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Assessment of Bio-Based Composite Building Envelopes for Thermal Inertia and Energy Efficiency

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Abstract. Building envelopes are a challenge in enhancing their thermal efficiency as well as minimizing construction impact to increase their sustainability. The research study aims to evaluate the thermal, energy, and environmental analysis capabilities of bio-based composite materials in wall systems, which serve as alternative material barriers to traditional mortar and plaster. The evaluated configurations are a 2 wt.% Ferula communis mortar and 3 plaster-based coating materials with 8 wt.% Ferula communis, 4 wt.% alfa fibers, and 6 wt.% spent coffee grounds. In the case of these solutions, they had been chosen from existing experimental methods for thermo-mechanical studies and were incorporated on several representative wall assemblies. Dynamic simulation with TRNSYS was carried out based on the climate characteristics of Fez (Morocco) under various façade orientations and seasonal variations. The findings demonstrated that bio-based composites, in particular, can efficiently mitigate the summer temperature variations and improve winter thermal stability. This enhanced behavior is also apparent in the lower values of the decrement factor for the components, which indicate increased thermal inertia. These reinforced walls can significantly decrease heating and cooling energy requirements with energy savings compared to older construction of the best design of over 26%, and decrease CO_2-equivalent emissions.

1 Introduction

With such high global environmental, climate, and energy pressure, the building sector itself should minimize its ecological footprint and fulfill more requests for comfort, durability, function, and overall performance in the industry. Buildings account for around 30% of global energy use and a significant proportion of greenhouse-gas emissions around the world. In Morocco, the contribution of the sector is more evident with buildings taking up close to 33% of all final energy consumption (approximately 26% in the residential sector and 7% in the tertiary sector) and accounting for over a third of national greenhouse-gas emissions [1]. The building sector is thus a strategic lever for the attainment of national objectives for energy transition and sustainable development.

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In light of these issues, Morocco has a clear legislative and regulatory framework. Among them, **Law 47-09** has set the aim of lowering building energy use by 15% by 2030, primarily through improved thermal performance in construction. This policy direction has been implemented through the Moroccan Thermal Construction Regulation (RTCM), developed by the Moroccan Agency for Energy Efficiency (AMEE), and it encourages energy conservation in three parallel areas: Passive approach: based on envelope optimization, architectural design, and the use of material properties to reduce energy demand without active energy input, Active approach: with respect to technical systems (heating, cooling, ventilation, etc.) whose efficiency is closely associated to proper sizing and optimized control, and Occupant behavior, which affects consumption through the use of openings and shading devices, lighting, electrical appliances, and comfort setpoints.

Throughout this research, the focus is on the passive pillar, with a specific interest in improving the building envelope using low-carbon bio-based materials capable of limiting heat transfer with the outdoor environment. Special emphasis is placed on integrating natural fibers and bio-based aggregates in cementitious or gypsum-based matrices, which can enhance thermal performance while valorizing locally available, renewable resources. This strategy thus positions itself as an environmentally sound, economically relevant, and climate-adapted alternative, which assists the construction of buildings that are more energy-efficient, more resilient, and better aligned with a sustainable trajectory for Morocco's construction sector.

A few studies were conducted to improve the physical properties of pure mortar and gypsum matrices by using bio-based materials. Due to their extensive use by a lot of ancient civilizations for traditional construction materialization, there is new, recent research interest in mortar and plaster as well to improve their physical properties with the potential ability to satisfy the energy-efficient and sustainability of today. Ouakarrouch et al. [2] studied the thermal performance of chicken feather waste in gypsum plaster for use in wall and ceiling applications. Using the highest tested dosage of 5 wt.%, the composite exhibited a marked reduction in heat-transfer indicators, with thermal conductivity decreasing from 0.481 to 0.309 $W\cdot m^{-1}\cdot K^{-1}$ and thermal diffusivity from 3.07×10^{-7} to 2.69×10^{-7} $m^2\cdot s^{-1}$; dynamic simulations further indicated that using the 5 wt% composite in the envelope would reduce winter heating demand by 29.4% and summer cooling demand by 24.8%. Another study has pointed out the potential for Washingtonia plant waste to become sustainable construction materials. In this work, Boumaaza et al. [3] prepared biochar from lignocellulosic residues formed on Washingtonia stems and leaves by pyrolysis and incorporated it into bio-based mortars with a hydraulic binder. It was found that, incorporating 2% biochar with a particle size of 75μm, thermal conductivity decreased by 30%, while providing adequate mechanical performance. This was attributed to the improved microstructure combined with reduced porosity, benefiting from both thermal insulation and durability.

This study aims to support three bio-based reinforcements previously studied as building material reinforcements: **Alfa Fibers (ALFA)**, **Coffee Grounds (CG)**, and **Ferula Communis (FC) [4-6]**, and to validate their thermal applicability. For ALFA, the thermal conductivity is about 0.041 $W\cdot m^{-1}\cdot K^{-1}$; for CG, it is 0.165 $W\cdot m^{-1}\cdot K^{-1}$; and for FC, it is 0.048 $W\cdot m^{-1}\cdot K^{-1}$, indicating that these components can improve insulation properties. Environmental rationale, lowered carbon footprint, and waste valorization also drive the inclusion of such reinforcements, and the economic factors related to their availability and abundance. These materials are aggregated into gypsum and mortar matrices at already specified contents. They do not yet fully scale up their deployment, but the classification procedure also serves to ensure a good decision of possible optimal composite formulations due to both thermal properties and a minimum tolerable mechanical property. From this, the chosen formulations are employed in a building envelope constructed out of conventional materials, with a view to investigating thermal and energy efficiency effects.

