Study of the Compressive Strength and Thermal Behaviour of Lightweight Concrete in Cameroon

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Abstract: *This thesis contributes to sustainable innovation in construction materials. The primary objective is to evaluate the balance between mechanical strength, thermal behavior, and structural lightness, with the goal of identifying formulations best suited to energy-efficient and environmentally friendly building applications. To this end, several lightweight concrete mixtures were developed by partially replacing conventional aggregates with natural lightweight ones pozzolan and PKS used independently. The Dreux-Gorise method guided the mix design, and a cement fixed dosage of CPJ 42.5 is adopted. cylindrical specimens* $(16 \times 32\ cm)$ *are cast and subjected to standardized tests to assess fresh and dry density, compressive strength, porosity, and thermal behavior. The experimental results show a clear relationship between the type of lightweight aggregate and the overall concrete with 34% PKS achieved a dry density of 1850 kg/m*^{3} *and a compressive strength of 19.3 MPa at 28 days, while the formulation with 23% demonstrated a superior compressive strength of 24 MPa at 28 days with a density of 2100 kg/m*^{3}*. In addition to experimental testing, a digital validation of the compressive strength was conducted exclusively through numerical simulations performed in ANSYS, using literature-based values of thermal conductivity, specific heat capacity, and density consistent with the concrete*

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formulations developed in this study. The simulation aimed to analyzed transient heat transfer and to highlight the thermal insulation potential of lightweight concrete. This research provides a comparative insight into two rarely juxtaposed natural aggregates and reinforces the role of digital methods in evaluating thermal performance of materials

Keywords: lightweight concrete, palm kernel shell, compressive strength, thermal performance, digital simulation

INTRODUCTION

Gambhir in 2018 The use of lightweight materials in construction dates back to ancient times. As the Roman era, builders used natural volcanic aggregates, such as pozzolan, to lighten their structures and improve their durability. The Pantheon in Roma, completed in 128 AD, is a remarkable example of this approach, with its massive dome partially composed of lightweight concrete.

Figure 1: Roma Pantheon source (photos, 2021)

During the 20th century, advances in technology led to the industrial-scale production of lightweight concrete, facilitated by the introduction of artificial aggregates such as expanded clay, perlite, expanded polystyrene, and expanded shale. These materials were widely adopted in industrialized countries to reduce structural self-weight, improve thermal insulation, and simply handling during construction. According (Gambhir, 2018), this evolution paved the way for the standardization of lightweight concrete in modern prefabrication and composite structures. Since 1990s, interest in lightweight concrete has grown significantly in response to

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sustainable development goals and the need to reduce the environmental impact of construction materials. Numerous studies have explored the incorporation of recycled waste or industrial and agricultural by-products such as palm kernel shell, recycled polystyrene, and natural pozzolan, aligning with the principles of sustainable development and circular economy. This scientific and technical movement has opened the door to innovative formulations aimed at reconciling mechanical performance, thermal insulation, and valorization of underutilized resources. Today, lightweight concretes stand out as future- oriented materials, particularly well suited to the needs of modern construction, especially in high-energy-performance buildings.

LITERATURE REVIEW

Compressive strength is the primary indicator used to evaluate the performance of concrete. In lightweight concretes, compressive strength is closely related to bulk density: the lower the density, the lower the compressive strength tends to be several factors influence the compressive strength of lightweight concrete, including: the intrinsic strength of the lightweight aggregates, the paste content, the quality of the interfacial transition zone (ITZ) between the aggregates and cement matrix. With appropriate formulation and the right selection of lightweight aggregates, it is possible to achieve compressive strength comparable to that of conventional concrete, especially for non-structural or semi-structural applications (Dr. Peter Lunk, 2015).

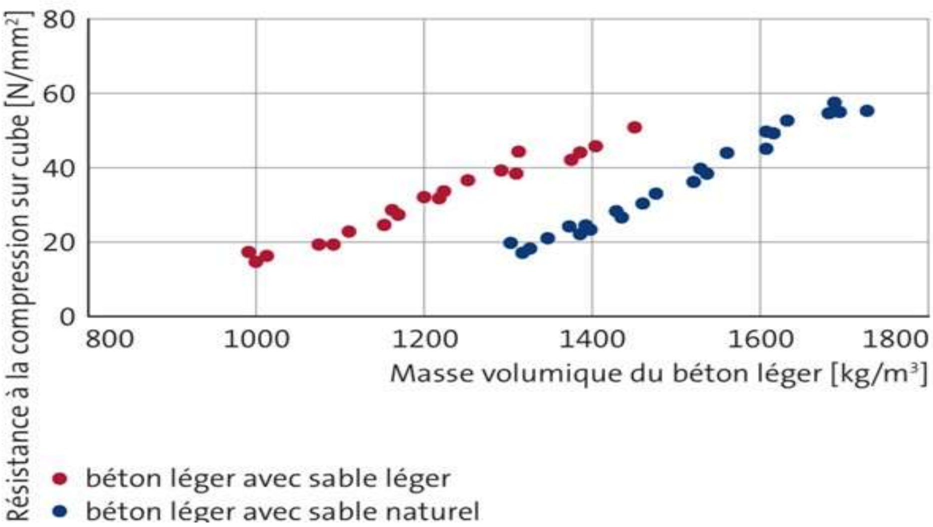

Figure 2:Variation of compressive strength with bulk density source (Dr. Peter Lunk, 2015)

The modulus of elasticity, or young's modulus, expressed in GPa, reflects the rigidity of a material under stress. In concrete, it indicates the resistance of the material to deformation when subjected to loads such as compression. The modulus of elasticity in lightweight in lightweight concrete is generally lower than that of conventional concrete, due to: the porosity of lightweight aggregates, which have a lower modulus than dense natural aggregates, the overall porosity of the concrete matrix, mix design factors such as the w/c ratio, curing conditions, and use of admixtures. The relationship between the dry density and the modulus of elasticity for various types of lightweight concrete is illustrated in the following figure:

