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ORIGINAL ARTICLE

Mechanical and thermal properties optimization of an innovative mortar incorporating PVC waste for enhanced energy efficiency

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Abstract: Given the significant environmental challenges posed by plastic waste, innovative reuse strategies are essential. This study seeks to bridge a gap in prior research by investigating the novel application of polyvinyl chloride drainage pipe waste (PVC) as a partial sand substitute in mortar, aiming to enhance both the thermal behavior and mechanical performance. Previous studies have noted that while integrating plastic waste into construction materials can enhance thermal properties, it frequently results in a reduction of mechanical strength. To address this issue, our study carefully considered the size of PVC aggregates. Seven substitution rates (0%, 5%, 10%, 15%, 20%, 25%, and 30% by weight) were evaluated through laboratory tests, including bulk density, water absorption, compressive and flexural strength, thermal conductivity, volumetric heat capacity, and thermal diffusivity. Additionally, numerical simulations using TRNSYS software on office buildings assessed the energy-saving potential. Furthermore, a multi-objective optimization approach was introduced to identify the optimal mix composition, balancing mechanical strength and thermal performance. Results showed that increasing PVC content improved thermal properties, with an optimal substitution rate also enhancing mechanical characteristics. Notably, a 30% replacement rate demonstrated significant energy savings, which could be further increased by increasing the mortar thickness.

Keywords: eco-friendly mortar, plastic waste, mechanical characterization, thermal characterization, energy efficiency, optimization

1 Introduction

In Morocco, the building sector stands out as the leading consumer of energy, accounting for 25% of the overall energy consumption (**Fig. 1**). This energy consumption is anticipated to escalate rapidly in the upcoming years due to two key reasons: the significant growth of the building stock and the noticeable rise in household equipment rates (heating, cooling, water heating, refrigeration, etc.) [1]. To address this situation, the country has implemented several programs and measures aimed at improving energy efficiency in the construction industry. The objective is to diminish energy consumption to minimize the effects of climate change through a decrease in greenhouse gas emissions. These initiatives are a direct response to the guidelines of the Conference of the Parties (COP) [2], which strives to reduce global greenhouse gas emissions. Among these measures, the enhancement of

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the building's external structure holds a prominent position. This strategy involves interventions to strengthen thermal insulation, optimize the use of solar energy, and adopt more sustainable construction materials. By focusing on improving the building envelope, Morocco aims to create more energy-efficient structures, making a significant contribution to the transition toward more sustainable energy consumption and the fight against climate change [3].

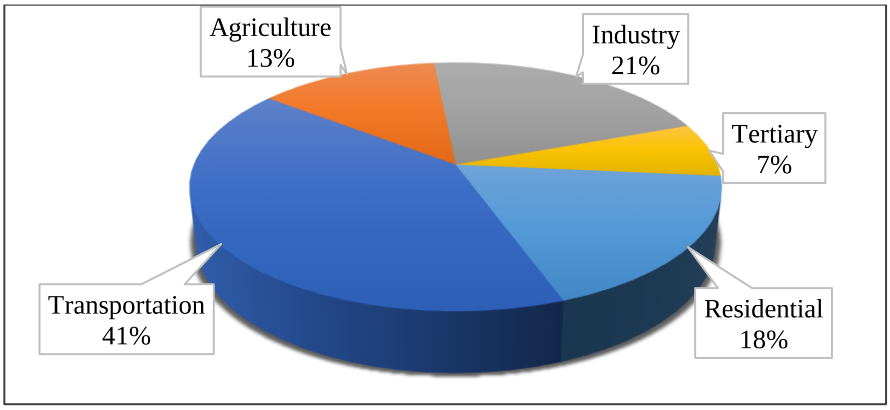

Fig. 1: Structure of energy consumption by sector.

