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Thermal and Mechanical Performances Optimization of Plaster–Polystyrene Bio-Composites for Building Applications

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Abstract: Polystyrene is renowned for its excellent thermal insulation due to its closed-cell structure that traps air and reduces heat conduction. This study aims to develop sustainable, energy-efficient building materials by enhancing the thermal and mechanical properties of plaster–polystyrene bio-composites. By incorporating varying amounts of polystyrene (5% to 25%) into plaster, our research investigates changes in thermal conductivity, thermal resistance, and mechanical properties such as Young's modulus and maximum stress. Meticulous preparation of composite samples ensures consistency, with thermal and mechanical properties assessed using a thermal chamber and four-point bending and tensile tests. The results show that increasing the polystyrene content significantly improved thermal insulation and stiffness, though maximum stress decreased, indicating a trade-off between insulation and mechanical strength.

Keywords: bio-composites; plaster; polystyrene; thermal performance; mechanical performance; smart buildings

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1. Introduction

Polystyrene, a widely utilized thermoplastic polymer, is renowned for its exceptional thermal insulation properties, making it indispensable in applications demanding efficient heat control. This lightweight and rigid plastic foam finds extensive use in construction, packaging, and various industries where thermal isolation is paramount [1]. The effectiveness of polystyrene as a thermal insulator is attributed to its unique closed-cell structure, where air-filled cells act as a barrier to heat conduction. This structure creates an intricate network of trapped air pockets, significantly impeding heat transfer by minimizing direct contact between molecules [2]. Since air is a poor conductor of heat, the low thermal conductivity of polystyrene further enhances its insulation capabilities, contributing to energy savings and improved energy efficiency in diverse applications [3].

In the context of sustainable construction, there is an increasing focus on developing building materials that not only offer superior thermal insulation but also reduce environmental impact. Recent advancements in material engineering have paved the way for the creation of bio-composites, which integrate natural or renewable components with conventional materials to enhance performance while minimizing ecological footprint [4]. This study explores the development of sustainable and energy-efficient building materials by optimizing the thermal and mechanical properties of plaster–polystyrene bio-composites. Plaster, traditionally valued for its versatility and ability to provide smooth and durable finishes, has not been widely recognized for its thermal insulation properties. However, recent innovations have demonstrated that by incorporating additives such as polystyrene, it is possible to significantly enhance plaster's thermal performance [5]. The combination of polystyrene with plaster seeks to capitalize on the exceptional thermal insulation capabilities of polystyrene while retaining the favorable mechanical properties of plaster. This synergy has the potential to yield a bio-composite material that not only offers improved thermal insulation but also maintains desirable attributes such as workability and aesthetic appeal [5].

The term "bio-composite" in this study refers to a material system that combines traditional construction materials like plaster with a polymer such as polystyrene, which is derived from petrochemical sources. Although polystyrene is not a bio-based material, the integration of such composites is driven by the need to enhance sustainability through improved energy efficiency and reduced material usage, aligning with the broader goals of sustainable development [6]. This approach follows similar trends in the literature, where researchers have explored various composite systems combining traditional materials with synthetic or natural additives to improve performance while addressing environmental concerns [7].

Recent studies have also highlighted the durability challenges of composite materials combining plaster and expanded polystyrene (EPS). While traditional plaster excels in terms of its compressive strength and durability, the inclusion of EPS can reduce its resistance to environmental factors such as humidity, temperature fluctuations, and freeze–thaw cycles. García-González et al. (2021) demonstrated that although EPS–plaster composites offer superior thermal insulation, their long-term mechanical integrity may require further optimization to withstand adverse conditions [8]. Additional studies emphasize the need for protective coatings or additives to mitigate these effects [9,10]. These findings underline the importance of balancing thermal efficiency with mechanical durability to support the long-term performance of EPS-modified plasters.

