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Analysis of thermally treated “plastic-pozzolanic” modified mortars and their mechanical properties

ABSTRACT

The recycling of plastic waste in construction materials offers a potential pathway toward sustainability while improving thermal performance. This study examines mortars in which natural sand is partially replaced by thermally treated PET waste by a natural source (pozzolan). Three phases were conducted: (i) experimental determination of compressive strength, Young’s modulus, and thermal conductivity at different LCA replacement levels; (ii) homogenization analysis to estimate equivalent elastic and thermal parameters, compared with literature data; and (iii) numerical simulations of heat transfer through simply supported beams with 2 cm and 4 cm coatings. The results indicate that thermally treated PET incorporation reduces compressive strength relative to the control mortar, though values remain sufficient for non-structural applications such as finishing mortars (e.g., 22 MPa at 100% substitution). In contrast, thermal performance improved significantly, with conductivity decreasing from 1.5 to 0.71 W/m·K, leading to enhanced resistance to heat transfer. These findings demonstrate the potential of thermally treated PET-modified mortars as eco-efficient materials that combine adequate mechanical capacity with excellent thermal comfort.

Keywords: *Plastic waste, mortar, thermomechanical properties, the deflection, heat transfer*

1. INTRODUCTION

The valorization of plastic waste in cementitious materials addresses two major challenges simultaneously: reducing environmental pollution from non-biodegradable plastics and promoting the development of sustainable construction materials.

Most current research focuses on the possibility of reducing waste and achieving a cleaner environment. Plastics constitute a significant portion of this waste. For this reason, this research aims to use this waste to produce an ecological mortar. Ikpong Sunday Umo [1] studies specifies the impact of climate change, caused by pollution, on rivers. Ikpong Sunday Umo [2] examined the accumulation of waste and the resulting geographical changes can lead to damage.

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Several studies have been conducted on the topic of recycling and the reinforcement of concrete or mortars in order to minimize waste or carbon gas emissions. Harrat et al. [3] have investigated silica and studied the phenomena within beams. Chatbi et al. [4] examine the addition of silica within slabs. Benfrid et al. [5] found that nano-glass negatively influences thermal bending. Dine el hannani et al. [6] developed several additives for concrete. Kecir et al. [7] studied the specific characteristics of adding nano-iron to concrete. Chatbi et al. use the inclusion of nano-clay to reinforce concrete [8]. Harrat et al. [9] added iron particles to concrete, which resulted in a very good performance. Benfrid et al. [10] studied the non-linear behavior of plaster reinforced with Diss.

Latroch et al. [11] study the feasibility of using plastics as additives in mortars. Benosman et al. [12] have developed a very detailed study on polymer mortars, particularly on their physical, chemical, and mechanical properties. Benosman et al. [13] also studied the chemical and thermophysical behavior of PET waste polymers. Haba et al. [14] are investigating the vision of creating a new construction material using plastic mortars. Barka et al. [15] use plastic fibers to study the rheological behavior of mortars, along with mechanical tests. Turpin et al. [16] examine the thermomechanical behavior of mortars whose formulation is modified by geopolymers. Hacini et al. [17] modified the microstructure of mortars by introducing SPET-type polymers into the cementitious matrix. Badache et al. [18] examined mortars reinforced with innovative composites from plastic resources. Houti et al. [19] in their study, focused on the hygrothermal effect on mortars containing PVC waste plastic. Omar et al. [20] are studying the valorization of plastics in construction materials. Gouasmi et al. [21] replaced natural sand with a siliceous plastic composite sand. Gouasmi et al. [22] fabricated a new lightweight mortar by incorporating plastic waste. Gouasmi et al. [23] are pursuing advanced studies on the damage of mortars containing plastic, using both destructive and non-destructive resistance tests. Kazi Tani et al. [24] are conducting complex studies on the resistance of plastic-reinforced mortars in different aggressive environments. Benosman et al. [25] address the topic of PET material durability, including its use in a cementitious matrix for the production of new mortars. C.C. Ike [26] proposes analytical solutions for beam deflection using the Ritz method. CC Ike [27] also provides solutions to beam problems through the mathematical analogy of Fourier. CC Ike [28] studies the deflection of beams resting on elastic foundations. Ercan Işık [29] examines the effects of polymer fibers on concrete strength. The results reveal that these fibers significantly increase the shear capacity. Ercan Işık et al. [30] studied concrete failures during the 2023 Kahramanmaraş earthquakes. F. Turan et al. [31] examine nonlinearity in the bending of beams with included porosity. F. Turan et al. [32] are involved in studying all possible mechanical behaviors of porous beams. Benfrid et al. [33] provide new methods for calculating thermal transfer in concrete walls reinforced with glass powder. Kwasi-Effah et al. [34] conducted a study on heat transfer in fluid media. Kwasi-Effah et al. [35] develop energy systems and measure conductivity for an efficient solar energy system.