Based on this selection, the paper examines the integration of the retained configurations and proposes an environmental impact assessment to quantify the actual benefits associated with their use. The investigated composites include renders reinforced with 4% alfa fibers (PALFA/4/0.7), 6% coffee grounds (PCG/6/0.7), and 8% Ferula communis (MFC/8/0.7), as well as mortars reinforced with 2% Ferula communis (PFC/2/0.7).

This paper aims to investigate the thermal properties and potential of composite materials for incorporation into a building envelope using TRNSYS. (Transient System Simulation Tool) based dynamic thermal simulation (DTS). The findings come from the examination of the indoor temperature distributions and the establishment of important dynamic thermal parameters, the thermal decrement factor under various façade configurations (north, south, east, and west). The analysis is then complemented by an estimate of the energy loads necessary to maintain thermal comfort setpoints fixed at 20 °C for heating and 26 °C for cooling. Finally, an environmental survey is performed to estimate the ecological impact of our proposed composites. All in all, this approach gets us a better grasp of the concrete, deeper meaning of the composite thermal performances under nearly real conditions.

2 Materials, tools, and methods

2.1 Investigated Materials

As previously mentioned, the configurations investigated in this manuscript correspond to formulations selected on the basis of three experimental campaigns aimed at characterizing the thermo-mechanical behavior of bio-based composites. The first study focuses on the use of spent coffee grounds (**Fig. 1a**), a widely available residue due to high coffee consumption, particularly in cafés and restaurants. In this context, Touil et al. [4] carried out an experimental investigation to assess the effect of incorporating 0%, 2%, 4%, and 6% CG on the thermo-mechanical properties of gypsum-based composites. The material, collected from a café in Meknes (Morocco), was pre-treated through cleaning, drying, and grinding to improve homogeneity, and then dried further to remove residual moisture. The results indicated that increasing the CG content significantly enhanced the thermal insulation performance of the gypsum composite.

In the arid Mediterranean, one of the most prevalent native species is the perennial tussock grass Stipa tenacissima L., which is often referred to in the literature as ALFA (**Fig. 1b**). This North African endemic is adapted to semi-arid environments, and it has such a wide range that, in Morocco, it is reported to cover approximately 2.2 million hectares of natural steppe. Aside from its ecological significance, ALFA has been utilized as a raw material for traditional industries for a long time and is an emerging contributor to engineering applications, especially in bio-based reinforcement to enhance the thermo-mechanical performance of polymers and construction materials. Due to low thermal conductivity (0.041 W/m·K as reported), alfa has been increasingly investigated as a bio-based insulating constituent. In the second experimental study, Touil et al. [5] evaluated plaster composites with 2% and 4% ALFA fibers. Thermal measurements demonstrated a significant improvement, with the 4% fiber formulation giving a 32.25% reduction in thermal conductivity. Mechanically, the addition of alfa did reduce flexural strength but was favorable for the failure mode and led to a more ductile approach (non-linear), which is often used with respect to improving damage resistance and robustness.

The third of these articles involves Ferula communis (**Fig. 1c**). Touil et al. [6] studied its application as a partial replacement material in gypsum plaster and mortar applications. The stems were harvested, cut, washed, dried, and ground until sufficiently fine-grained to allow their incorporation. Thermal testing revealed significant reductions in thermal conductivity of 29.42% for plaster and 53.46% for mortar. But greater incorporation levels negatively impacted mechanical performance, reducing flexural strength by up to 91.2% and compressive strength by almost 87.93% in mortar. These results require an optimization of mix designs to promote thermal efficiency and adequate structural performance, which are critical for sustainable construction applications.

Fig. 1. Selected materials: (a) Coffee Grounds, (b) ALFA Fibers, (c) Ferula Communis [4, 5, 6].

2.2 Thermomechanical characterization methods

Characterization of thermo-mechanical properties of composite materials is crucial before using them in construction. From a thermal perspective, such characterization helps provide an accurate understanding of how the material responds to heat and temperature fluctuations by quantifying its ability to conduct, store, and attenuate heat transfer. From a mechanical standpoint, the extent to which the material is capable of supporting external loads under service conditions, maintaining adequate strength, and ensuring long-term durability is crucial. Overall, this combined thermo-mechanical assessment is a prerequisite for reliable performance and safe integration of composites in building applications.

2.2.1 Thermal Characterization

After preparing 27 × 27 cm parallelepiped specimens (2–7 cm thick), thermal conductivity was measured with a guarded hot box (EI702) (**Fig.** *2*a), under steady-state conditions following EN ISO 8990 [7]. A one-dimensional heat flux was imposed between a hot box (Tb) and a cooled side (Ta), with surface temperatures recorded at steady state while minimizing heat losses. Thermal diffusivity was determined using the flash method in EI702 Box B2 (**Fig.** *2*b): a short heat pulse (≈8 s) was applied to the specimen's lower face with a 1000 W lamp, and the temperature response on the upper face was monitored to extract diffusivity from the thermogram using the partial-time method.