The primary objective of this research is to investigate the impact of adding polystyrene to plaster on the thermal and mechanical properties of the resulting composite material. By studying the synergistic effects of this combination, this research aims to contribute valuable insights into the development of sustainable building materials that meet both thermal efficiency and construction requirements. The practical significance of this work lies in its potential to reduce energy consumption in buildings, thus contributing to broader efforts to combat climate change through enhanced energy efficiency in the built environment [11,12]. Moreover, the findings could inform the design of future construction materials, offering an innovative solution that balances performance, sustainability, and cost-effectiveness.

2. Materials and Methods

2.1. Materials and Elaboration Processing

2.1.1. Materials

The plaster used in this study was obtained from Safi ores, a region situated in southwestern Morocco near the Atlantic Ocean. This particular location was chosen due to the availability of high-quality plaster deposits. To prepare the plaster for experimental purposes, it underwent a series of initial treatments, including grinding. The grinding process reduced the plaster material into smaller particles, ensuring uniformity and improved handling characteristics. This preliminary treatment aims to enhance the workability of the plaster and facilitate its incorporation into the bio-composite material [13].

The polystyrene utilized in this research was repurposed from protective packaging commonly used for electronic and scientific equipment, as illustrated in Figure 1. This polystyrene, which is typically found in packaging materials accompanying purchased devices, is recognized for its lightweight, shock-absorbing, and insulating properties. It is often utilized in its expanded polystyrene (EPS) form, which features a closed-cell structure ideal for insulation.

Figure 1. Transformation of polystyrene material through the treatment process.

For the experiments, polystyrene walls typically used to safeguard scientific equipment were collected and carefully processed into uniform spherical shapes, resulting in polystyrene balls with diameters ranging between 3 and 4 mm [14]. This treatment process was crucial for creating consistent-sized polystyrene particles, ensuring controlled and uniform mixing with plaster during the development of the bio-composite material.

This implementation of the treatment process highlights the research team's commitment to meticulous experimentation and reproducibility. By incorporating such details, the study ensures that methods and outcomes are represented accurately, facilitating the dissemination of valuable insights into the development of sustainable building materials.

2.1.2. Elaboration Processing

The composite samples were prepared by blending plaster and water with various mass fractions (ϕm) of polystyrene (PS), ranging from 5% to 25% in increments of 10%. To compare thermal property variations with plain plaster, a reference sample without polystyrene was also prepared [14].

The mixing process involved the use of distilled water, and an identical amount of plaster was used for each mixture to ensure the highest possible reproducibility. The mass fraction of polystyrene (ϕm) was calculated using Equation (1):

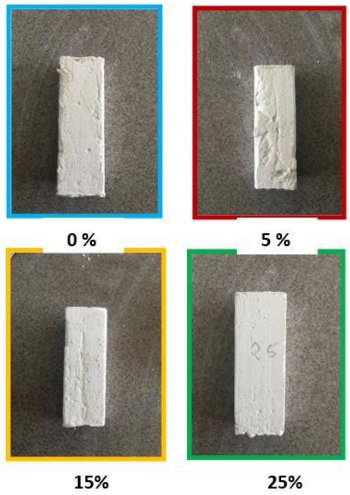
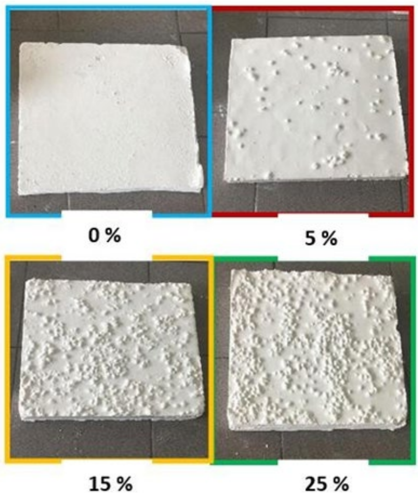
$$\phi m\ (PS) = (\rho\_PS \times \%V\_PS)/(\rho\_P \times (1 - \%V\_PS) + \rho\_PS \times \%V\_PS) \times 100 \quad (1)$$

where ρPS, ρP, and $\%VPS$ represent the density of the polystyrene, plaster, and the volume percentage of the polystyrene, respectively.

