With 34% PKS	With 33% pozzolan
Cement (kg)	370.0	385.0	370.0	370.0	370.0
Water (kg)	194.5	194.5	194.5	194.5	194.5
Sand (%)	41.0	31.0	22.8	27.0	18.8
Sand (kg)	692.7	431.4	364.3	431.4	300.4
Gravel (%)	59.0	39.0	54.2	39.0	48.2
Gravel (kg)	1115.2	893.0	967.1	695.9	860.1
Pozzolan (%)	-	-	23.0	-	33.0
Pozzolan (kg)	-	-	268.0	-	384.5
PKS (%)	-	24.0		34.0	-
PKS (kg)	-	199.7		283.0	-
Theoretical density	2372.0	2062.6	2164.0	1974.8	2109.5

Table 5: Water absorption values of the different concrete formulations at various curing ages (3 to 28 days)

Curing age	NOR. Abs (%)	23% P. Abs (%)	24% PKS. Abs (%)	33% P. Abs (%)	34% PKS. Abs (%)
3.00	1.20	1.67	1.74	2.20	2.15
7.00	1.60	2.32	2.87	3.10	3.50
14.00	1.71	2.47	3.00	3.21	3.72
21.00	1.80	2.55	3.17	3.34	3.70
28.00	1.94	2.70	3.23	3.39	3.83