In this study, the preparation of a mortar with different concentrations of thermally treated plastic was carried out. The reinforcement concentration ranges from 0% to 100% of this a thermally treated plastic acting as a pozzolanic material. Within the cementitious matrix, with a binder content of 25%. The mixtures are designated as LMPNS"#" (for " Lightweight Mortar obtained by adding lightweight composite aggregate from Plastic waste and Natural Sources"). Mixture number 1 serves as the reference. These are mortars used for finishing, cladding, and insulating a building's structure. They include specialized types such as leveling mortars to prepare screeds, tile adhesives for tiling, rendering mortars for facades and interiors, and repair mortars to correct defects and make surfaces flat and ready for finishes.

This study is structured in three main stages. First, experimental tests were carried out to determine the thermomechanical properties of mortars incorporating thermally treated PET waste by a natural source (pozzolan) as a partial replacement for natural sand. Second, a homogenization analysis was conducted to estimate equivalent elastic and thermal parameters and to compare them with values reported in the literature. Third, numerical simulations were performed to evaluate heat transfer and mechanical behavior in simply supported beams with mortar coatings of different thicknesses. The novelty of this work lies in the combined use of experimental and numerical approaches to assess both mechanical and thermal performance of PET-modified mortars, which has not been comprehensively investigated in previous studies. The research addresses the gap in understanding the dual effect of thermally treated PET inclusion on strength and thermal efficiency. The main contributions of this study are: (i) providing experimental evidence of the trade-off between mechanical strength and thermal performance, (ii) validating homogenization models through comparison with experimental data, and (iii) demonstrating the potential of PET-modified mortars for sustainable non-structural applications where thermal comfort is a priority.

2. EXPERIMENTAL METHOD AND AN ANALYTICAL MODE

2.1. Experimental method

Analysis of the mechanical properties of composite mortars based on composite lightweight aggregates designed from a thermally treated PET plastic waste by a natural source (pozzolan) at 28 days of age. The composite lightweight aggregate (LCA) fraction is 0 to 3.15 mm. Test specimens measuring 4 x 4 x 16 cm^3 were used for the tests. The mortar formulation and the measurement of its mechanical properties were carried out using the standard NF EN 196-1 [36]. To estimate the thermal conductivity, the standard ISO 8302-91 [37] was applied. The formulation is noted in table 1.

Table 1. Composition of LMPNS composite mortars

Parameters	LMPNS1	LMPNS2	LMPNS3	LMPNS4	LMPNS5
LCA/S substitution rate (%) *	0	25	50	75	100
SP Superplasticizer (%) **	2.00	1.20	1.00	0.75	0.50
Cement (g)	450	450	450	450	450
W/C	0.5	0.5	0.5	0.5	0.5

*:Volumetric substitution of sand by LCA.

**:Percentage of superplasticizer relative to the mass of cement.

Figure 1 illustrates the experimental program adopted in this study, including the flowability test, mechanical strength tests, ultrasonic pulse velocity (UPV) test, and thermal properties measurements. These tests were selected to comprehensively evaluate both the fresh and hardened state performance of the composite mortars.

Figure 1. Experimental Methods. (a) Shredded PET; (b) Natural source; (c) Synthetic pozzolan–PET rock; (d) LCA composite aggregates; (e) Flow table; (f) Composite mortar sample; (g) Strength testing machine; (h) Thermal device; (i) Compressive device

2.2. Analytical mode

1. The theoretical Young's modulus

According to the new Eurocode 2 regulation for mortars, the Young's modulus is given by the following formula.

$$E_{Ec2} = 22\left(\frac{R_c}{10}\right)^{0.3} \quad (1)$$

Zouaoui et al. [38] propose a simpler iterative method to estimate the mechanical properties of heterogeneous materials.

$$E_f = \frac{9K_f}{1+3\frac{K_f}{G_f}} \quad (2)$$

When:

$$K_f = \frac{K_M + V_R(K_R - K_M)}{1+\frac{V_M(K_R-K_M)(K_R+\frac{3}{4}G_R)}{V_M(K_R-K_M)}}; G_f = \frac{G_M + V_R(G_R - G_M)}{1+\frac{V_M(G_R-G_M)(G_R+\frac{3}{4}K_R)}{V_M(G_R-G_M)}} \quad (3)$$