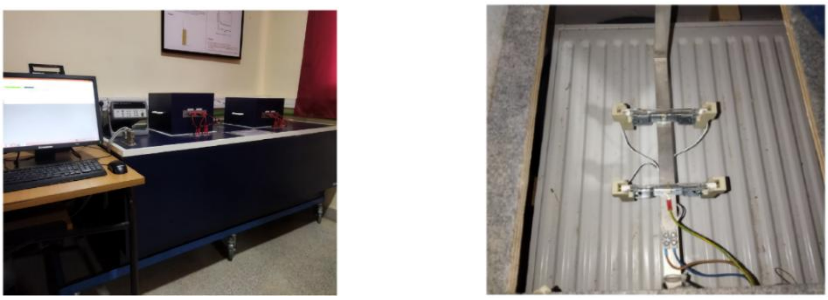

Fig. 2. EI700 measuring cell: (a) Thermal Characterization Setup, (b) Incandescent lamp [6].

2.2.2 Mechanical Characterization

For mechanical characterization, two tests are considered: compressive strength and flexural strength. Mechanical performance was assessed through flexural and compressive tests. Flexural strength was measured by a three-point bending test using an H10KL machine in accordance with EN 13279-2 [8] (**Fig. 3a**), where specimens were supported on two rollers and loaded at mid-span at 50 N/s while recording displacement and deflection. In addition, compressive strength was determined by loading specimens between two platens at the same rate (50 N/s) until failure (**Fig. 3b**), and the elastic–plastic behavior was examined from the load–displacement curve.

Fig. 3. Mechanical test setup: (a) 3-Point bending apparatus, (b) Compression apparatus [6].

2.3 *Numerical approach*

This section provides a comprehensive description of the building characteristics implemented in TRNSYS, and clearly states the simulation assumptions and the calculation procedures adopted for each physical parameter considered.

2.3.1 Dynamic assessment of a building's thermal performance

Integrating the formulated composites into a typical building form is an essential requirement to assess their application. In the present work, this is achieved by means of dynamic thermal simulation using TRNSYS, a world-class climate modelling platform for heat transfer within an existing building envelope coupled with the determination of related energy effects. The selection of TRNSYS is mainly inspired by its modular nature, also because it can directly parameterize materials, geometry, and boundary conditions, allowing simulation methods to effectively mimic actual operating environments. To implement the model, two complementary components work as necessary. TRNBuild is used to describe the building at the physical level: wall components (layer and materials), thermophysical properties, surface areas and dimensions, facade orientations, glazing characteristics, and heat exchanges with the external environment. It also allows the specification of interactions between envelope and thermal gains (both internal and external) and supports the exploration of multiple construction scenarios. After the building description is finished, we use Simulation Studio to build the simulation project, run calculations, and extract outputs, including the relevant weather files and, where necessary, add more modules to enhance the external conditions imposed on the simulation.

The simulated cases represent envelope variants and allow comparative analysis. The conventional mortar is replaced with the MFC/2/0.7 composite for each configuration, while the reference render is replaced with one of the following composites: PALFA/4/0.7, PCG/6/0.7, or PFC/8/0.7. The output is compared with the baseline structure of MFC/0/0.7 mortar and render PCG/0/0.7, chosen as the standard reference mix. The simulation results are evaluated in four main ways through the following metrics: (i) monitoring the temperature evolution for the four main orientations (North/South/East/West); (ii) deriving the envelope dynamic-response indices, especially the decrement factor (DF); (iii) the estimation of the heating and cooling energy demands required to maintain comfort setpoints fixed at 20 °C for heating operation and 26 °C for cooling operation; and (iv) estimation of the environmental impact of each construction option to quantify potential reductions in avoided CO_2 emissions.

The simulation is based on the following assumptions:

- ⇒ Initial indoor temperature and humidity were set at 20°C and 50%, respectively.
- ⇒ Thermal bridges and shading effects are not considered.
- ⇒ Heating is activated when the indoor temperature drops below 20°C.
- ⇒ Cooling is activated when the indoor temperature exceeds 26°C.
- ⇒ Infiltration and ventilation rates are set at 0.6 air changes per hour (ACH).
- ⇒ An annual simulation was carried out with hourly resolution.

2.3.2 Climatic Conditions of Fez

Selected configurations have been evaluated under Fez's climatic conditions, which belong to the third Moroccan climate zone, and for different façade orientations (north, east, south, and west). The given inputs cover two short representative periods: three winter days (December 24-27) and three summer days (July 16–19) [6]. The weather files were primarily generated by Meteonorm, which provides an extensive compilation of meteorological records drawn from a global database. It delivers key climate variables needed for building simulation, like solar irradiation, air temperature, relative humidity, and wind speed.

Situated in northern Morocco at an altitude of about 414 m, Fez has a Mediterranean climate with a pronounced continental influence, so warm summers and relatively cool winters are characteristic. This climatic variability is shown in (**Fig. 4**), which presents a monthly scale of global solar irradiation as well as of minimum and maximum temperatures. Solar radiation increases progressively from the start of the year until the summer, peaking in July at around 235 kWh/m², and decreasing thereafter, down to the lowest value in December at around 90 kWh/m². Thermal aspects also display marked seasonal contrasts: monthly minimum temperatures range approximately from 6 °C in winter to 22 °C in summer, while monthly maximum temperatures rise from about 15 °C in January to above 40 °C in August. This, along with elevated summer solar potential and elevated warm-season temperatures but milder winter conditions, makes Fez an important case to compare, on a thermal and energy performance basis, for envelope-integrated construction materials. Thus, the meteorological data provided constitute the critical climatic input required to execute the TRNSYS dynamic simulations.