A precise mixing procedure was followed to ensure uniformity, as it significantly influences the final properties of the material. The following steps were undertaken:

1. The hemihydrate powder was gradually poured into the water over a 30 s period, ensuring that excessive air bubbles were not incorporated. The mixture was allowed to rest undisturbed for 1 min to ensure complete powder–water contact.
2. The plaster–polystyrene mixture was stirred with a magnetic agitator for 30 s, using 30 helical movements, then rested for 30 s for 30 s before stirring again for another 30 s.
3. The water–plaster mass ratio (w/g) was maintained at 0.8. Parallelepiped molds were used to create samples for testing.
4. Initially, the prepared samples were dried at room temperature for four days to remove any moisture present in the pores. Dry mass measurements were taken and then the samples were stored in plastic bags to ensure consistent moisture levels.
5. The mixture was left to rest in the bowl for approximately 2 min to thicken before being poured into the parallelepiped molds.
6. The paste reached a sufficiently viscous consistency after 18 min at a reference water–plaster ratio (E/P = 0.8).
7. The specimens were demolded after one day and dried at 45 °C for two days to eliminate interstitial water. This meticulous process guarantees accurate characterization of the composite's thermal and mechanical properties (Table 1).

Table 1. Prototypes of mechanical and thermal tests.

Tests	Test Specimens' Size mm^3	Pictures
Mechanical Tests	70 × 30 × 40	
Thermal Tests	250 × 250 × 30	

Meticulously following this procedure guarantees precise and dependable results for the subsequent assessment and analysis of the thermal and mechanical characteristics of the plaster–polystyrene composite material.

This detailed procedure based on the literature ensures consistency and reliability in the subsequent assessment of the thermal and mechanical properties of the plaster–polystyrene composite material [15]. Adjustments to the mixing and curing processes were made to further enhance the properties of the composite material. Future work should explore varying ratios of plaster to polystyrene and incorporate additional additives to balance thermal efficiency and mechanical strength.

2.2. Materials' Characterization

2.2.1. Thermal Analysis

Thermogravimetric Analysis (TGA) was employed to study the thermal properties of polystyrene–plaster composites. This technique provides critical insights into decomposition, oxidation, dehydration, and other thermal events [16].

This technique provides critical insights into material characteristics such as decomposition, oxidation, dehydration, and other thermal events. TGA is extensively used in research and quality control for materials like polymers, pharmaceuticals, and ceramics, aiding in the understanding of thermal stability, composition, and decomposition kinetics.

Its versatility allows for the analysis of a wide range of sample types, making it invaluable for optimizing material properties in various scientific and industrial fields.

For polystyrene–plaster bio-composites, TGA can identify the temperature ranges at which each component undergoes thermal degradation or decomposition. Typically, polystyrene decomposes at lower temperatures, while plaster exhibits distinct thermal events.

To determine other thermal properties, a thermal chamber was used. A thermal chamber is an experimental device that allows for the measurement of the amount of heat that passes through a material under steady-state conditions [17]. This device (Figure 2) is thermally insulated from the external environment, ensuring that heat transfer occurs solely through the material being tested. It measures thermal transition coefficients and the thermal conductivity of various materials. A Temperature Data Logger HD32.8.16 card is employed to record the temperature at different points on the material's surface.

Figure 2. Thermal tests.

2.2.2. Mechanical Characterization

Rectangular samples (three per composite) were tested under uniaxial tensile stress at a crosshead speed of 10 mm/min. Testing was conducted at room temperature to maintain consistent environmental conditions and minimize external influences.