2. The theoretical thermal conductivity

Hatta and Taya [39] provided an empirical formula capable of estimating the effective thermal conductivity.

$$\lambda_f = \lambda_M + (V_R\frac{V_M}{3} + \frac{\lambda_M}{\lambda_M - \lambda_R}) \quad (4)$$

3. Thermal resistance and the coefficient of heat transfer

Swartz et al. [40] define thermal resistance and the heat transfer coefficient as follows:

$$R_{th} = e\lambda^{-1}{}_f; U_f = R^{-1}{}_{th} \quad (5)$$

4. Bending Beam

The displacement field is written in the form of the refined theory.

$$u_1(x,z,t) = u(x,z,t) - z\frac{dw_b}{dx} - f(z)\frac{dw_s}{dx}$$

$$u_2(x,z,t) = 0;$$

$$u_3(x,y,z_{ns},t) = w_b(x,t) + w_s(x,t) \quad (6)$$

The deformation and distortion are defined as follows:

$$\varepsilon_x = \frac{du}{dx} + z\frac{\partial^2 w_b}{\partial x^2} - f\frac{\partial^2 w_s}{\partial x^2};$$

$$\gamma_{xz} = \left(1-\frac{df}{dz}\right)\frac{dw_s}{dx} = g\frac{dw_s}{dx} \quad (7)$$

Noted that:

$$f = 0.67z^3 + 0.5z - 0.16\sin(\pi z) \quad (8)$$

Where:

$$g = 1 - \frac{df}{dz} \quad (9)$$

The equations of motion with virtual principal

$$\int_{-h/2}^{h/2}\int_\Omega [\sigma_x\delta\varepsilon_x + \tau_{xz}\delta\gamma_{xz}]d\Omega w dz - \int_\Omega q\delta w d\Omega = 0 \quad (10)$$

The variation of deformation is defined as follows:

$$\delta U = \int_0^L\int_A(\sigma_x\delta\varepsilon_x + \tau_{xz}\delta\gamma_{xz})dAdx = \int_0^L\left(N\frac{d\delta_u}{dx} - M_b\frac{d^2\delta w_b}{dx^2} - M_s\frac{d^2\delta w_s}{dx^2} + Q\frac{d\delta w_s}{dx}\right)dx \quad (11)$$

The variance of the potential

$$\delta V = -\int_0^L q\delta(w_b + w_s)dx \quad (12)$$

The resultant forces, moments, and shear forces are designated as follows:

$$N = \int_A \sigma_x dA;\quad N_b = \int_A z\sigma_x dA;$$

$$M_S = \int_A f(z)\sigma_x dA;\quad Q = \int_A g(z)\tau_{xz}dA \quad (13)$$

By replacing (13) in (11) the equilibrium equations are written:

$$\delta u: \frac{dN}{dx} = 0$$

$$\delta w_b: \frac{d^2M_b}{dx^2} + q = 0 \quad (14)$$

$$\delta w_s: \frac{d^2M_s}{dx^2} + \frac{dQ}{dx} + q = 0$$

The boundary conditions

$$w_b \, or Q_b = \frac{dM_b}{dx}$$

$$w_s \, or Q_s = \frac{dM_s}{dx} + Q$$

$$\frac{dM_b}{dx} \, or M_b$$

$$\frac{dM_s}{dx} \, or M_s \quad (15)$$

The relationship between constraint and deformation is defined as follows:

$$\sigma_x = Q_{11}\varepsilon_x \,;\, \tau_{xz} = Q_{55}\gamma_{xz} \qquad (16)$$

Where:

$$Q_{11} = E\,; Q_{55} = \frac{E}{2} + [1+\nu] \qquad (17)$$

By substituting:

$$N = A\frac{du}{dx} - B\frac{d^2w_b}{dx^2} - B_s\frac{d^2w_s}{dx^2};$$

$$M_s = B_s\frac{du}{dx} - D_s\frac{d^2w_b}{dx^2} - H_s\frac{d^2w_s}{dx^2};$$

$$Q = A_s\frac{dw_s}{dx} \qquad (18)$$

With:

$$A = \int_A Q_{11}dA\,;\; B = \int_A zQ_{11}dA\,;\; B_s = \int_A f(z)Q_{11}dA$$

$$D = \int_A z^2 f(z)Q_{11}dA\,; \qquad (19)$$

$$D_s = \int_A z\; f(z)Q_{11}dA\,;\; H_s = \int_A f^2(z)Q_{11}dA\,;$$

$$A_s = \int_A g^2(z)Q_{55}dA \qquad (20)$$

Equation of motion:

$$A\frac{d^2u}{dx^2} - B\frac{d^3w_b}{dx^3} - B_s\frac{d^3w_s}{dx^3} = 0$$

$$B\frac{d^3u}{dx^3} - D\frac{d^4w_b}{dx^4} - D_s\frac{d4w_s}{dx^4} + q = 0$$

$$B\frac{d^3u}{dx^3} - D_s\frac{d^4w_b}{dx^4} - H_s\frac{d^4w_s}{dx^4} + A_s\frac{d^2w_s}{dx^2} + q = 0 \qquad \$\,(21)$$