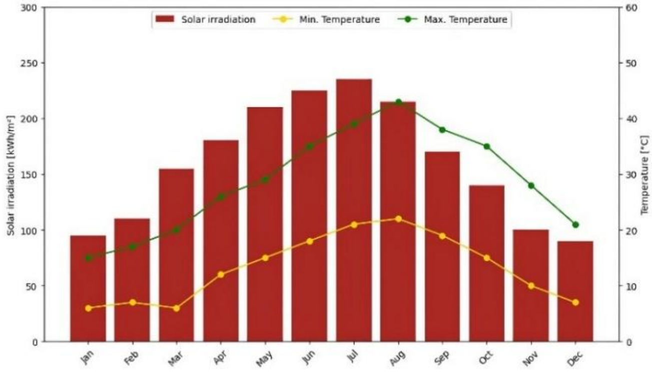

Fig. 4. Climatic conditions of the city of Fez.

2.3.3 Characteristics of the building envelope

To ensure representative results, the selected construction system corresponds to a typology commonly used across most regions of Morocco. The reference building analyzed has a ground-floor area of 70 m² and is arranged into four distinct functional spaces: a bedroom, a kitchen, a living room, and a bathroom. (**Fig. 5**) presents the architectural floor plan and the three-dimensional geometric model of the studied building. The ceiling height is set to 3 m. The entrance door has a surface area of 2.55 m² and a thickness of 4 cm, while the interior doors have a surface area of 2.3 m² and a thickness of 3 cm. All doors are made of wood, characterized by a thermal conductivity of 0.19 W/m·K, a density of 754 kg/m³, and a specific heat capacity of 1500 J/kg·K. The glazed openings consist of single-glazed windows with aluminum frames, each having a surface area of 1.8 m². The building envelope is built using a conventional multilayer configuration. The external walls adopt a double-leaf assembly made of two 10 cm hollow clay brick layers separated by a 5 cm air cavity, with 2 cm cement-mortar coatings applied on both the inner and outer faces. Internal partition walls consist of a 10 cm hollow brick core finished with 2 cm of cement mortar on each side. The roof is based on an hourdis slab system, including 16 cm hollow blocks, a 7 cm reinforced-concrete topping, a 5 cm mortar layer, and a 2 cm ceramic tile finish on the exterior, while the interior side is finished with 1 cm of plaster. The floor, laid over compacted soil, comprises a 20 cm concrete slab covered by a 5 cm mortar screed and a 2 cm interior ceramic tile layer.

Fig. 5. 2D & 3D geometric model of the building.

2.3.4 Thermal performance indicators and inertia assessment

The thermal behavior of the building envelope is evaluated from the post-processing of wall surface temperatures at the inner and outer interfaces (TIS, TOS). Calculations were performed for the four principal orientations (N, E, S, W), and the roof, and for two representative short-term climatic sequences corresponding to winter (December 24-27) and summer (July 16-19) conditions. These datasets enable a comparative analysis of heat transfer through the walls and the identification of assemblies that effectively mitigate summer heat gains while maintaining thermal stability during colder periods. Beyond instantaneous temperature levels, the analysis focuses on the thermal inertia of the wall systems, defined as their ability to store heat and delay its transmission toward the indoor environment. This dynamic response is characterized using a complementary indicator. The decrement factor (DF), expressed as a dimensionless ratio, measures the attenuation of temperature oscillation amplitudes across the wall, providing a direct indicator of the damping effect associated with thermal inertia and its contribution to indoor thermal comfort (**Eq.1**).

$$DF = \frac{T_{IS}^{max} - T_{IS}^{min}}{T_{OS}^{max} - T_{OS}^{min}} \tag{1}$$

2.3.5 Environmental impact

In addition to reducing heating and cooling energy demand, incorporating bio-based reinforcements within wall assemblies offers a route for valorizing renewable resources and limiting dependence on non-renewable, carbon-intensive material streams, for example, certain synthetic insulation products. By lowering the building's energy loads, this strategy decreases primary energy consumption and, consequently, the indirect CO_2 emissions associated with electricity generation and natural-gas use. The estimation of avoided emissions is therefore derived from the simulated heating and cooling requirements combined with energy-carrier-specific emission factors. In this work, the electricity emission factor is assumed to be **χ=0.734 kg CO2eq/ kWh**, whereas the natural-gas emission factor is taken as **β=12.6 g CO2eq/ MJ**. The total emissions are then computed using **(Eq.2)**

$$m(CO_2) = \beta Q_h + \chi Q_C \tag{2}$$

3 Results and discussion

3.1 Analysis of building temperature

In this section, the indoor air temperature evolution of one representative zone is examined in order to compare the reference building with the bio-based reinforced configurations over two seasonal periods (December 24-27 and July 16-19). (**Fig. *6* and 7**) indicates that the passive envelope-enhancement strategy effectively modifies the indoor temperature pattern. During the winter period, the average indoor air temperature for the selected area increases from 11.5 °C to 12.3 °C for the reinforced cases, with the most pronounced improvement observed for the P-ALFA configuration, reaching an increase of about 0.8 °C. In summer, under the severe climatic conditions of Fez, the improved configurations lead to a reduction in indoor air temperature, with a maximum decrease of approximately 0.95 °C relative to the reference case for the same configuration. Comparable trends are observed in the other building zones.