During the tests, the load cell measured the force applied to each sample, while a computer recorded the elongation (Figure 3). These data were used to generate stress–strain curves, which provided insights into the mechanical properties of the composites, including their tensile strength, Young's modulus, and elongation at break.

Figure 3. ERM mechanical testing.

The study effectively utilized tensile testing to analyze the mechanical properties of the composites. However, it does not provide detailed data on how these properties change with varying polystyrene contents. Specific information on tensile strength and stress–strain behavior for different polystyrene concentrations is missing, and this information would be crucial for understanding the full impact of polystyrene on the mechanical performance of the composites. These additional data would be valuable for optimizing the composite formulation to achieve the desired balance between thermal insulation and mechanical strength.

3. Results

3.1. Chemical Composition of Plaster

Microanalysis X enables basic quantitative analysis by detecting specific characteristic lines associated with the elements present. Table 2 presents the compositions of plaster used in this study.

Table 2. Chemical compositions of plaster used (%).

Element	O	Fe	Al	Si	S	Ca
Atomic (%)	65.4	0.4	0.5	0.4	16.4	16.9

The atomic percentage represents the proportion of atoms of each element in the compound, expressed as a percentage of the total number of atoms. For this plaster, the atomic percentages of the elements sum to 100%. The table indicates that oxygen is the most abundant element, with an atomic percentage of 65.4%. This is followed by sulfur and calcium, with atomic percentages of 16.4% and 16.9%, respectively. Iron, aluminum, and silicon are present in much smaller quantities, each comprising 0.4%, 0.5%, and 0.4% of the total atoms, respectively.

3.2. Thermal Properties

3.2.1. Powder Thermal Characterization

Thermal analysis techniques were employed to investigate the stability properties of raw plaster in greater detail. The analyses were conducted in an atmospheric air environment, spanning a temperature range from ambient to 1000 °C, using a heating rate of 10 °C/min [18]. The obtained TGA (Thermogravimetric Analysis) and DTA (Differential Thermal Analysis) curves for the plaster can be found in Figure 4.

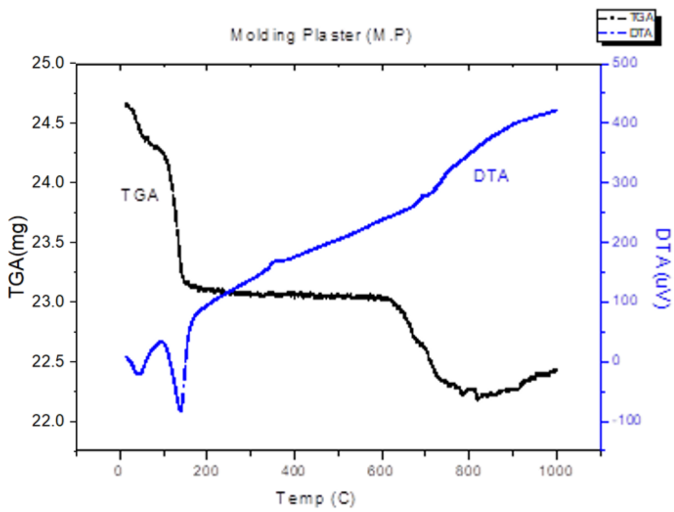


Figure 4. Thermal Gravimetric (TG) and Differential Thermal Analysis (DTA) curves for plaster materials.