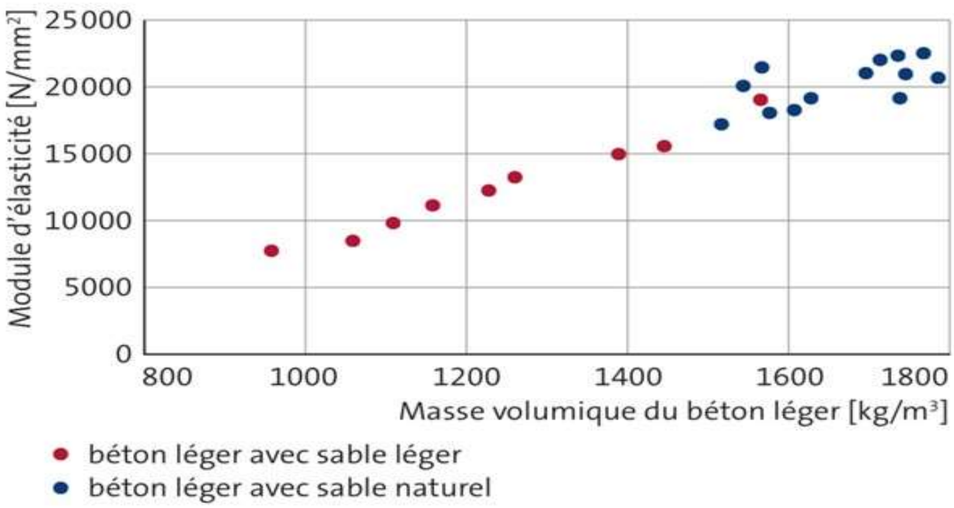

Figure 3: Relationship between the dry density and the modulus of elasticity for various types of lightweight concretes . (Dr. Peter Lunk, 2015)

Refers to the ability of a material to conduct heat. This parameter is essential for describing how heat distributes through the material during heating. Lightweight concretes exhibit significantly lower thermal conductivity values than conventional concretes, mainly due to their porous structure and the low thermal conductivity of their constituents. The primary factors influencing thermal conductivity include: the water content of the concrete, the type of aggregates, the degree of saturation with liquid water, the overall mix design (Real, 2023). Moreover, thermal conductivity tends to decrease as the temperature rises, making lightweight concrete an effective insulating material for thermal management in building.

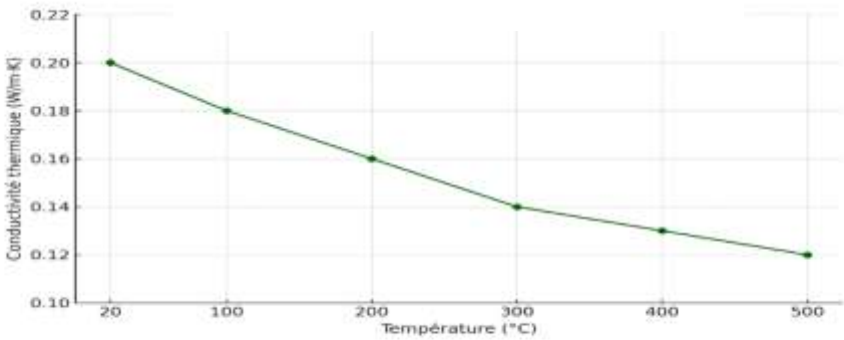

Figure 4: Evolution of the thermal conductivity of lightweight concrete based on palm kernel shell versus temperature source (Anowai, 2023).

Refers to the amount of energy required to raise the temperature of a unit mass of that material by 1°C. In other words, it describes the material's ability to store thermal energy. The variation in specific heat capacity in concrete is mainly related to the composition of the cement paste and the type of aggregates used. Lightweight concrete typically exhibits higher specific heat capacity values than conventional concretes (Sci., 2021). This is attributed to the greater ability of lightweight aggregates to retain thermal energy within their porous structure. As temperature increases, specific heat capacity also rises, this increase is linked to the desorption of water from concrete's components. At high temperatures, additional energy is required for processes such as dehydration and chemical decomposition occurring in the concrete matrix.

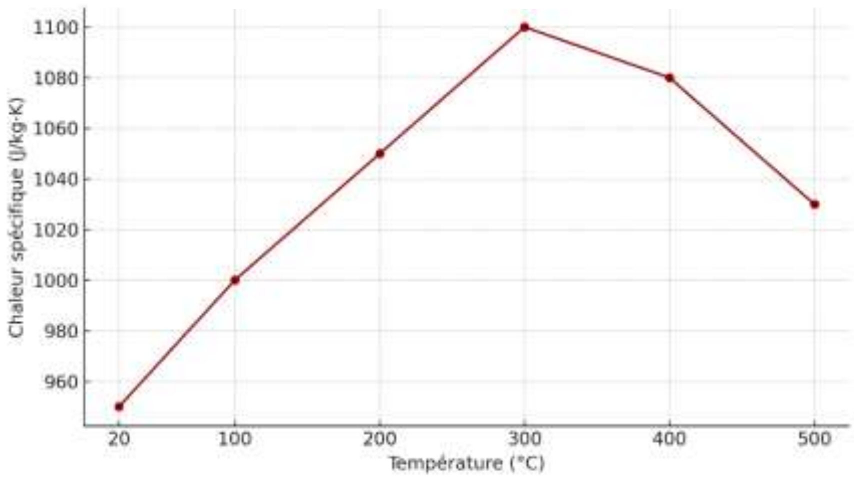

Figure 5 : Evolution of the specific heat capacity of lightweight concrete based on palm kernel shell as a function of temperature source (Anowai, 2023).

MATERIALS AND METHODS

- **Mix design of lightweight concrete**

The mix design of concrete is a crucial phase in the research process, as it directly determines the material's physical, mechanical, and thermal properties. The objective is to determine, for a given volume typically 1 m^3, the optimal quantities of each component (cement aggregates, water, and possibly admixtures) in order to produce concrete that meets performance requirements in terms of workability, strength, and durability all while satisfying the constraints related to bulk density and thermal performance, especially very important in the case of lightweight concrete.

The Dreux-Gorisse method

- Determination of the water-to-cement ratio (c/w) which links the compressive strength to the ratio of c/w, as follows:

$$\sigma'_{28} = G'\sigma'_{c}.(\frac{C}{W} - 0.5) \quad (1)$$

With

σ'_{28}: mean compressive strength at 28 days

σ'_{c}: true strength class of the cement at 28 days (MPa)

C: cement content in kg/m^3 of concrete

W: total water content (liters per m^3 of dry material)

G': granular coefficient, which depends on the aggregate quality and maximum grain size (D_{max})

Table 1 : Granular coefficient G' based on aggregate quality and size source (Yousfi, 2016).

Aggregate quality	Dimension D_{max} of aggregates		
	Fine $D_{max} < 12.5$ mm	Medium $20 < D_{max} < 31.5$	Coarse $D_{max} > 50$ mm
Excellent	0.55	0.60	0.65
Good / Common	0.45	0.50	0.55
Fair	0.35	0.40	0.45

- Determination of cement dosage C

Once the c/w and desired slump value are fixed, the cement content C can be obtained using design charts (abaci) correlating slump, cement content, and water demand. These design aids are derived from empirical observations and standard concrete formulation databases, adapted in the Dreux-Gorisse method.