Given that the building envelope, specifically the walls, is responsible for 29%-59% of heat losses [4], researchers have turned their attention to the construction materials composing them. They are focusing on modifying the formulation of concrete, brick, and mortar to enhance their thermal insulation [5–7]. This modification may involve the total or partial replacement of cement, sand, or gravel with insulating materials. Plastic is among the chosen materials due to its widespread use in our daily lives, often followed by poor management after use. Its insulation properties make it suitable for incorporation into construction materials, which can help reduce its presence, preserve natural resources, and improve building energy efficiency [8]. Various types of plastics have been used to assess their impact on the structural and thermal characteristics of construction materials [9, 10]. Results have shown promising enhancements in thermal resistance and reduction in thermal conductivity [11]. According to a study by Hannawi et al. [12], it was demonstrated that introducing recycled PET as a substitute for aggregates in cement-based composites led to a decline in thermal conductivity. The decrease in thermal conductivity observed in the composites was attributed to the lower conductivity of PET in comparison to that of the natural aggregates. Many researchers have previously observed a decline in thermal conductivity with higher levels of PET replacement. For instance, Coppola et al. [13] studied the impact of PET aggregates on the thermal behavior and long-term durability of mortars, confirming the improved thermal resistance and durability of PET-incorporated mortars. These findings align with the results published in [14]. Moreover, Badache et al. [15] found that replacing 15%, 30%, 45%, and 60% of natural sand with High-Density Polyethylene (HDPE) resulted in a conductivity reduction of 10%, 20%, 31%, and 41%, respectively, in comparison to the conventional mortar. Mechanical properties have also been investigated in various research studies. Safi et al. [16] found that the compressive strength of self-compacting mortars reduced with increasing the plastic waste proportion at every curing duration, likely due to poor bonding between the cement paste and the plastic wastes or the low strength of the plastic waste. Similar findings were noticed by Lazorenko et al. [17], indicating that substituting natural fine aggregate with PET particles reduces the compressive and flexural strength of geopolymer mortar. This decrease is linked to the inadequate adhesion of PET particles to the geopolymer matrix.

Polyvinyl chloride (PVC) ranks among the most commonly employed plastics in the production of construction materials, including windows, doors, and pipes. In 2018, global PVC production was reported at 44.3 million tonnes, with projections suggesting it will exceed 60 million tonnes by 2025 [18]. The disposal and management of PVC waste have become significant environmental issues. Thus, identifying alternative uses for the large volumes of PVC waste is crucial for safe disposal. Reusing plastic waste stands as one of the most environmentally friendly methods of waste management. For this purpose, this study focuses on the reuse of polyvinyl chloride drainage pipe waste (PVC), a type of PVC that has been the subject of research by only a few researchers, primarily in concrete applications [19–25]. After reviewing these studies, it was concluded that particle size distribution plays a critical role in enhancing the mechanical properties of concrete. Smaller particles can fill the gaps between larger particles, which reduces porosity and, in turn, enhances the compressive strength of the concrete. As stated by various authors, the key factor behind the decline in strength was the inadequate bond between the cement and larger aggregates [26]. To address this issue, our study carefully considers the size of PVC aggregates, employing a particle size range not previously utilized in mortar production. This approach aims to improve the mechanical properties of the mortar and support sustainable construction practices.

According to the literature, it has been demonstrated that the mechanical strength of mortar based on plastic waste decreases with higher replacements, while thermal resistance increases with a higher proportion of waste in the mortar [22]. An increase in thermal resistance implies an enhancement in the energy efficiency of the building [27]. To determine the energy demand and potential energy gains resulting from the insulation of construction materials, researchers have turned to numerical simulations. Horma et al. [11] demonstrated that thermal performance simulations had revealed a notable enhancement in the thermal insulation capacity of cement-based mortar when incorporating 0.6% recycled expanded polystyrene (EPS). This resulted in a reduction of heating and cooling demands by 20% and 15%, respectively, compared to conventional mortar. Annaba et al. [28] demonstrated through numerical simulations that their novel sandwich material, comprising a pozzolan-granular, plaster composite core with two cement mortar protective layers, exhibits remarkable energy performance improvements. The sandwich material showcased a 22% decline in the consumption of cooling energy and a 14% decrease in heating energy consumption compared to conventional wall materials. Moreover, their study revealed a substantial yearly reduction in $\mathrm{CO_2}$ emissions, with reductions of approximately 611.57 $\mathrm{kgCO_2e}$ for cooling and 810 $\mathrm{kgCO_2e}$ for heating.