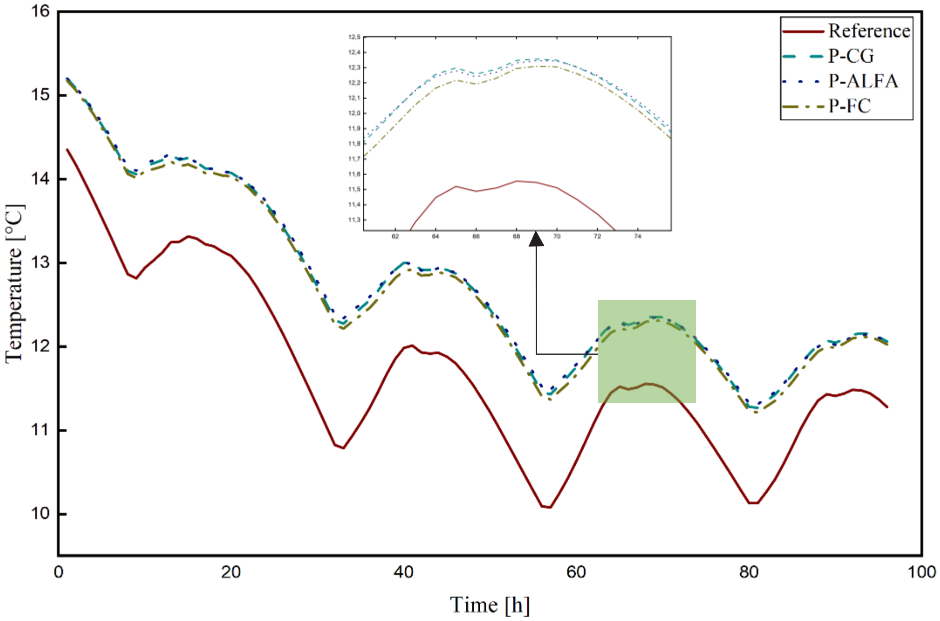

Fig. 6. Internal temperature evolution of the building in winter (December 24-27).

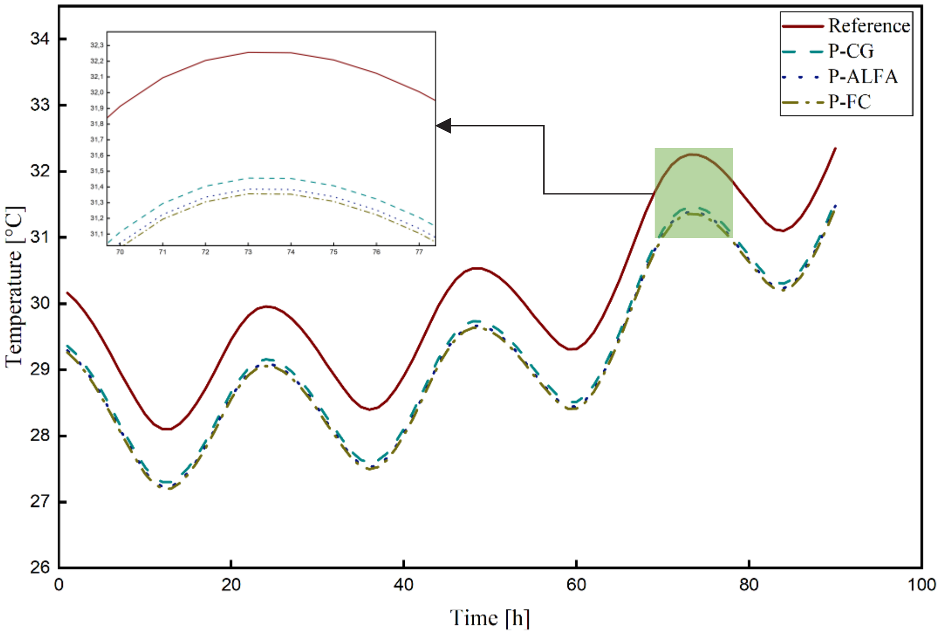

Fig. 7. Internal temperature evolution of the building in summer (July 16-19).