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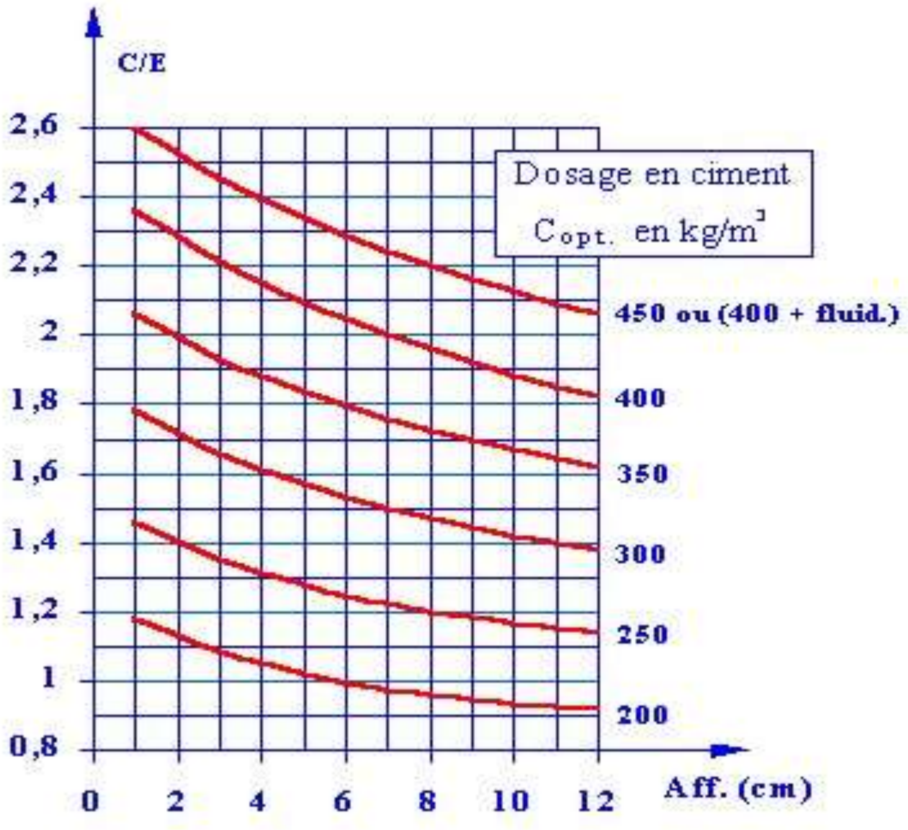

Figure 6 : Chart for determining C_{opt} source (Yousfi, 2016)

- Determination of water content
- adjustment on the cement and water dosage

It is important to note that when the maximum grain size (D_{max}) of the aggregates present in the mix differs from 20 mm, a correction on the cement and water content is required in order to achieve the desired workability.

Table 2 : Paste content correction according to maximum aggregate size D_{max} source (Yousfi, 2016)

Maximum aggregate size D_{max} (mm)	5	8	12.5	20	31.5	50	80
Correction on paste dosage (%)	+ 15	+ 9	+ 4	0	- 4	- 8	- 12

- Determination of the optimal granular mixture with minimum voids
- Ideal packing curve according to Dreux

The Dreux reference line represents the theoretical grading line of an aggregate mixture that achieves minimum void content. The Abscissa (X) and the ordinate (Y), expressed respectively in terms of the modulus of the sieve size and the cumulative passing percentage. Since the maximum aggregate size D_{max} exceed 20 mm, the abscissa module X is computed using the following empirical relationship:

$$Module(X) = \frac{Module(D_{max})+38}{2} \qquad (1)$$

For $D_{max} = 31.5\ mm \quad , Module(31.5) = 46$

$$Module(X) = \frac{46+38}{2} = 42$$

This value is used to define the breakpoint A of ideal packing line, as proposed by Dreux.

Table 3 : Correction factor K based on Aggregate shape, vibration mode, and cement dosage source (Yousfi, 2016)

Vibration		Low		Normal		High	
Aggregate shape (of sand particularly)		Rounded	Crushed	Rounded	Crushed	Rounded	Crushed
Cement dosage	400 + Fluid	- 2	0	- 4	- 2	- 6	- 4
	400	0	+ 2	- 2	0	- 4	- 2
	350	+ 2	+ 4	0	+ 2	- 2	0
	300	+ 4	+ 6	+ 2	+ 4	0	+ 2
	250	+ 6	+ 8	+ 4	+ 6	+ 2	+ 4
	200	+ 8	+ 10	+ 6	+ 8	+ 4	+ 6

In this study:

Chosen value of K=1

The sand shape correction factor K_s is computed using the formula

$$K_s = 6 \times M_{fs} - 15 \ \ with\ M_{fs} = 2.68\ , K_p = 0 \qquad (2)$$

$K_s = 6 \times 2.68 - 15 = 1.08$

$$Y = 50 - \sqrt{1.25D_{max}} + K' \quad with \quad K' = K + K_p + K_s \qquad (3)$$

Thus, the reference points of the ideal grading line (OAB)

- Point O is (0, 0)
- Point A is (42, 45.8)
- Point B is (42, 100)
- The X-axis corresponds to the sieve modulus, and the Y-axis to the cumulative passing percentage. This broken line OAB serves as the target Grading curve for granular skeleton with minimum voids.

- Determination of concrete compactness
  - For conventional concrete

$$\gamma = \gamma_0 + \gamma_r \qquad (4)$$

$\gamma = 0.830 - 0.01 = 0.82$

  - for lightweight concrete

$$\gamma = \gamma_0 + \gamma_r + \gamma_l \qquad (5)$$

$\gamma = 0.830 - 0.01 - 0.03 = 0.790$

- Calculation of the absolute volume of cement

To compute the absolute volume of cement (V_c) used in the mix design, the following formula is applied:

$$V_c = \frac{M_c}{\rho_C}$$

Where: V_c absolute volume of cement in m^3, M_c mass of cement used in kg, ρ_c density of the cement in kg/m^3.

- Determination of the volume fractions of aggregates
- Determination of the masses of Aggregates

The mass of each aggregate is computed from its absolute volume using the following relationships:

Example for sand

$$V_s = \frac{\%S \times V_{agg}}{100} \qquad (6)$$

$M_s = \rho_{ab.s} \times V_s$

- Final theoretical mix design

The final theoretical formulation of the lightweight concrete expresses the mass (in kg) of each constituent per cubic meter of concrete. The total mass of the mix is given by:

$$M_{con} = M_c + M_w + M_{agg} \qquad (7)$$

RESULTS

Compressive strength tests were carried out on five concrete formulations at different ages (3, 7, 10, 14, 21, 28, and 90 days). The results are presented in table 15 and discussed thereafter.

Table 4 : Compressive strength results of the different lightweight concrete formulations.