The Thermal Gravimetric (TG) technique is used to measure the change in mass of a material as it is heated or cooled. It is commonly used to study the thermal stability of materials [19]. Differential Thermal Analysis (DTA) is a technique used to measure the difference in temperature between a sample and a reference material as they are heated or cooled [20]. It is commonly used to study phase transitions and thermal events in materials. The curves in Figure 4 show the changes in the mass and temperature of the plaster material as it is heated from ambient temperature to 1000 °C at a rate of 10 °C/min. The primary thermal effect observed in the TG curve occurs at 140 °C, resulting in a total mass loss of 20.5 wt%. This means that the plaster material loses 20.5% of its weight due to thermal decomposition at this temperature. The mass loss can be attributed to two distinct stages. Initially, a mass loss of 19 wt% is observed before the temperature reaches 160 °C, which can be attributed to the evaporation of water present in the plaster. This means that the plaster material contains 19% water by weight. Subsequently, at 700 °C, a small mass loss of 3 wt% is observed, which corresponds to the simultaneous elimination of chemical water within the plaster's structure. This means that the plaster material contains 3% chemical water by weight. The information provided in the figure is important for understanding the thermal stability and composition of the plaster material, which is useful for optimizing its performance in building applications [21].

3.2.2. Plaster–Polystyrene Composites' Thermal Conductivity

The setup comprises a heated chamber and a sealed side that includes a compartment for placing square samples (up to 250 × 250 mm^2). The experiments were conducted under steady-state conditions. The heat flux passing through the sample and the average surface temperatures of the specimen on the cold and hot sides were measured using a heat flow meter (with precision of ±5%), positioned at the center of the sample, and eight thermo-resistances (with precision of ±10%), respectively. The thermal conductivity was determined using the thermal flux meter method [22].

It is noticeable that thermal conductivity decreases as the percentage of polystyrene increases, which allows us to conclude that the smaller the amount of thermal conductivity, the more insulating the material is.

Figure 5 shows how the thermal conductivity of the bio-composite material varies with the amount of polystyrene content. Thermal conductivity refers to the ability of a material to conduct heat. It is measured in watts per meter-kelvin (W/mK). Polystyrene is a type of plastic foam that is known for its excellent thermal insulation properties. The bio-composite material being studied is a mixture of plaster and polystyrene, with varying amounts of polystyrene added to it. The results of the study show how the addition of Polystyrene affects the thermal conductivity of the bio-composite material. The data are presented in the form of a graph, with the amount of Polystyrene on the x-axis and the thermal conductivity on the y-axis. The graph shows that as the amount of polystyrene in the bio-composite material increases, the thermal conductivity decreases [23]. This means that the material becomes a better insulator as more polystyrene is added to it. The relationship between the amount of polystyrene and the thermal conductivity is likely to be non-linear, as shown by the curve in the graph. The data presented in the figure are important for optimizing the thermal performance of the bio-composite material for building applications [24].

Figure 6 shows how the thermal resistance of the bio-composite material varies with the amount of polystyrene content. Thermal resistance is a measure of a material's ability to resist the flow of heat through it, and polystyrene content refers to the amount of polystyrene present in the material being studied [25]. The graph shows a curve that represents the variation in thermal resistance with polystyrene content. The x-axis of the graph represents the polystyrene content, while the y-axis represents the thermal resistance. The mathematical relationship between thermal resistance and polystyrene content can be expressed as $R = \frac{L}{kA}$, where R is the thermal resistance, L is the thickness of the material, k is the thermal conductivity of the material, and A is the area of the material.

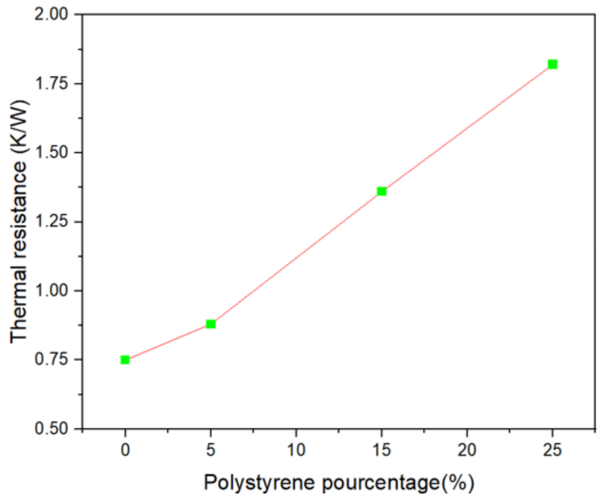


Figure 5. Thermal conductivity variation as a function.