Afterwards, the internal and external surface temperatures of the building envelope were assessed for the main façade orientations and the roof under two contrasting seasonal conditions. By comparing the selected wall configurations and their thermal response, an examination was conducted. Only one representative orientation is shown for the results here, while the same overall trends were observed for the other orientations. During the summer season (**Fig. 8**), high solar irradiance tends to induce a significant increase in the interior (TIS) and exterior (TOS) surface temperatures of the building envelope. Among the components, the roof features the highest heat loads (peak temperatures of 49 °C), with the west-facing façade reaching approximately 47 °C. The measurements indicate a decrease in surface temperature values when incorporating bio-based reinforcements into wall configurations. When compared to the reference configuration under peak external thermal loading, a wall system reinforced by Ferula communis fibers (P-FC) reduces interior surface temperature variations by approximately 0.20, 0.25, 0.23, 0.22, and 0.45 °C for the north-, east-, south-, west-facing walls and the roof, respectively. Likewise, the composite with coffee grounds (P-CG) demonstrates a similar moderating effect, with reductions of approximately 0.19, 0.24, 0.22, 0.19, and 0.44 °C across the same orientations. The most appropriate thermal response is obtained with the alfa fiber-reinforced composite (P-ALFA). This configuration leads to interior surface temperature declines of ~0.224, 0.253, 0.225, 0.221, and 0.453 °C for the north, east, south, west façades, and the roof, respectively. This solution also shows a significant gain on the roof the average temperature reduction of around 0.45 °C under summer conditions from the P-ALFA system is notable.

For the winter (**Fig. 9**), indoor surface condition reveals that thermal comfort is deteriorating, especially in the north- and east-facing walls, with lower solar availability and reduced outdoor temperatures that increase the difference from the heating setpoint. By contrast, the south- and west-facing façades are relatively stable due to an increase in solar gain. Regardless of orientation, composite-based walls exhibit a higher thermal stability when compared to the reference structure architecture in all orientations. In line with a minimum outdoor temperature, the P-ALFA configuration is the one that is the most thermally beneficial: inside thermal strength shows increased interior surface temperature of about 0.22 °C for the south façade, 0.15 °C for the east façade, 0.19 °C for the west façade, 0.20 °C for the north façade, as well as 0.35 °C for roof level at P-ALFA. The other reinforced structures likewise show similar performance at slightly lower magnitudes but similar trends.

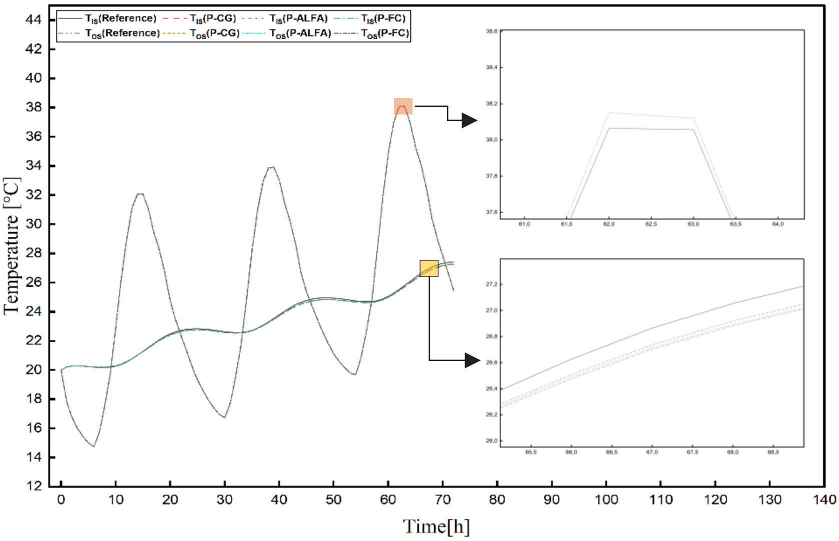

Fig. 8. Summer surface temperature profiles for the south-facing wall.

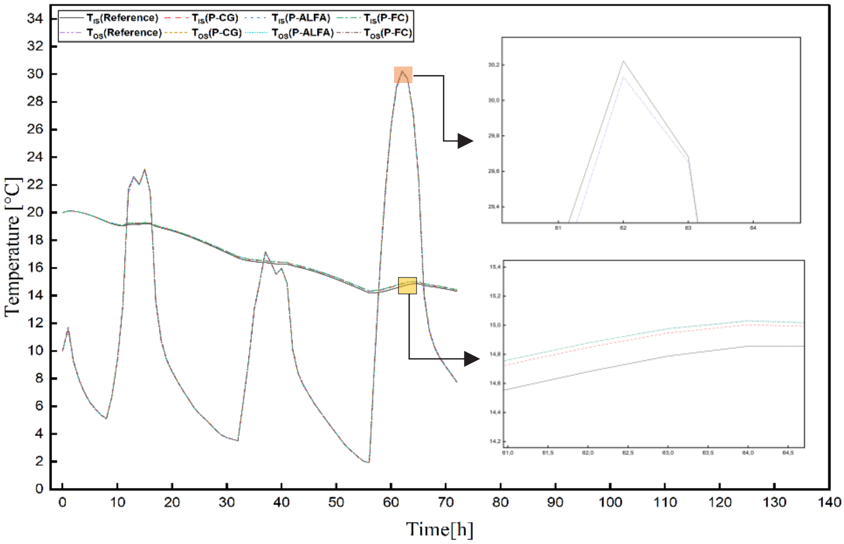

Fig. 9. Winter surface temperature profiles for the south-facing wall.

3.2 Analysis of the decrement factor

The thermal response analysis indicates that, despite prominent external thermal changes, the temperature evolution on the interior side remains significantly moderated despite the exposure of the wall surface to external thermal fluctuations. Such a discrepancy indicates the abatement capacity of the building envelope to attenuate external thermal excitations. Based on this, a dynamic index called the thermal decrement factor is developed for a quantitative measure of this behavior. This property indicates the extent to which external temperature variations are transferred to the wall's inner surface and so gives a direct indication of the wall's contribution to limiting heat transfer. Lower values indicate better thermal buffering performance. The decrement factor was examined at both winter and summer temperatures and for the dominant façade orientations, with results reported in (**Fig. 10 and 11**).