CURING DAYS	STRESS (MPa). NOR	STRESS (MPa). 23% P	STRESS (MPa). 24% PKS	STRESS (MPa). 33% P	STRESS (MPa). 34% PKS
3	12.1	10.4	10	9.9	8.7
7	15.1	13.9	13.4	13	11.1
10	17.2	16	15.9	15.4	13.3
14	19.6	18.9	18.1	17.6	16.2
21	22.4	21.2	19.9	19.9	18
28	24	23.1	21.7	21.8	19.3
90	27	26	24	24.5	21.3

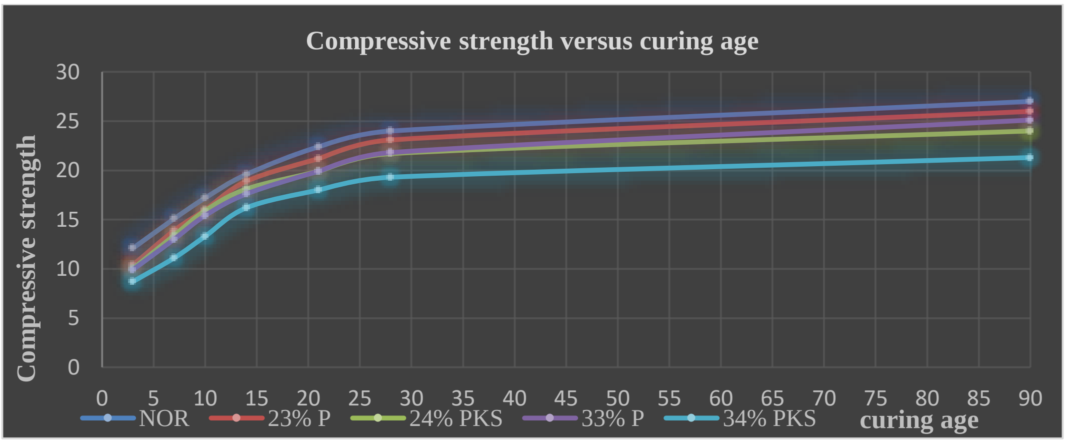

Figure 7 : Variation of compressive strength with curing age for all formulations

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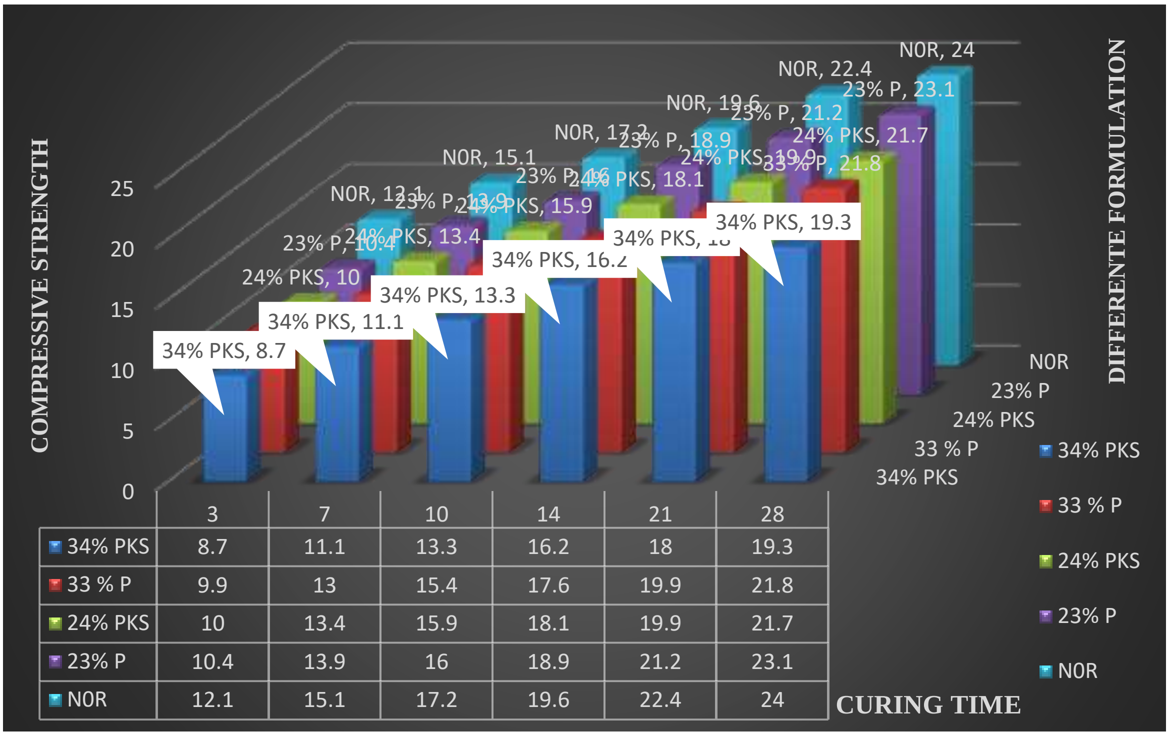

Figure 8 : Comparative compressive strength of the formulations at 3, 7, 21. And 28 days.

Table 5 : mechanical and physical properties of concrete mixes used for ANSYS simulation

formulation	Density (kg/m^3)	Young modulus E (GPa)	Poison coefficient	Stress at 28 days (MPa)	Force (kN)
Normal concrete	2350	28	0.21	24	482.4
23% pozzolan	2100	26.5	0.21	23.1	464.3
24% PKS	1975	24	0.21	21.7	436.2
33% pozzolan	2025	25	0.21	21.8	438.2
34% PKS	1850	22.5	0.21	19.3	387.9

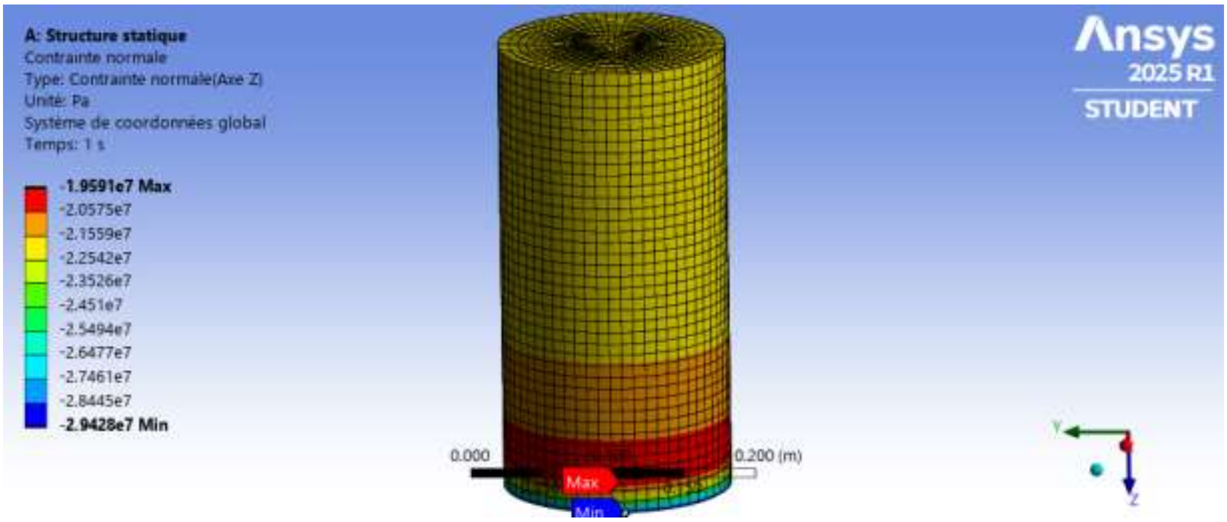

Figure 9 : Normal stress Distribution in concrete with 33% pouzzolan under axial load ANSYS static structural simulation