Analytical solution (Navier):

$$u(x,t) = \sum_{n=1}^{\infty} U_n \cos(\alpha x);$$

$$w_b(x,t) = \sum_{n=1}^{\infty} W_{bn} \sin(\alpha x);$$

$$w_s(x,t) = \sum_{n=1}^{\infty} w_{sn} \sin(\alpha x) \qquad (22)$$

Where:

$$\alpha = \frac{n\pi}{L}, (U_n, W_{bn}, W_{sn}) \qquad (23)$$

Usining Fourier series:

$$q(x) = \sum_{n=1}^{\infty} Q_n \sin(\alpha x) \qquad (24)$$

Where load amplitude noted by:

$$Q_n = \frac{2}{L}\int_0^L q(x)\sin(\alpha x)dx \qquad (25)$$

The coefficients Qn are given calculated from:

$$Q_n = \frac{4q_0}{n\pi}(n = 1,3,5,....) \text{ *for a uniform load} \qquad (26)$$

By replacing (22) in (21) the stiffness matrix noted:

$$\begin{bmatrix} S_{11} & S_{12} & S_{13} \\ S_{21} & S_{22} & S_{23} \\ S_{13} & S_{23} & S_{33} \end{bmatrix} \begin{Bmatrix} U_n \\ W_{bn} \\ W_{sn} \end{Bmatrix} = \begin{Bmatrix} 0 \\ Q_n \\ Q_{sn} \end{Bmatrix} \qquad (27)$$

$$S_{11} = A\alpha^2,\; S_{12} = B\alpha^3,\; S_{13} = B_s\alpha^3,$$
$$S_{22} = D\alpha^4,\; S_{33} = H_s\alpha^4 + A_s\alpha^2 \qquad (28)$$

The dimensional parameters are written in this formula:

$$w = 100\frac{E_m h^3}{q_0 L^4} w\left(\frac{L}{2}\right),$$
$$u = 100\frac{E_m h^3}{q_0 L^4} u\left(0, -\frac{h}{2}\right) \qquad (29)$$

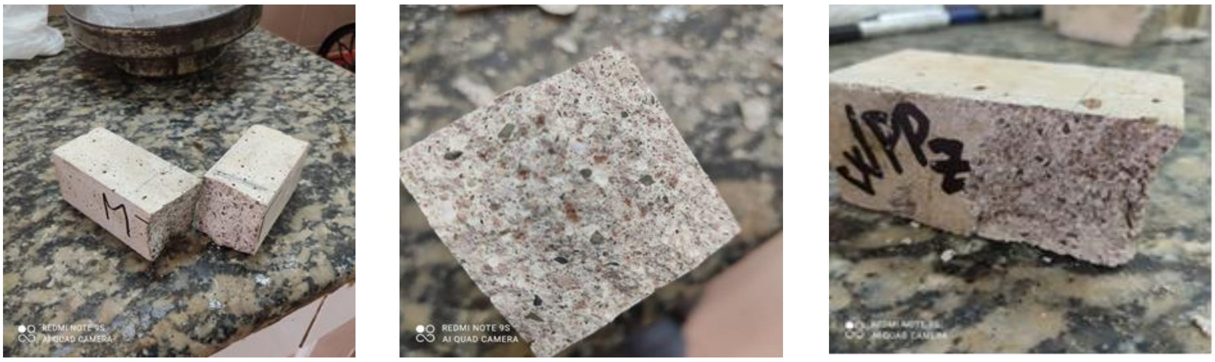
$$\sigma_x = \frac{h}{q_0 L}\sigma_x\left(\frac{L}{2}, \frac{h}{2}\right),\quad \tau_{xz} = \frac{h}{q_0 L}\sigma_{xz}(0,0) \qquad (30)$$

3. RESULTS AND DISCUSSION

The thermomechanical properties of composite mortars (LMPNS) incorporating composite aggregates (LCA) derived from PET plastic waste and natural pozzolan were evaluated at 28 days of curing. The LCA aggregates exhibited a particle size distribution in the range of 0–3.15 mm. Three prismatic specimens with dimensions of 4 × 4 × 16 cm³ were prepared and tested (Figure 2). The corresponding results are summarized in Table 2.