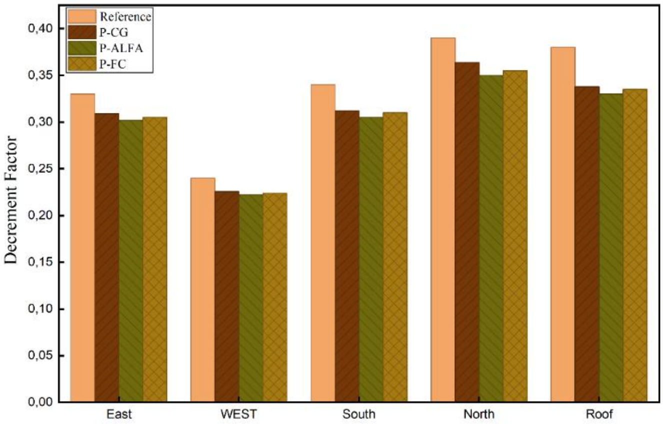

Fig. 10. Decrement factor for the summer period.

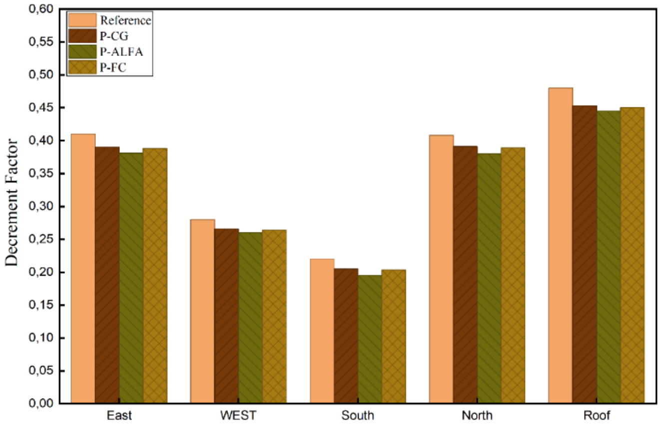

Fig. 11. Decrement factor for the winter period.

In the wintertime, the decrement factor has a strong dependence on the orientation of the façade and the configuration of the wall. For all cases, the roof exhibits the highest values, reflecting more thermal transmission, whereas the south-facing walls display the lowest values due to increased attenuation. For the reference wall, average decrement factors are approximately 0.41, 0.28, 0.41, 0.23, and 0.47 for the east, west, north, south, and roof orientations, respectively. The addition of bio-based reinforcements results in a gradual decrease in these values. Particularly, the average factor values for the P-CG configuration are approximately 0.39, 0.26, 0.39, 0.20, and 0.45. Likewise, the P-FC and P-ALFA scenarios present similar (but slightly enhanced) performance, as shown by the decrement factors of 0.38, 0.25, 0.38, 0.195, and 0.44, suggesting a small, yet consistent, advantage over the coffee-ground-based design.

Disproportionality of the decrement factors also varies during the summer period. The walls and roof oriented to the north are the most peaked, and the façade towards the west is the most attenuated. In the reference case, the levels of summer decrement factors are relatively large with 0.33, 0.24, 0.38, 0.32, and 0.36 for east, west, north, south, and roof orientations. The application of composite walls drastically reduces these coefficients, lowering the mean to around 0.30, 0.22, 0.36, 0.31, and 0.34. As observed in winter, the P-FC and P-ALFA systems exhibit marginally better performance than P-CG.

Overall, these findings confirm that bio-based reinforcement materials enhance the dynamic thermal behavior of building envelopes by reducing the amplitude of temperature oscillations transmitted indoors. This improved thermal damping is particularly beneficial under summer conditions, where it contributes directly to limiting overheating and improving indoor thermal comfort.

3.3 Analysis of heating and cooling loads

The yearly energy consumption analysis reflects that envelope geometry largely controls building heating and cooling demand. Under fixed indoor comfort conditions (setpoint 20 °C for heating and 26 °C for cooling), simulations were performed to evaluate the impact of wall configurations under investigation in a uniform manner. Annual energy consumption obtained for all cases is shown in (**Fig. 12)**.

The reference building has the highest overall energy demand, 85.3 kWh/m²·year. This increase in the consumption was because the strong solar gain in summer (which increases cooling loads) is complemented by a relatively low outdoor temperature in winter, which makes a great demand on heating. Conversely, switching conventional layers to bio-based composite materials in the building envelope would lead to a significant reduction in the overall energy utilized. Of all these alternative configurations, the P-ALFA approach can attain the best total energy saving up to 62 kWh/m²·year, and a final energy reduction of up to 27.3 % compared to the reference case is obtained. Similar benefits apply to the P-FC and P-CG solutions, but to a lesser extent. The annual consumption in the wall system with Ferula communis is close to 64 kWh/m²·year, thus about 24.9 % is reduced, while for the wall system with spent coffee grounds it is 67.1 kWh/m²·year, by around 21.3 %. Taken together, these results further support that the application of bio-based composites in architectural envelopes is suitable for reducing the overall energy consumption as compared to conventional construction, and as such, it is helpful for achieving the current energy-efficiency targets of the building industry.