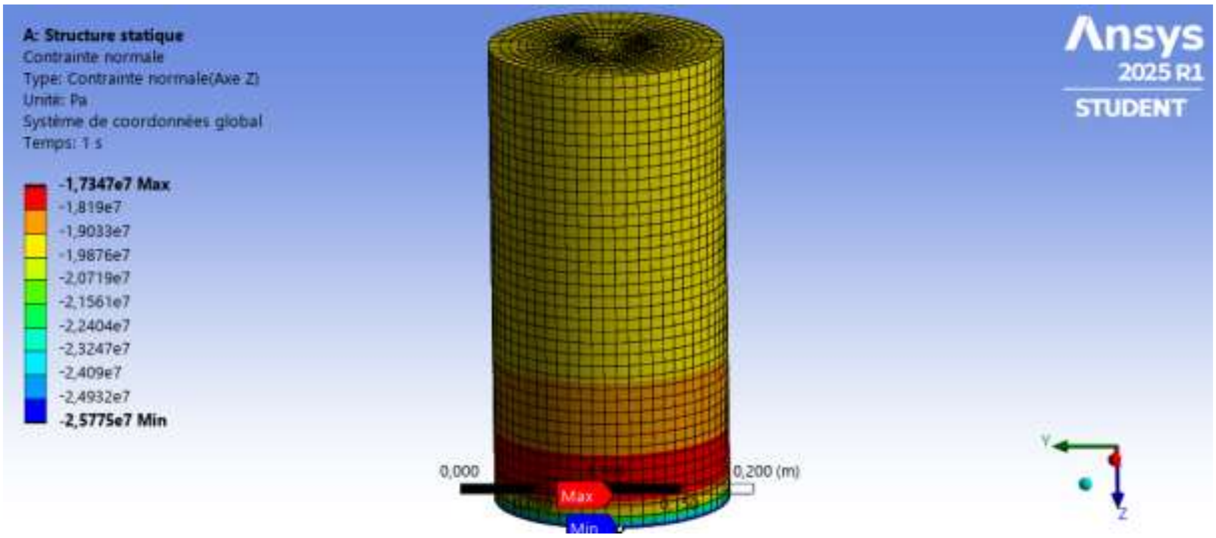

Figure 10 : Normal stress Distribution in concrete with 34% palm kernel shell under axial load ANSYS static structural simulation.

Note:

The thermal analysis of the five concrete including normal concrete, variants incorporating palm kernel shell and pozzolan was carried out using numerical simulation in ANSYS. The results were visualized through two main thermal indicators.

- The evolution of average internal temperature with time

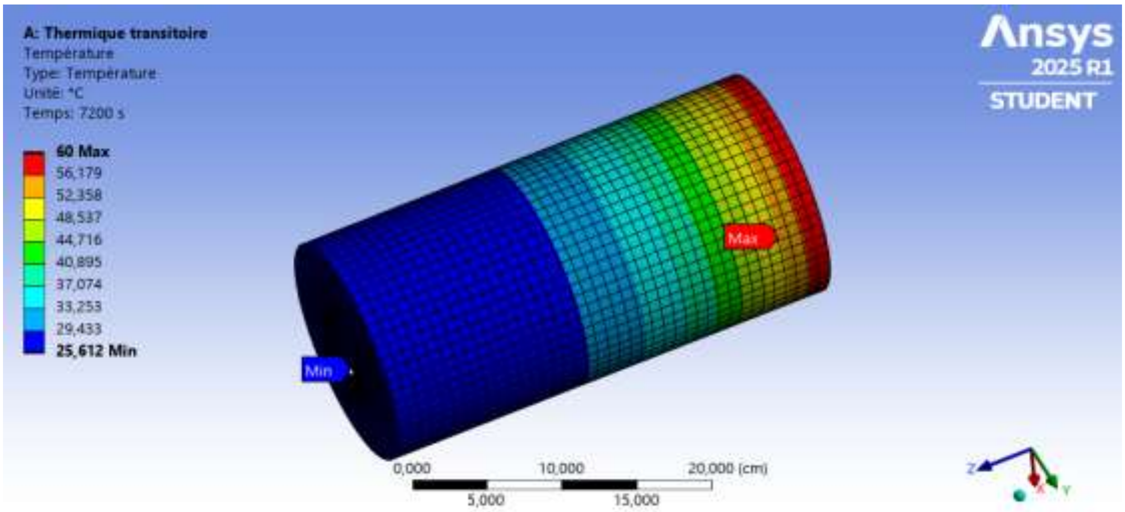

Figure 11 : Transient thermal simulation in ANSYS showing heat propagation in normal concrete after 7200 seconds

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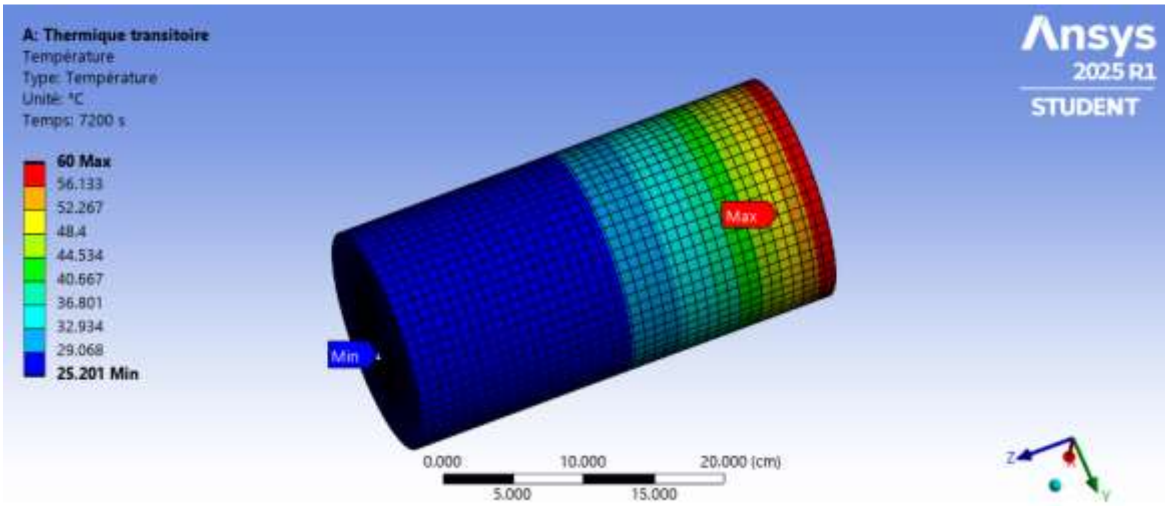