Table 2. The thermo-mechanical properties at 28 days

Results at 28 days			
Specimen code	Sand composite, LCA (%)	Compression Strength (MPa)	Thermal Conductivity (W/m·K)
LMPNS1	0	51.47	1.5
LMPNS2	25	37.27	1.3
LMPNS3	50	33.96	1.08
LMPNS4	75	24.09	0.86
LMPNS5	100	22.24	0.71



(a) (b) (c)

Figure 2. (a) LMPNS1 composite after bending test; (b) LMPNS5 surface after bending test; (c) LMPNS5 composite after compressive test.

Based on the 28-day results, it is noteworthy that each time the LCA composite concentration increases, both the resistance and conductivity decrease, as shown in table 2.

Table 3 presents the theoretical results, obtained by the homogenization rule, and the experimental results for the mortar. The mortar's modulus of elasticity is 36 MPa with a Poisson's ratio of 0.2, while that of the treated PET is 2.8 GPa with a Poisson's ratio of 0.2.

Regarding conductivity, the mortar has a value of 1.5 W/(m·K) and the PET has a value of 0.15 W/(m·K).

Table 3. Comparison between theoretical and experimental results.

Specimen code	Compression Strength (MPa)	Young’s Modulus by EC2 (MPa)	Young’s Zouaoui et al. [38] rule by EC2 (MPa)	Thermal Conductivity (W/m·K)	Thermal Conductivity by Hatta and Taya [39] rule (W/m·K)
LMPNS1	51.47	35.97	36	1.50	1.50
LMPNS2	37.27	32.65	32.57	1.30	1.17
LMPNS3	33.96	31.75	31.20	1.08	0.95
LMPNS4	24.09	28.64	29.88	0.86	0.73
LMPNS5	22.24	27.96	28.61	0.71	0.62

Table 3 reveals a degree of discrepancy between the theoretical and experimental results. Nevertheless, the experimental data are considered more reliable, while the theoretical model serves as an approximation tool that can reduce computation time. In Figure 3, the results are presented for two mortar thicknesses, 2 cm and 4 cm. It is evident that thermal resistance increases with thickness. Conversely, a reduction in resistance is observed with higher concentrations of thermally treated PET plastic. This comparison highlights the influence of the 2 cm mortar layer on the thermal behavior of the composite.

Figure 4 illustrates the results for the heat transfer factor. It is noted that this factor increases as a function of the concentration of a thermally treated PET plastic (LCA composite) that replaces the natural sand. A thickness of 2 cm is sufficient as a mortar coating. For a better contribution to thermal energy savings, the optimal choice is 2 cm, with only 4 cm of mortar needed.

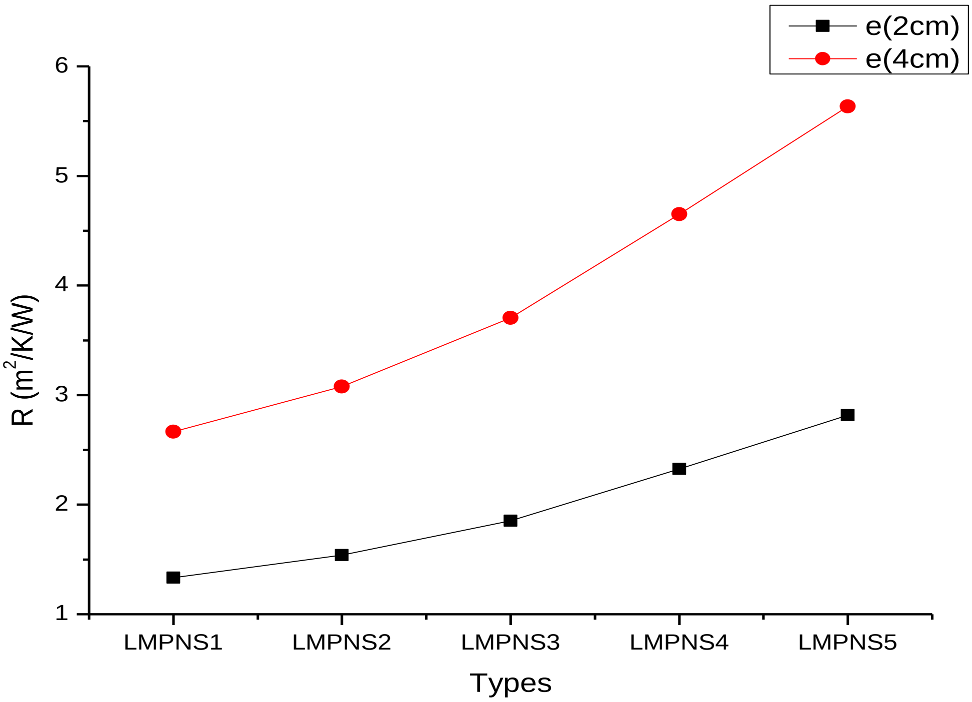


Figure 3. The thermal resistance of different types of mortars with two thicknesses