In this paper, a novel eco-friendly mortar was introduced to investigate its physical, mechanical, and thermal properties as an insulating material in building envelopes. The mortar incorporates PVC drainage pipe waste as a partial substitution for sand by weight, with seven proportions: 0%, 5%, 10%, 15%, 20%, 25%, and 30%. The study was structured into three primary sections. The first part involved the physical, mechanical, and thermal characterization of this innovative mortar through various laboratory tests, including bulk density, water absorption, compressive strength, flexural strength, thermal conductivity, volumetric heat capacity, and thermal diffusivity. The second part focused on numerically simulating two office buildings using TRNSYS software (Transient System Simulation tool), one in Ifrane and the other in Er-rachidia, to evaluate the energy-saving potential of this new mortar. Finally, a multi-objective optimization approach was introduced to identify the optimal mix, balancing mechanical strength and thermal conductivity for improved structural performance and energy efficiency.

Fig. 2: Reused PVC obtained from drainage pipes

2 Materials and methods

2.1 Composition and formulation

In this investigation, CPj35 cement manufactured by ASMENT TEMERA was employed, possessing a density of 2.8 g/cm^3. The sand was obtained from a Moroccan firm, featuring a maximum particle size of 2.5mm. The plastic particles were sourced from reused unplasticized polyvinyl chloride (UPVC) drainage pipes provided by a Moroccan firm dedicated to plastic waste recycling (**Fig. 2**). The pipes were sorted, crushed, washed, dried, and ground into fine PVC sand using specialized machinery. The Sieve analysis of the aggregates is presented in **Fig. 3**. To investigate the impact of PVC drainage pipes on the mortar's physical, mechanical, and thermal characteristics, seven mortar mixtures were designed by substituting sand with PVC pipe waste at weight percentages of 0%, 5%, 10%, 15%, 20%, 25%, and 30%. The mortar mix consisted of a 1:3 ratio of cement to sand, with a water-to-cement proportion of 0.5 according to NF EN 196-1 standard [29] (**Table 1**). These mortar mixtures are designated as M-0, MPVC-5, MPVC-10, MPVC-15, MPVC-20, MPVC-25, and MPVC-30, respectively.

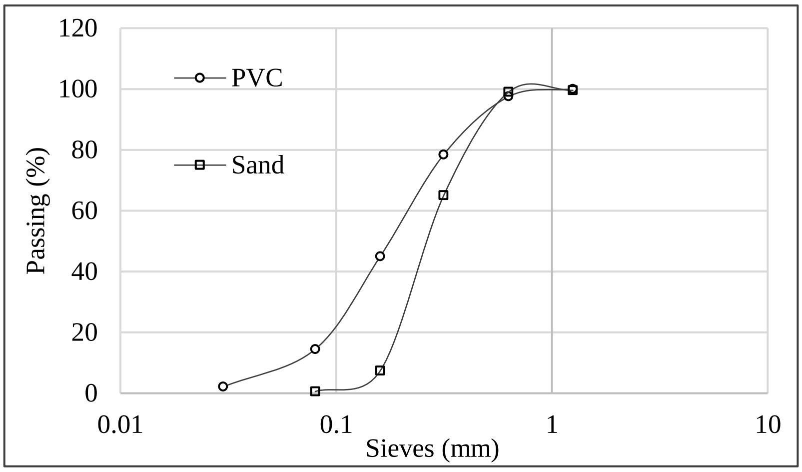

Fig. 3: Grain size analysis of sand and PVC waste.

Table 1: Proportions of mortar components in **kg/m^3**.

Materials (kg/m^3)	Mix type						
	M-0	MPVC-5	MPVC-10	MPVC-15	MPVC-20	MPVC-25	MPVC-30
Cement	250	250	250	250	250	250	250
Sand	1125	1068.75	1012.5	956.25	900	843.75	787.5
PVC	0	56.25	112.5	168.75	225	281.25	337.5
Water	125	125	125	125	125	125	125

2.2 Laboratory evaluation methods

After the mixing process, the prepared mixture containing varying percentages of PVC drainage pipe waste (0%, 5%, 10%, 15%, 20%, 25%, and 30%) was then poured into two different types of samples: one with a prismatic shape measuring 4cm × 4cm × 16cm and another with a rectangular parallelepiped shape measuring 4cm ×8cm ×12cm (**Fig. 4**). The first type was manufactured to evaluate bulk density according to EN 1015-10 [30], water absorption following the EN 13755 standard [31] and mechanical strength, including compressive and flexural strength in compliance with EN 1015-11[32].

Fig. 4: Geometric configuration of the mortar specimens produced.