Figure 12 :Transient thermal simulation in ANSYS showing heat propagation in 33% pozzolan concrete after 7200 seconds

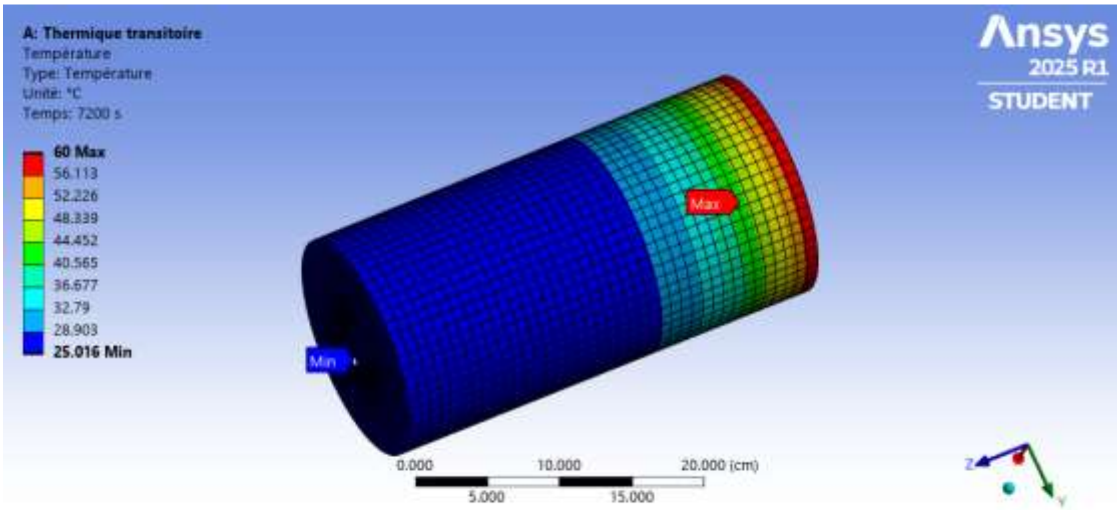

Figure 13 :Transient thermal simulation in ANSYS showing heat propagation in 34% PKS concrete after 7200 seconds

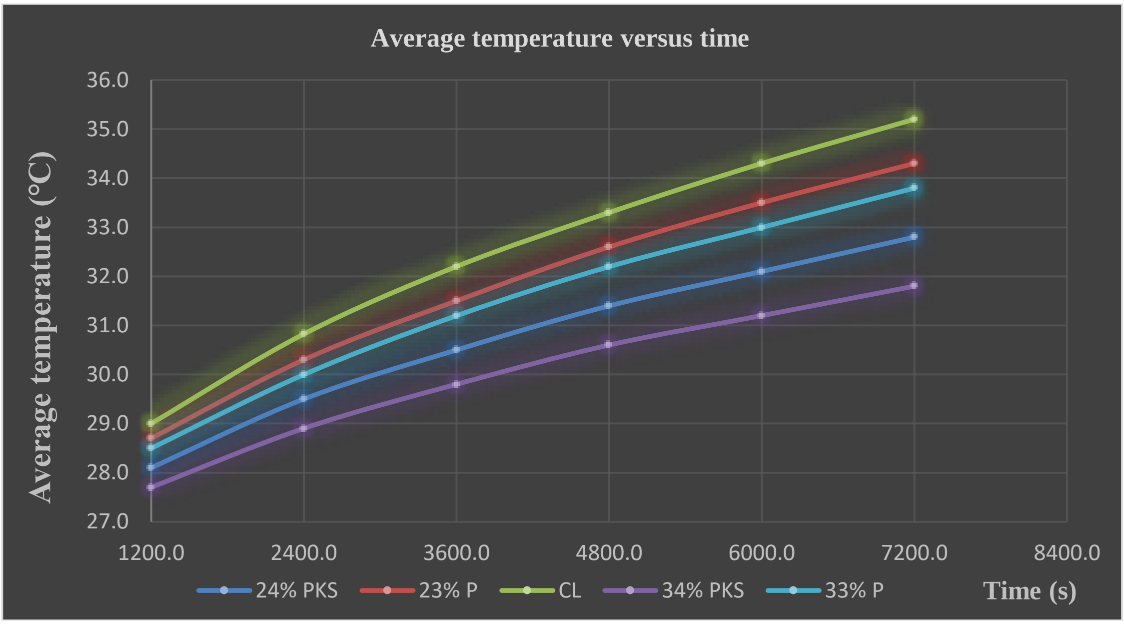

Figure 14: Average temperature versus time

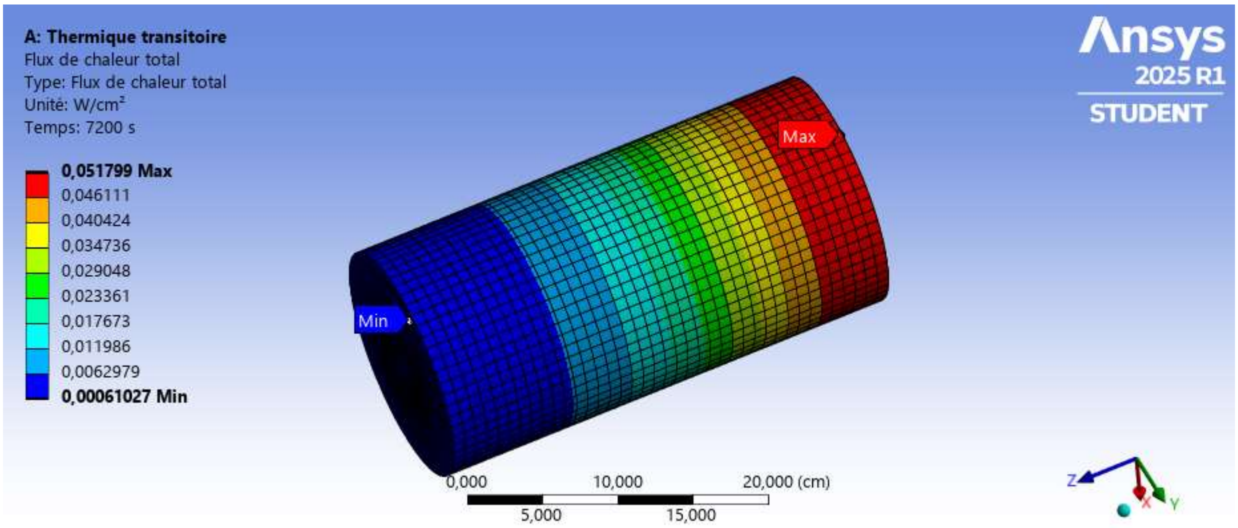

Figure 15: Heat flux distribution in the normal concrete formulation after 7200 seconds