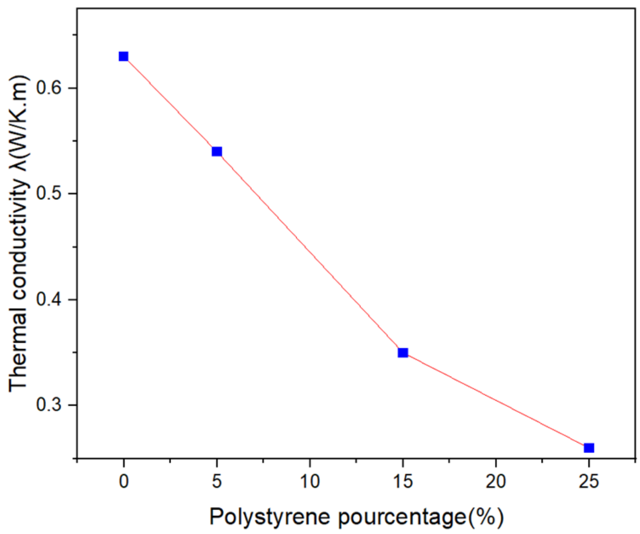


Figure 6. Thermal resistance variation as a function of polystyrene content.

Although the data in Figures 5 and 6 suggest a linear relationship between polystyrene content and thermal properties, further statistical analysis would be required to confirm this trend. It is possible that non-linear effects may become more pronounced at higher polystyrene percentages due to changes in composite microstructure and interaction effects.

3.3. Mechanical Properties

To present the mechanical properties of plaster with varying percentages of polystyrene, four-point bending tests were conducted on prismatic specimens. The percentage of polystyrene in composite materials directly influences their mechanical and thermal properties, which is crucial for predicting the insulation effects of these materials [24].

The Young's modulus, a measure of a material's stiffness defined as the ratio of stress to strain under elastic deformation [26], improves with the addition of polystyrene. Figure 7 illustrates how the Young's modulus of the composite material changes with different amounts of polystyrene. This graph shows the relationship between the polystyrene content and the resulting Young's modulus, helping to determine the optimal amount of polystyrene for achieving the desired mechanical properties [27].

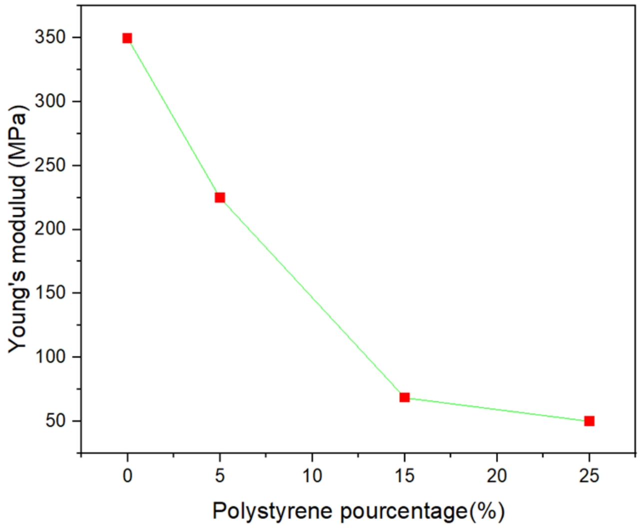


Figure 7. Influence of the polystyrene content on Young's modulus.

The variation in polystyrene content affects the Young's modulus, as shown in Figure 8. The modulus decreases with the presence of polystyrene balls, a common outcome in polymer materials [28].