Following 24 hours of hardening at room temperature (20 ℃), the specimens were removed from their molds, subjected to a 28-day curing process under controlled humidity, and then oven-dried before testing to ensure consistent results.

The water absorption of mortar was assessed by employing the total immersion technique. Prismatic specimens were submerged in water for 24 hours to obtain their wet mass (M_{wet}), followed by a 24-hours drying period at 70 ℃ to obtain their dry mass (M_{Dry}). The water absorption can be computed directly utilizing the subsequent equation, which relies on the wet and dry mass measurements of the samples see **Eq (1)**.

$$\text{Water absorption} = \frac{M_{wet} - M_{Dry}}{M_{Dry}} \tag{1}$$

The mortar strength evaluation was conducted using the STDE machine (SMART TESTING and DRILLING EQUIPMENT). Initially, the specimen underwent flexural strength testing, followed by the two halves being subjected to compressive strength testing (**Fig. 5**). The other type of samples was dedicated to examining the thermal properties of the proposed eco-friendly mortar, including different percentages of PVC drainage pipe waste. The transient state method was employed to rapidly compute thermal conductivity, thermal diffusivity, and volumetric heat capacity according to NF EN ISO 22007-2 [33]. Among the transient methods, the Transient Planar Source Method 1500 hot disk instrument (TPS1500) was chosen for its notable precision, covering a broad spectrum of thermal conductivity ranging from 0.005 W/m.k to 1800 W/m.k (**Fig. 6**).

Fig. 5: STDE machine utilized to measure (a): flexural strength and (b): compressive strength.

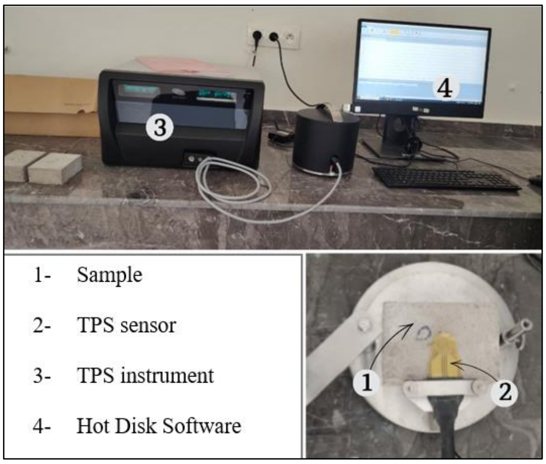

Fig. 6: Transient Planar Source Method 1500 hot disk instrument (TPS1500).

This method was recognized for its high-speed capabilities, enabling the completion of tests on each sample in just a few minutes. Three samples were prepared to test each property at every replacement level, and the mean value was taken. After the experimental investigation, samples exhibiting favorable thermal properties with acceptable mechanical strength will be selected as the optimal choices for integration into numerical thermal modeling.

2.3 Numerical simulation with TRNSYS

In the TRNSYS software, a building energy simulation was conducted to evaluate the thermal efficiency of the eco-friendly mortar when employed as an insulating construction material in the Ifrane and Er-rachidia climate. The choice of the cities Ifrane (Latitude = 33.5, Longitude = -5.2, Altitude = 1665) and Er-rachidia (Latitude = 31.9, Longitude = -4.4, Altitude = 1045) was based on the climatic zoning adopted by the thermal regulations in Morocco[1]. Ifrane, for instance, exhibits the highest annual heating demand, while Er-rachidia requires a greater need for annual cooling. Two small office buildings, identical in size (5 m length, 4 m depth, and 3 m height), located in Ifrane and Er-rachidia are being modeled (**Fig. 7**). Both office buildings have a south orientation, one south facing door having a size of 0.85 m by 2.1 m and one simple glazed window measuring 1 m by 1 m on the southern façade. The office building's entire surface area is exposed to the outdoor environment. The purpose of this work is to simulate the impact of modifying the characteristics of the building envelope, specifically the mortar composition in external walls, on the annual heating and cooling requirements of the structure under standard usage conditions in the climatic zones of Ifrane and Er-rachidia (**Table 2**). Weather data for the studied regions are sourced from the Climate Meteonorm software (**Fig. 8**, **Fig. 9**)