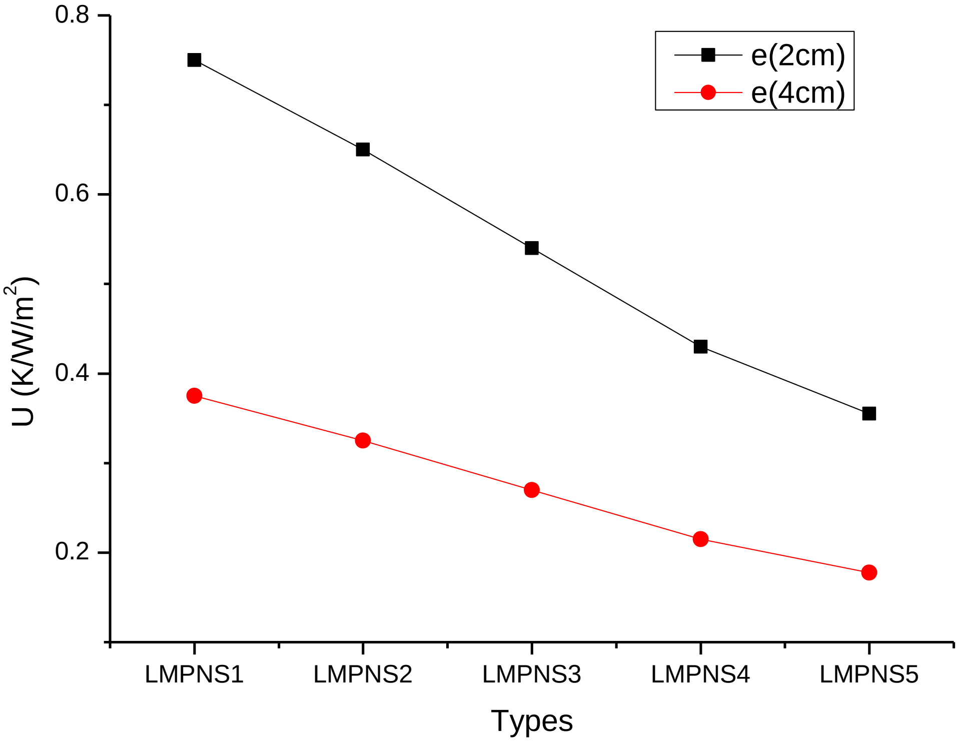


Figure 4. The heat transfer factor of different types of mortars with two thicknesses

Figure 5 illustrates the deflection behavior of mortar beams reinforced with thermally treated PET plastic. A clear trend can be observed: as the volumetric fraction of treated plastic increases, the deflection of the beams also increases. This response indicates a deterioration in the mechanical performance of the mortars. To better understand this behavior, bending tests were carried out, as they provide valuable insight into the adherence and load-bearing capacity of mortars within beams. Consequently, a static bending analysis was deemed necessary