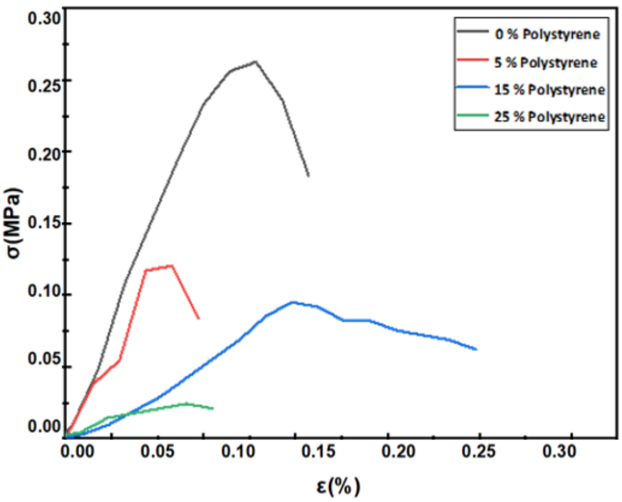


Figure 8. Stress–strain's influence of the polystyrene content.

Figure 9 demonstrates the effect of polystyrene on the maximum stress a composite material can withstand under compression. This property is critical for determining the material's strength and durability [29]. The inclusion of plaster in the composite reduces its thermal conductivity and enhances its mechanical properties. Polystyrene's closed-cell structure restricts heat conduction, and adding plaster improves strength and stiffness.

Table 3 provides a comprehensive overview, showing that as the percentage of polystyrene increases, thermal resistance and Young's modulus increase, while thermal conductivity and maximum stress decrease. This suggests that higher polystyrene content results in better insulation and increased stiffness but decreased strength. This information is valuable for researchers and engineers developing bio-composites for building applications [30,31].

The thermal conductivity value of 0.26 W/m·K for plaster with 25% polystyrene exceeds the threshold set by European standard EN 998-1 for thermal plasters (<0.2 W/m·K). This discrepancy highlights a limitation of the current composite formulation. While the addition of polystyrene significantly reduces thermal conductivity compared to plain plaster, the material may not meet insulation standards for certain applications. Further optimization of the formulation, including increasing the EPS–plaster ratio or introducing additional insulating additives, could help align the thermal properties with standard requirements. However, this would need to be balanced with mechanical property considerations.

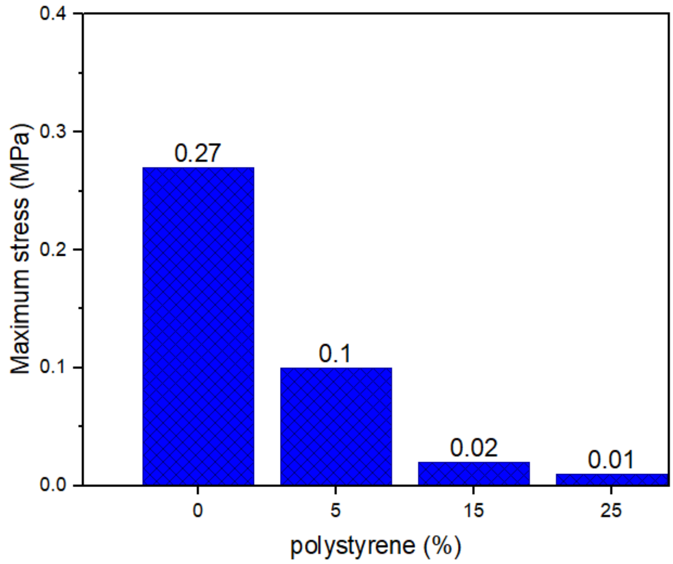


Figure 9. Influence of the polystyrene on maximum compression stress.

Table 3. Thermal and mechanical properties of plaster–polystyrene composites at varying polystyrene percentages.