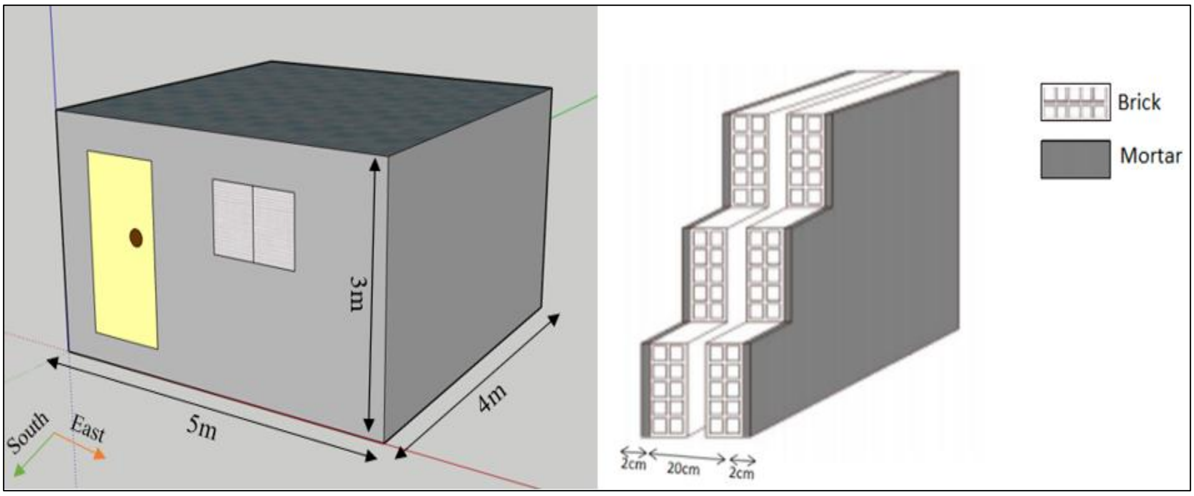

Fig. 7: Office building prototype with external wall composition.

Table 2: Envelope composition for the office building.

Envelope composition		Layers (from outside to inside)	Thickness (cm)	U-value (w/m².k)
External walls	I	M-0	2	2.344
		Brick	20	
		M-0	2	
	II	MPVC-15	2	2.269
		Brick	20	
		MPVC-15	2	
	III	MPVC-30	2	2.057
		Brick	20	
		MPVC-30	2	
Floor		Floor	0.5	0.313
		Stone	6	
		Silence	4	
		Concrete	24	
Roof		Insul	8	0.233
		Concrete	24	
		Insul	16	

Several assumptions are considered to analyze the effects of modifying the composition of the building envelope, especially external walls on energy consumption.

- The building was assumed to be unoccupied to directly examine how building materials impact annual thermal demands.
- 20 ℃ and 26 ℃ are the setpoint temperatures for heating and cooling, respectively.
- The infiltration rate is set at 0.6 vol/h.
- Heating and cooling schedules are established for office working hours, Monday through Friday, spanning from 8 a.m. to 6 p.m.
- The simulation was conducted for a full year (8760 [hr]).