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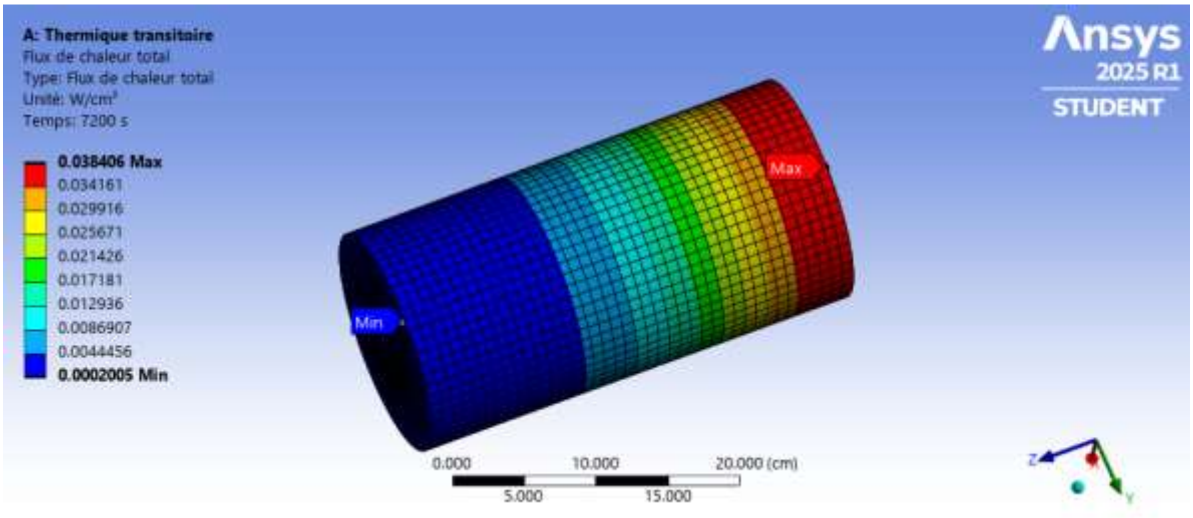

Figure 16: Heat flux distribution in the 33% pozzolan concrete formulation after 7200 seconds

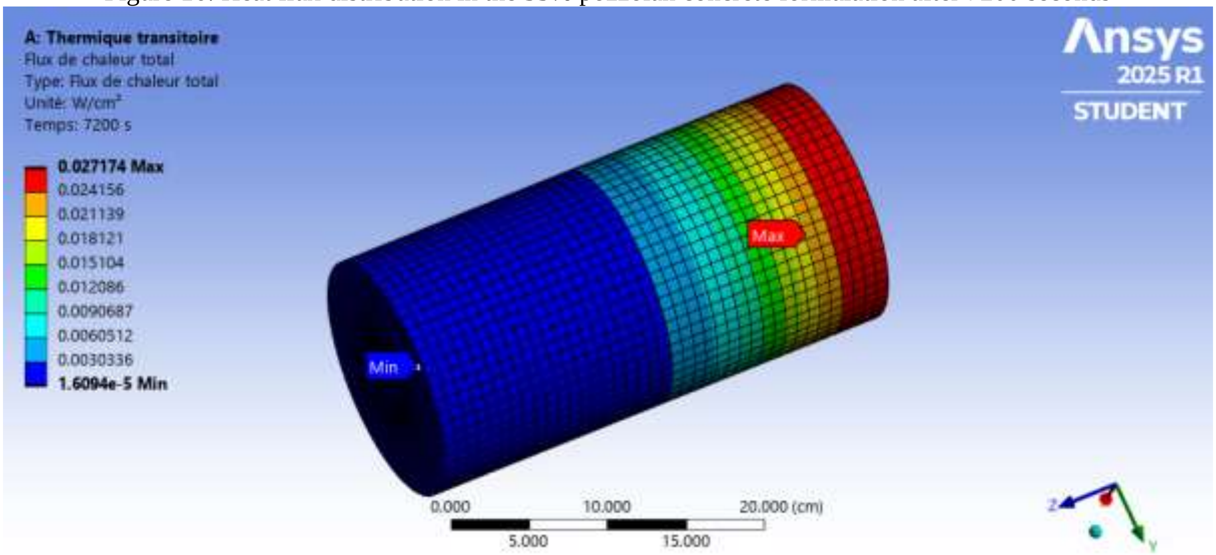

Figure 17: Heat flux distribution in the 34% PKS concrete formulation after 7200 seconds

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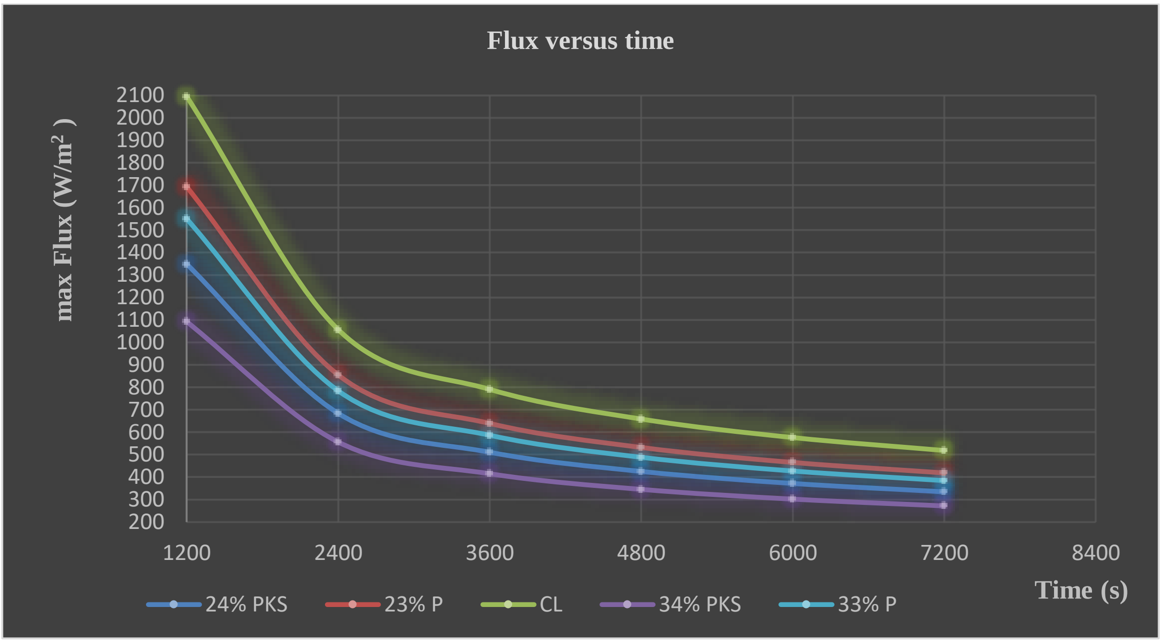

Figure 18: The graph presents the time-dependent evolution of the maximum heat flux in different concrete formulations during the transient thermal simulation.