Percentage of Polystyrene (%)	0	5	15	25
Thermal resistance R (K/W)	0.75	0.88	1.36	1.82
Thermal conductivity λ (W/K.m)	0.63	0.54	0.35	0.26
Young's Modulus (MPa)	349.65	224.72	68.4	50
Maximum stress (MPa)	0.27	0.1	0.02	0.01

4. Discussion

The study's results indicate that increasing the polystyrene content in plaster composites significantly improves thermal insulation by lowering thermal conductivity. This finding aligns with established research on polystyrene's thermal insulation properties, which benefit from its closed-cell structure that effectively traps air and reduces heat conduction [1,3]. The hypothesis that incorporating polystyrene into plaster enhances thermal insulation is thus confirmed.

However, the study also reveals a decrease in mechanical properties, such as Young's modulus and maximum stress, with higher polystyrene content. This reduction in stiffness and strength is consistent with typical outcomes when polymers are added to composites [31,32]. Despite these decreases, the composites retain adequate mechanical integrity for many building applications, suggesting their practical viability. The improved thermal insulation provided by the plaster–polystyrene composites can lead to significant energy savings in buildings by reducing the need for heating and cooling. This reduces the environmental impact and aligns with global efforts towards sustainable building practices. Furthermore, utilizing polystyrene, which is often derived from waste packaging materials, supports sustainability by reducing waste and enhancing resource efficiency. The combination of plaster and polystyrene leverages the strengths of both materials, offering a sustainable alternative to traditional building products.

Although the reduction in mechanical properties with increased polystyrene content presents challenges, the composites still meet the requirements for applications where thermal insulation is critical and mechanical loads are relatively low. Future research should focus on optimizing the composition to balance thermal insulation and mechanical strength, possibly by adjusting the ratio of plaster to polystyrene or adding other materials to enhance properties.

Long-term durability and performance under varying environmental conditions were not explored in this study. Future investigations should address these aspects by examining the effects of moisture, temperature fluctuations, and mechanical wear over time to ensure the composites' reliability and effectiveness in real-world applications. Additionally, exploring alternative additives and treatment processes, such as nanomaterials or advanced polymers, could further improve the composite's properties, offering enhanced performance and greater versatility.

5. Conclusions

This research has explored the potential of plaster–polystyrene bio-composites as sustainable and energy-efficient building materials. The findings reveal that incorporating polystyrene into plaster significantly enhances the thermal and mechanical properties of the composite. The addition of polystyrene reduced the thermal conductivity of the composite from 0.63 W/K·m to 0.26 W/K·m as the polystyrene content increased from 0% to 25%. This improvement in thermal conductivity indicates enhanced insulation capabilities. Similarly, the thermal resistance increased from 0.76 K/W to 1.82 K/W, further demonstrating the effectiveness of polystyrene in improving thermal insulation. However, these thermal benefits come with a trade-off in their mechanical properties. The Young's modulus decreased from 350 MPa to 50 MPa, and the maximum stress the composite can withstand dropped from 0.27 MPa to 0.01 MPa as the polystyrene content increased. This reduction reflects a significant decrease in the material's stiffness and strength. These results suggest that plaster–polystyrene bio-composites are promising for applications where thermal insulation is prioritized over mechanical strength. Future research should focus on optimizing the polystyrene content to achieve a balance between thermal efficiency and mechanical performance. Additionally, assessing the long-term durability and environmental resistance of these composites will be essential for determining their suitability in real-world construction applications. Overall, this study contributes valuable insights into developing innovative and sustainable building materials, highlighting their potential to enhance energy efficiency and reduce environmental impact in the construction sector.

In summary, plaster–polystyrene composites offer notable improvements in thermal insulation compared to traditional plaster and can compete with fiberglass insulation. They are less efficient than EPS or XPS in terms of thermal performance but are more viable for applications where insulation is critical. Despite their reduced mechanical strength compared to concrete and traditional plaster, these composites can be a valuable option for certain building applications. Balancing their thermal efficiency, mechanical performance, cost, and environmental impact is essential for determining their suitability in specific construction scenarios. Future research and development should focus on optimizing these properties to enhance their practical applications and sustainability.

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