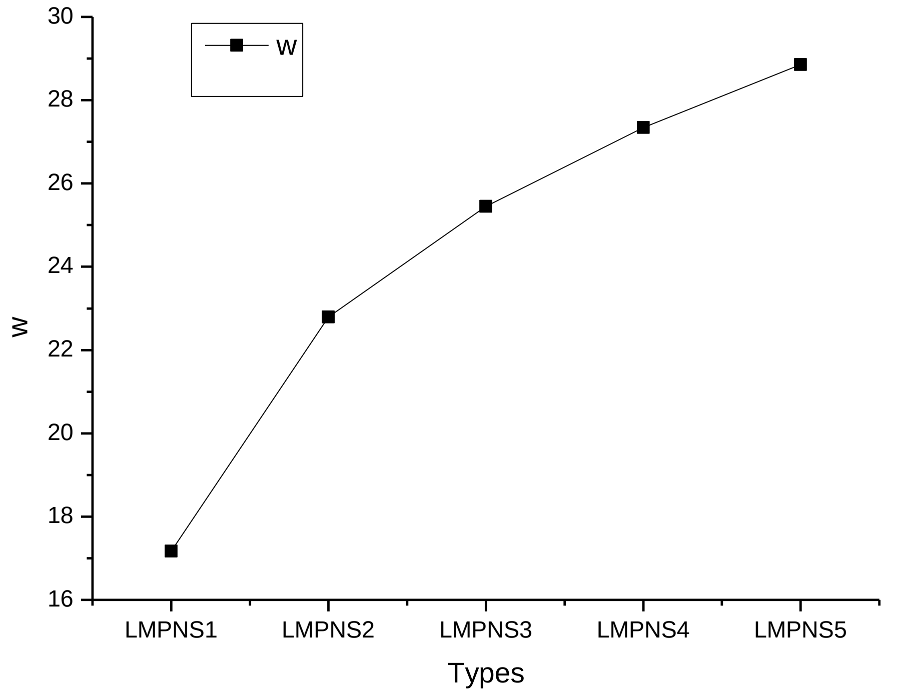


Figure 5. The deflection for all types of composite mortars

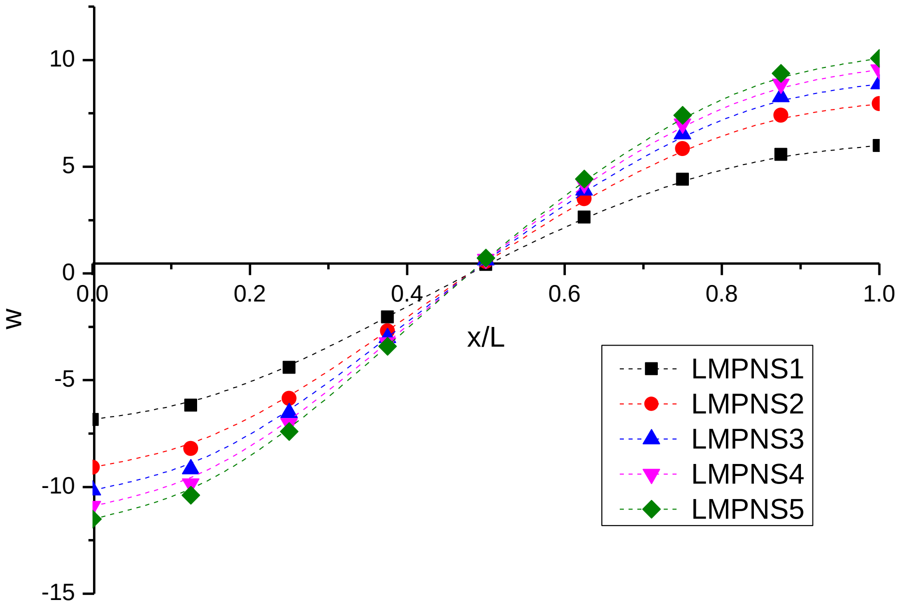


Figure 6. The displacements due to sliding along the beam's length

Subsequently, we check the sliding displacement along the length of the beam in Figure 6. It's noted that the displacement is zero at the mid-span and maximum at the supports. It is also observed that the mortars do not resist well if a percentage of treated plastic (LCA) is added. Shear forces are less effectively resisted by the mortars compared to ordinary mortar. For this reason, it is necessary to explore other methods to maintain cohesion.

Furthermore, Figure 7 shows the verified deflection: it is maximum at the mid-span and zero at the ends. It can also be observed that a thermally treated PET causes large deflections, which means that mortars dosed with this plastic replacing the sand are not highly resistant; they are weak. This means that the modified mortars show a very weak positive response to bending and provide low resistance at the center of the beams.

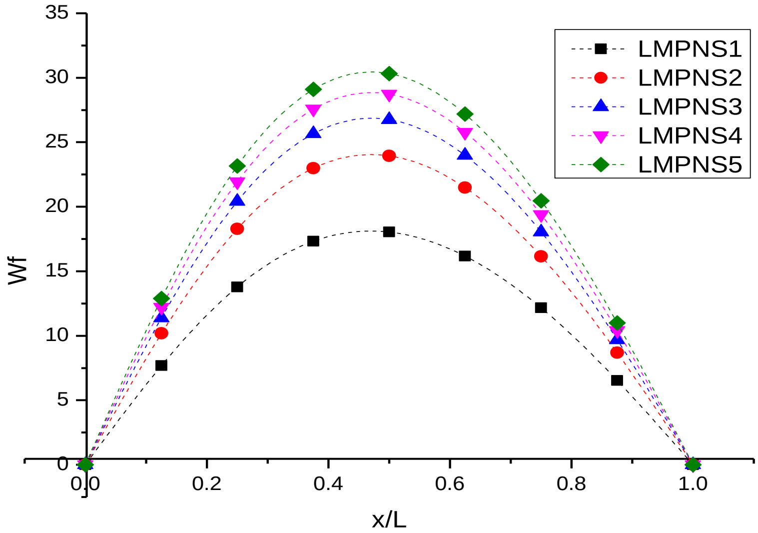


Figure 7. The beam's deflection, including the shear deformation factors along its entire length