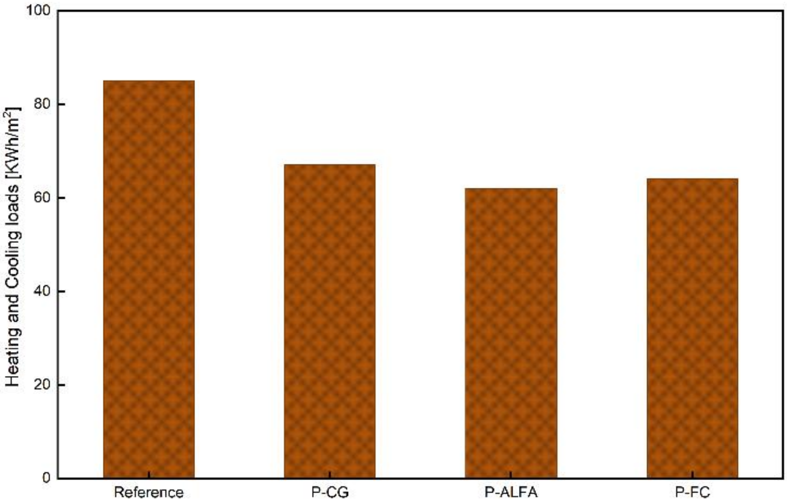

Fig. 12. Heating and cooling loads were calculated for the different configurations studied.

3.4 Environmental study

Apart from building energy-performance assessment, evaluating environmental impacts is an essential aspect of sustainability studies, especially when considering that greenhouse gas emissions are a crucial driver of global warming, which is reflected in the current discussions. Estimates of CO_2 emissions depend on the energy carrier employed and its emissions intensity. Space-heating demand is presumed to be fulfilled by a natural-gas heating system (in this study), and cooling demand is met by an electric air-conditioning unit.

(**Fig. 13**) presents the CO_2 emissions for the various configurations. It is shown that using composite materials in the building structure significantly decreases CO_2 emissions compared to the reference case. The ALFA-fiber-based configuration, among the solutions investigated, has the best performance by avoiding emissions of approximately 553.4 kg CO_2-equivalent compared to the baseline building. On the other hand, the P-CG and P-FC configurations also achieve substantial reductions, approximately 394.3 kg and 502.35kg

CO_2-equivalent, respectively. In conclusion, the findings support the effectiveness of bio-based composite envelope solutions in lowering the carbon footprint of buildings through reduced energy demand.

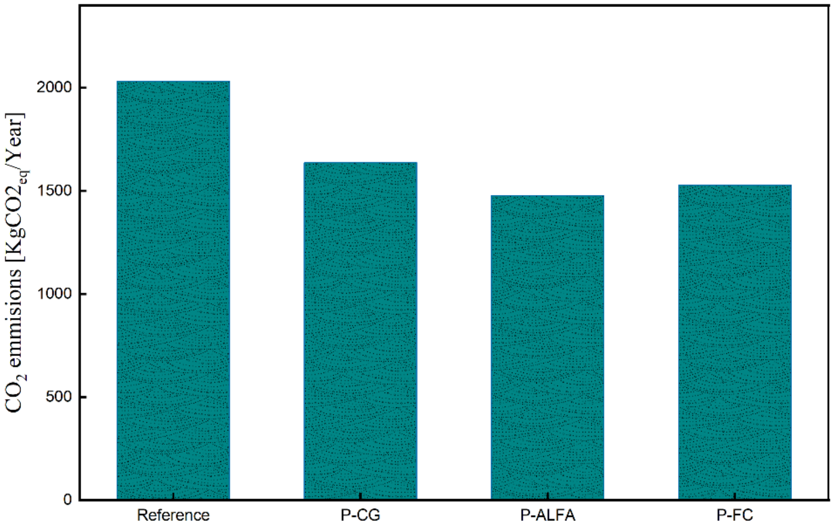

Fig. 13. Avoided CO_2 emission for different configurations.

4 Conclusion

Here, the evaluation of the bio-based composite materials used in the construction of building envelope solutions is centered on the evaluation of bio-based composite materials, chosen due to their greater thermal performance. The considered configurations are (modified 2 wt.% Ferula communis and three plaster-based coatings with 8 wt.% Ferula communis, 4 wt.% alfa fibers and 6 wt.% spent coffee grounds, respectively. The materials were engineered into different wall envelopes used for different thermal scenarios, thereby permitting the thermal performance and environmental effects to be discussed. Dynamic simulations performed using TRNSYS proved that the internal incorporation of highly optimized composites into building walls significantly enhances their thermal response. In summer, the reinforced walls can effectively regulate indoor temperature, while in winter, even while the wall is oriented in a certain way, the walls act as a means to retain heat. The better dynamic behavior is also reflected by low decrement factor values that indicate higher wall thermal inertia and more power to suppress external thermal changes. These thermal benefits lead to decreased heating and cooling energy requirements. Besides, utilization of bio compounds improves the environmental impact of the building, reducing the overall ecological footprint of the building, which signifies that the recommended actions are suitable for all other sustainable buildings.

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