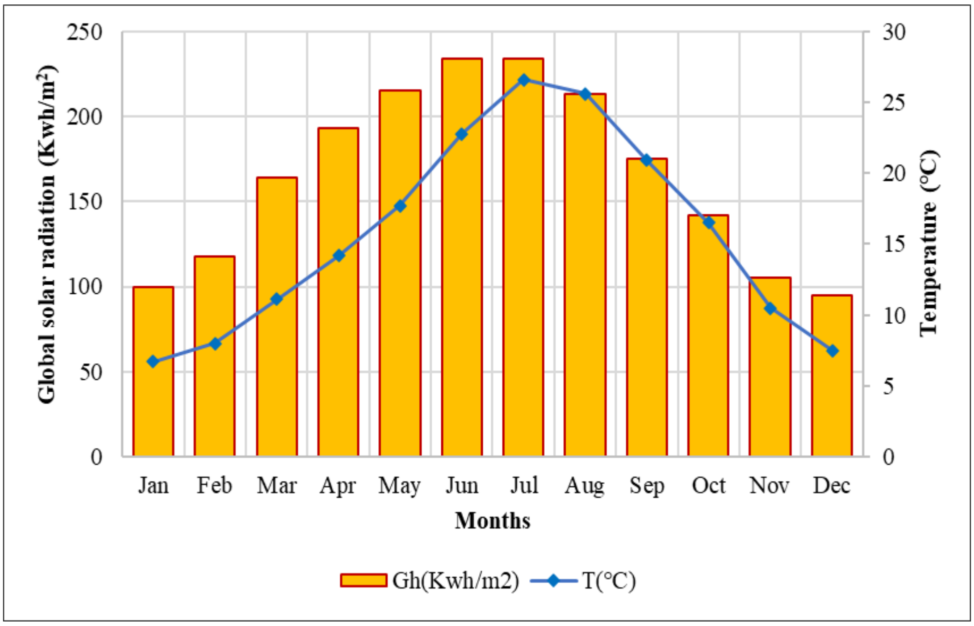

Fig. 8: Meteorological data for Ifrane's climate.

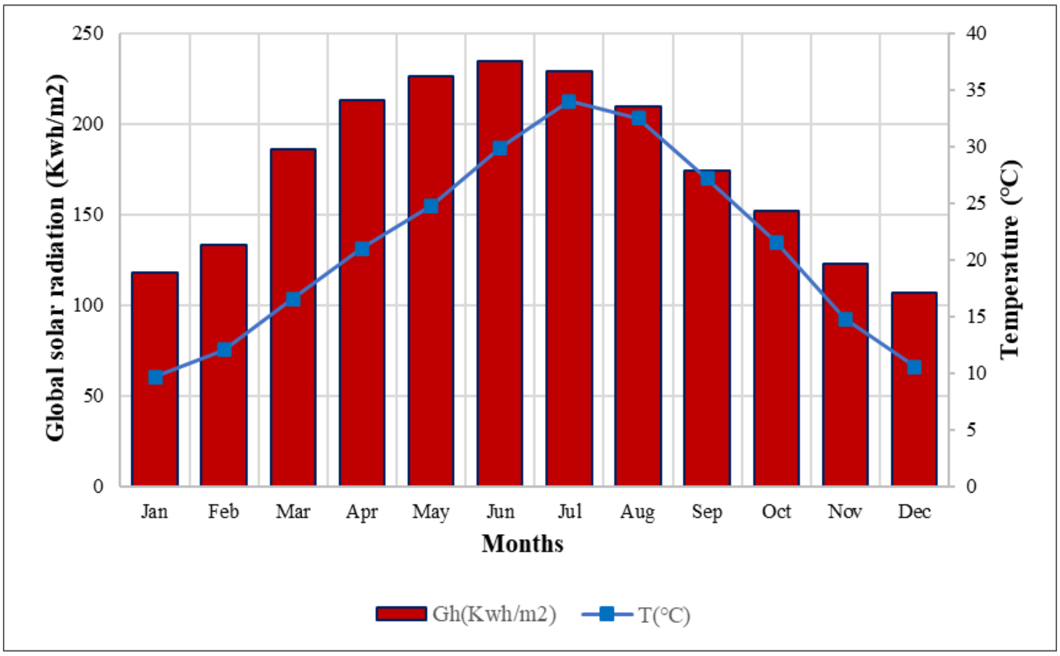

Fig. 9: Meteorological data for Er-rachidia's climate.

3 Results and discussion

3.1 Physical and mechanical characterization

3.1.1 Density

The bulk density test results revealed that as the PVC concentration increased, there was a noticeable decline in the mortar density, as presented in **Fig. 10**. M-0 recorded the highest bulk density at 1065.9 kg/m^3, while MPVC-30 exhibited a significant 26.57% reduction. For 5%, 10%, 15%, 20%, and 25% replacements, reductions were 1.22%, 6.36%, 10.68%, 19.61%, and 25%, respectively. This decline is attributed to the reduced density of PVC relative to sand (1.2 $\mathrm{g/cm^3}$ for PVC aggregates compared to 2.5 $\mathrm{g/cm^3}$ for natural sand), causing an overall decrease in the mortar density. These findings are consistent with previous experiments, highlighting that the inclusion of plastic waste in the mixture leads to a decrease in the bulk density of cementitious composites [22]. Badache et al. [15] revealed that incorporating High-Density Polyethylene (HDPE) at levels of 15%, 30%, 45%, and 60% resulted in density reductions of 5%, 12%, 19%, and 25%, respectively, when contrasted with the reference mortar. Studies have consistently shown that all types of plastic waste influence the density of mortar, leading to the development of lighter composite materials. This reduction in density can contribute to a lighter overall structural weight, which may help minimize potential damage during earthquakes [34].