Since each study must be validated and compared with a previous study, this step is very interesting. Table 4 presents a comparison between the deflection results obtained in this study and those reported by C.C. Ike [27]. The numerical values are in very close agreement, with deviations below 3% for all parameters. This close correspondence demonstrates that the developed analytical program reliably reproduces the reference results and accurately predicts structural behavior. Consequently, this comparison validates the robustness and correctness of the proposed analytical formulation used in the present work.

Table 4. Comparison between present results and results conclude by C.C. Ike [27].

Methods	w(l=2h)	Wf(l=2h)	W(l=4h)	Wf(l=4h)
Present	2.240	2.530	16.420	1.803
C.C. Ike [27]	2.185	2.590	16.192	1.807

4. CONCLUSION

This study established several key findings regarding the development and characterization of mortars based on thermally treated PET with natural source. First, the experimental results demonstrated that both mechanical strength and thermal conductivity decrease with the incorporation of the LCA composite based on shredded PET waste and ground pozzolan. Second, the homogenization theories employed proved effective in predicting the equivalent elastic and thermal properties, allowing researchers to estimate material behavior based on precise phase proportions. Third, the incorporation of thermally treated PET significantly reduced heat transfer, enhancing the thermal comfort potential of the mortars. Fourth, although mortars containing LCA composite aggregates exhibit lower mechanical strength than the control, their performance remains suitable for non-structural uses. Finally, the developed plastic-pozzolanic mortars show promising potential for applications such as wall coatings and prefabricated panels, where lightweight and thermally efficient materials are required. Their improved insulation capability can contribute to lowering building energy demand and promoting sustainability in the construction industry.

An important contribution of this study lies in the development of an analytical and numerical modeling approach capable of estimating the thermomechanical behavior of new composite materials prior to experimentation. This approach is not limited to mortars but can be extended to other heterogeneous materials.

In future studies, the research will be expanded to include large-scale testing to validate laboratory results under realistic construction conditions. Different thermal treatment parameters for PET waste will be explored to optimize interfacial bonding and overall performance. Further investigations on shrinkage and long-term durability will also be carried out to complete the material characterization. In addition, the modeling framework will be refined to consider microstructural imperfections, anisotropy, and transient thermal effects for more accurate and realistic predictions. These future developments aim to reinforce and extend the present findings, which already provide a solid experimental–numerical foundation demonstrating the feasibility and thermal advantages of PET-modified mortars as sustainable, eco-efficient construction materials.

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IZVOD

ANALIZA TERMIČKI OBRAĐENIH „PLASTIČNO-PUCOLANSKIH“ MALTERA I NJIHOVIH MEHANIČKIH SVOJSTVA

Reciklaža plastičnog otpada u građevinskim materijalima nudi potencijalni put ka održivosti, uz poboljšanje termičkih performansi. Ova studija ispituje maltere u kojima je prirodni pesak delimično zamenjen termički tretiranim PET otpadom iz prirodnog izvora (pucolan). Sprovedene su tri faze: (i) eksperimentalno određivanje čvrstoće na pritisak, Jangovog modula i toplotne provodljivosti na različitim nivoima zamene LCA; (ii) analiza homogenizacije za procenu ekvivalentnih elastičnih i termičkih parametara, u poređenju sa podacima iz literature; i (iii) numeričke simulacije prenosa toplote kroz jednostavno oslonjene grede sa premazima od 2 cm i 4 cm. Rezultati pokazuju da ugradnja termički tretiranog PET-a smanjuje čvrstoću na pritisak u odnosu na kontrolni malter, iako vrednosti ostaju dovoljne za nekonstrukcijske primene kao što su završni malteri (npr. 22 MPa pri 100% zamene). Nasuprot tome, termičke performanse su se značajno poboljšale, sa provodljivošću smanjenom sa 1,5 na 0,71 W/m•K, što dovodi do poboljšane otpornosti na prenos toplote. Ovi nalazi pokazuju potencijal termički tretiranih PET-modifikovanih maltera kao ekološki efikasnih materijala koji kombinuju adekvatan mehanički kapacitet sa odličnim termičkim komforom.

Ključne reči: *plastični otpad, malter, termomehanička svojstva, ugib, prenos toplote.*

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