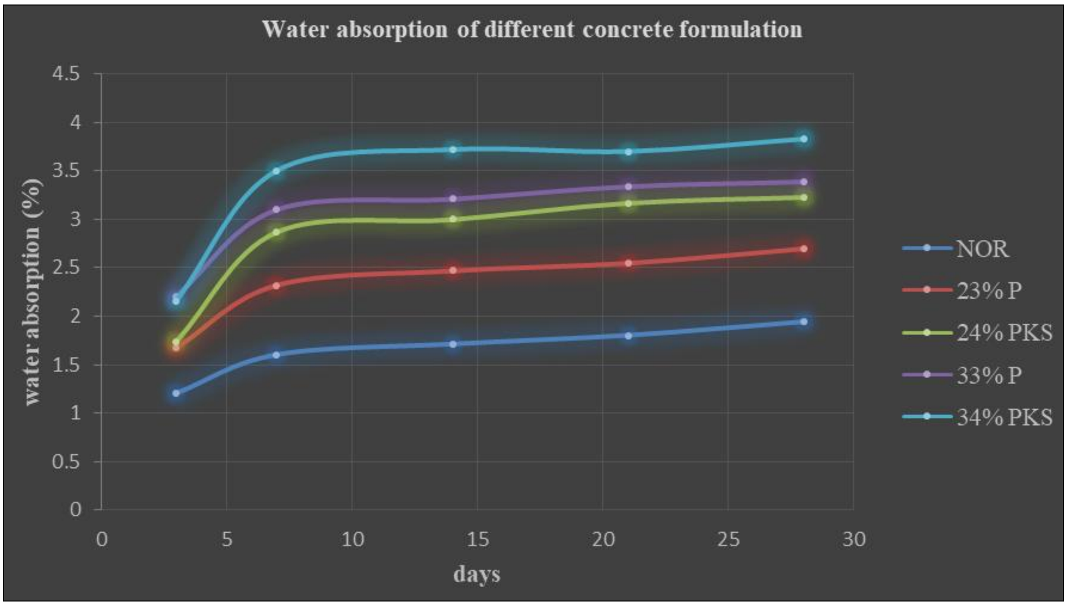

Fig 7: Evolution of water absorption with curing time for different formulation

Discussion

After laboratory work we obtained

- Grain size distribution of sand used in concrete mix design. The curve shows a good distribution of fine particles between 0.08 and 0.8 mm, indicating a moderately fine sand well suited to ensure good concrete workability. The sand exhibits a well-graded profile characterized by a smooth and continuous transition between grain sizes. The cumulative retained percentages are regularly distributed between sieves 2.5mm and 0.16 mm; the sand has a fineness modulus of 2.68, classifying it as medium sand. This fine grading promotes efficient filling of voids between gravel or other coarse aggregates, thereby improving the compactness of the concrete. It also enhances the workability and cohesion of the cement paste. However, overly fine sand may increase water demand, requiring careful control of water-to-cement (w/c) ratio.
- The gravel exhibits a discontinuous grading with a relatively narrow spread. This is typical of coarse aggregates, with 69.6% cumulative retained on 20 mm sieve and 96.1% cumulative retained up to 16 mm. Most particles fall within the 12 to 25 mm range, which may result in a high void ratio if not adequately balanced by well-proportioned fine aggregate. Nevertheless, it remains suitable for lightweight concrete applications.
- The particle size distribution of palm kernel shell shows high concentration of grains between the 6.3 and 12 mm sieves. The remaining sieves retain only minimal material. This distribution suggests a low packing efficiency if PKS is used alone. Its use in concrete mix design therefore requires formulation adjustments to prevent excessive voids in the cement paste.
- The pozzolan exhibits a well-spread particle size distribution, with retained materials ranging from the 10 mm to the o.5 mm sieve. This well-graded aggregate plays a crucial role in improving both the compactness and the workability of the concrete. Its fine particle size distribution allows it to fill the voids left by coarser

particles, thus enhancing the overall cohesion of the mix.

- The natural aggregates, particularly the palm kernel, show a less continuous distribution, which can affect the packing density of concrete.
- The combination of these lightweight aggregates with an appropriate cement/sand ratio is crucial to compensate for their porous structure and high water absorption.
- The particle size analysis highlights a valuable complementarity among the various aggregates. It confirms that each material used has a distribution well suited to its role in the design of lightweight concrete. Sand and gravel ensure compactness and load-bearing capacity, pozzolan and PKS contribute to reduced weight and optimize thermal insulation properties.
- Following this dimensional characterization, attention now shifts to the fundamental physical properties namely, the real and bulk densities
- The large difference between real and bulk density reveals high internal porosity, which is beneficial for thermal insulation but may reduce mechanical strength. A carefully balanced mix design is required. Palm kernel shell is the lightest aggregate tested. It's very low real (1250 kg/m^3) and bulk (625 kg/m^3) densities reflect both its lightweight nature and its high porosity.
- Conventional aggregates (gravel and sand) exhibit low water absorption, allowing for stable and predictable water dosing during concrete production. On the other hand, pozzolan and palm kernel shell, due to their internal porosity, show significantly higher absorption rates. While this enhances thermal insulation by entrapping air, it also it also introduces high water demand variability that must be compensated during mix design.

Failure to account for aggregate absorption can result in:

- Overdosing water, which reduces mechanical strength
- Premature drying of the cement paste, impairing long-term durability

After complete drying (standardized 28-day period), the bulk density of ordinary concrete was 2350 kg/m^3, while concrete with 23% pozzolan measured 21000 kg/m^3 and with 24% palm kernel shell 1950 kg/m^3. Higher dosages 33% pozzolan and 34% palm kernel shell showed densities of 2025 kg/m^3 and 1850 kg/m^3, respectively. This demonstrates the high porosity of lightweight aggregates, especially palm shells, which increases with aggregate size.

Conclusion and Perspectives

Conclusion

This research successfully analyzed the physico-mechanical and thermal behavior of lightweight concretes formulated with CPJ 42.5 cement, natural pozzolan, and palm kernel shells, with the aim of optimizing both structural performance and thermal efficiency for sustainable construction applications. Through a combination of experimental tests, several concrete formulations were evaluated using different proportions of lightweight aggregates. The results confirmed that pozzolan and palm kernel shells possess essential physical properties, such as porosity, low density, and water absorption capacity, making them suitable as partial substitutes for conventional aggregates in the formulation of lightweight concrete. This confirms that it is possible to design high-performance lightweight concretes without compromising structural reliability. Furthermore, the study highlighted a strong correlation between density, porosity, and thermal conductivity of concrete, which is a key finding for the future optimization of eco-energy-efficient construction materials.

Perspectives

Although the present study provided relevant results on the properties of lightweight concretes based on PKS and pozzolan, further research remains necessary to deepen understanding and broaden the scope of applications of these materials:

- Durability: Study long-term durability parameters such as shrinkage, freeze–thaw resistance, and behavior against chemical attacks.
- Fire resistance: Explore the fire resistance properties of these concretes in order to assess their safety in high-temperature applications.
- Full-scale validation: Test and validate the performance of these formulations at the real construction site scale.

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