DISCUSSION

- In the ANSYS simulations, the stress values displayed in the contour plots are inherently negative due to the compressive nature of the loading applied. However, since the concrete specimens undergo pure compression, only the absolute values of these stress results are considered for analysis and comparison. The ANSYS-based simulations provided a reliable visualization of compressive stress distribution across the five concrete formulation. Normal concrete formulations exhibited the most concentrated stress zones, indicating higher stiffness and less energy dissipation. In contrast, the lightweight concretes particularly the 34% PKS low concentrated zones. The simulated average compressive stress values were in strong agreement with experimental values obtained at 28 and 90 days, confirming the experimental results.
- This figure 34 highlights a rapid and deep temperature propagation through the entire concrete body. The intense red zones and sharp thermal gradients indicate minimal resistance to heat transfer, confirming the high thermal conductivity of dense normal concrete.
- This profile shows a moderate diffusion as compared to normal concrete, with shallower penetration compared to the control. The finer pozzolanic structure present in the mix slows heat infiltration while maintaining uniform internal distribution.

- Here, the thermal front is noticeably attenuated as we can see in the minimum value attained 25.201°C. the majority of the volume remains in lower temperature bands, confirming that increased pozzolan content improves internal thermal resistance and limits temperature accumulation.
- The temperature spread is less aggressive, with a visible reduction in high-temperature zones. The core remains cooler for longer, demonstrating that PKS introduces an internal barrier that delays and dampens thermal transmission.
- This is the most thermally resistant configuration. Figure 38 shows a highly localized surface heating with minimal spread toward the interior. The widespread blue zones confirm that this material configuration is highly effective in insulating against heat transfer.
- Classical concrete recorded the highest temperature rise, indicating rapid and deep heat penetration. This reflects a high thermal conductivity, confirming its known behavior as a dense, compact material with limited insulation capacity. Lightweight concretes, particularly those with PKS (24% and 34%) and pozzolan (23% and 33%), exhibited progressively lower internal temperatures. The 34% PKS formulation maintained the lowest temperature values, suggesting an excellent resistance to thermal penetration.
- High and concentrated heat flux zones confirm rapid thermal transfer due to is dense internal structure, indicating poor insulating capacity.
- Distributed but slightly elevated heat flux levels, suggesting passive thermal performance compared to conventional concrete.
- The distribution of the heat flux through the concrete specimen shows an improved thermal resistance since it attained a minimum flux of 2 W/m^2 and almost constants in a considerable range.
- Moderate heat flow intensity with partial diffusion, illustrating improved thermal resistance compared to conventional concrete.
- Highly diffuse and reduced heat flux, demonstrating strong thermal dampening and excellent insulating characteristics.

Classical concrete again displayed the highest heat flux, with a sharp peak, illustrating a fast transfer of energy a direct consequence of it dense mineral structure. The flux values in lightweight concretes are significantly lower especially in 34 PKS and 33% pozzolan, where the curves show gentle slopes and delayed peaks. Theses behavior point to their resistive, porous nature, which absorbs and slows down heat propagation. Interestingly the flux peak occurs earlier in lightweight concrete than in lightweight mixes, meaning that not only does it transmit more heat, but it does so more quickly. By superimposing the average temperature and heat flux behaviors, key thermal insights emerge:

- In classical concrete, high heat flux leads to rapid temperature buildup, resulting in a poor thermal regulation.
- In contrast, PKS and pozzolan-based concretes allow limited flux, which translates into slower and more controlled temperature rise.
- The best thermal balance is observed in 34% PKS concrete: its heat flux remained low and stable throughout, while its internal temperature curve was the flattest, a clear indicator of superior insulation.

CONCLUSION AND PERSPECTIVES

CONCLUSION

This research has successfully investigated the mechanical and thermal behavior of lightweight concretes formulated with CPJ 42.5 cement, natural pozzolan, palm kernel shell (PKS), aiming to optimize structural performance and thermal efficiency for sustainable construction applications. Through a combination of experimental testing and numerical simulations, several concrete formulations were evaluated based on varying proportions of lightweight aggregates. The results confirmed that pozzolan and PKS possess key physical Characteristics, such as porosity, low density, and water absorption capacity, that make them suitable for use as partial substitutes for conventional aggregates in lightweight concrete formulation in terms of mechanical performance, compressive strength tests showed that all lightweight concrete formulations maintained structural adequacy, with 90-day strength ranging from 19.3 MPa to 26 MPa. While the reference (classical) concrete reached the highest values, certain lightweight mixes, especially those with 24% and 34% PKS, achieved a favorable balance between strength and reduced mass, while those with pozzolan excelled in mechanical strength with comprehensible lightness and thermal properties suitable for mid-range balance properties demands. This confirm that it is possible to formulate efficient lightweight concretes without compromising structural reliability. Thermal simulations performed in ANSYS provided deeper insight into the insulating potential of each formulation. The results demonstrated that concrete incorporating higher proportions of PKS and pozzolan significantly reduced internal temperature rise and heat flux, indicating superior thermal resistance. Notably, the 34% PKS formulation exhibited the most stable thermal profile, confirming its high suitability for thermal insulation applications. The close alignment between simulated and experimental data reinforces the reliability of the approach used and validates the potential of these lightweight materials. The research has therefore fulfilled its primary objectives and successfully addressed the central research questions. It demonstrated that varying the type and proportion of natural lightweight aggregates can meaningfully influence the mechanical and thermal properties of concrete.

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:

- ✓ Microstructural analysis: Use scanning electron microscopy (SEM0 or X-ray diffraction (XRD) to examine the internal structure and hydration mechanisms of mixes.
- ✓ Hybrid Aggregates: Experiment with hybrid combinations of PKS and pozzolan or other bio-based materials to further improve performance.
- ✓ Life Cycle Assessment (LCA): Conduct full environmental impact assessments to validate the ecological benefits of these materials.

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