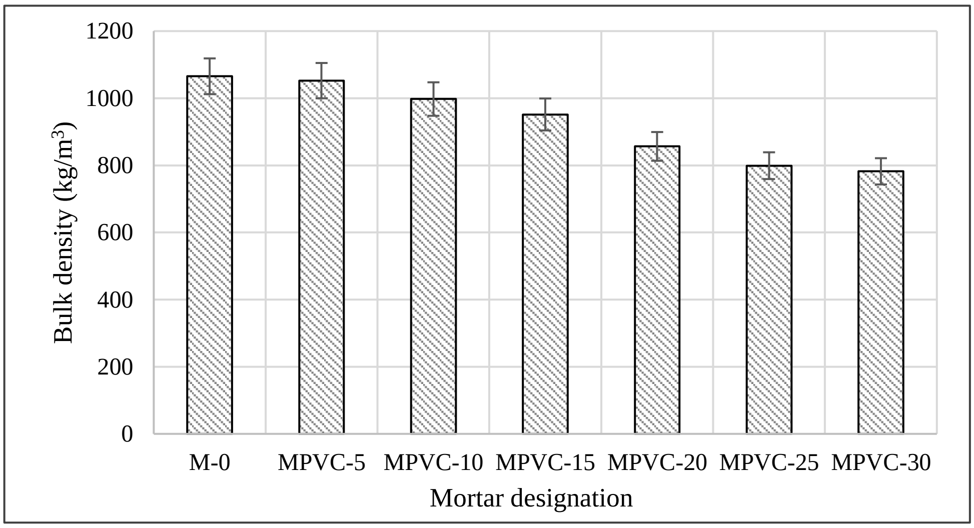

Fig. 10: Results of bulk density at different replacement levels.

3.1.2 Water absorption

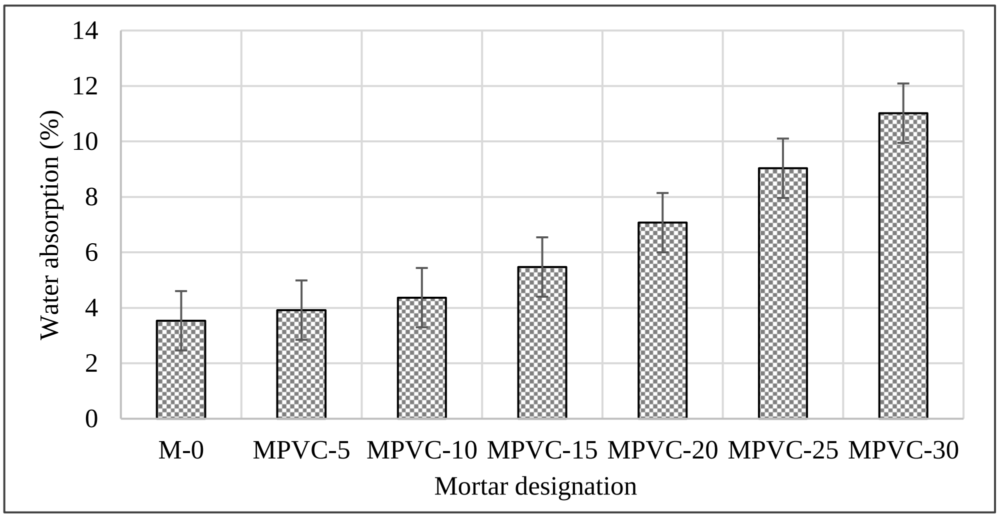

Fig. 11: Results of water absorption at different replacement levels.

Water absorption findings at 28 days exhibited a clear increase as the replacement level increased (**Fig. 11**). At replacement ratios of 0%, 5%, 10%, 15%, 20%, 25%, and 30%, the associated water absorption values were 3.53%, 3.91%, 4.36%, 5.57%, 7.07%, 9.03%, and 11.02%. The reason behind this increase can be explained by the non-absorbent nature of plastic waste, which contributes to the formation of micro-voids, thereby facilitating water infiltration. Moreover, the significant amount of fine granules present in the PVC material increases the ratio of surface area to weight, requiring a higher water content to surround these particles. As the water-to-cement ratio remains constant across all the mixtures, the effective water/cement ratio will be minimal, bringing about a rise in water absorption. The increase in water absorption aligns with the findings reported by [12, 13]. Water absorption is a key indicator for evaluating the mortar's long-term performance. Typically, higher water absorption levels are associated with reduced durability. However, mortars exhibiting water absorption rates below 10% could be classified as satisfactory in terms of durability [35]. In this study, at replacement levels up to 25%, a water absorption rate of 9% was observed, suggesting that mortar formulations with an appropriate amount of plastic are unlikely to negatively affect the durability of the resulting mortar.

3.1.3 Compressive strength

The 28-day compressive strength exhibited varying trends during the exchange of sand with PVC drainage pipes, as shown in **Fig. 12**. At first, there was a rise in compressive strength by 37%, 88.01%, and 45.8% for replacement rates of 5%, 10%, and 15%, respectively. However, once the replacement rate exceeded 15%, the compressive strength began to decrease, showing reductions of 17.29%, 33.46%, and 61.54% for replacement rates of 20%, 25%, and 30%, respectively. The results underscore the beneficial effect of an optimal replacement level on improving the compressive strength of the mortar. This improvement can be ascribed to the enhanced mechanical bonding strength between the PVC and the cementitious paste, which is influenced by differences in the distribution of particle sizes between the sand and the plastic used [36]. Small particles have the capacity to fill voids among larger particles, consequently reducing porosity. This reduction in porosity brings about an enhancement of the compressive strength of the mortar [26]. However, excessive replacement adversely impacts the performance of this innovative mortar, leading to a drop in compressive strength. This is due to the formation of microvoids in the interfacial transition zone (ITZ), which weakens the adhesion between the cement matrix and the plastic waste. Hannawi et al. [12] observed that as the content of plastic aggregates increased, the compressive strength of the mortar decreased. However, this decline was not directly proportional to the amount of sand replaced with plastic aggregates. For example, when Polyethylene terephthalate aggregates were included at 3%, 10%, 20%, and 50%, the compressive strength was reduced by 9.8%, 30.5%, 47.1%, and 69%, respectively. Similarly, for mixtures containing 3%, 10%, 20%, and 50% Polycarbonate aggregates, the compressive strength fell by 6.8%, 27.2%, 46.1%, and 63.9%, respectively. This drop in strength was primarily linked to the poor bond between the cement matrix and the plastic particles. Comparable findings were reported in studies by [37, 38].

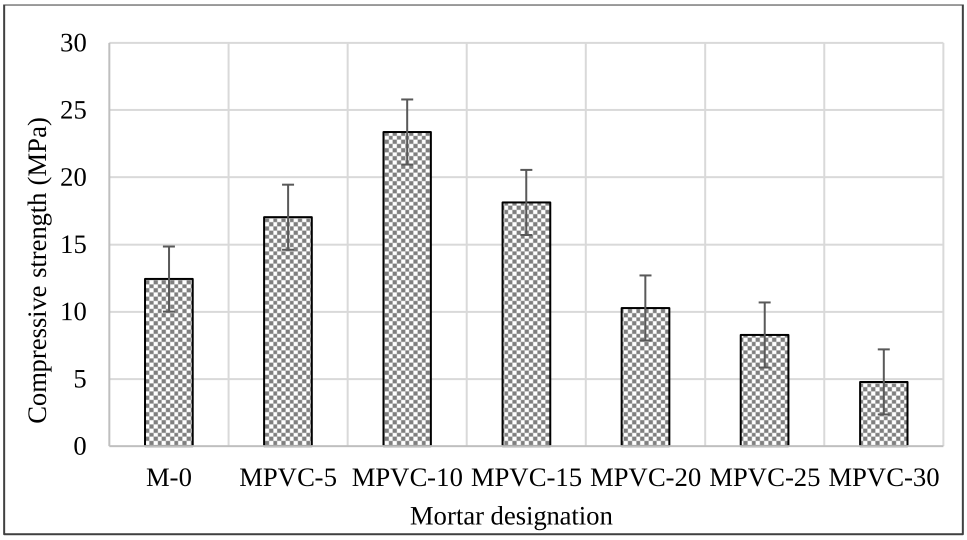

Fig. 12: Results of compressive strength at different replacement levels.

3.1.4 Flexural strength

The 28-day flexural strength results of the mortar, shown in **Fig. 13**, demonstrated a pattern resembling that of compressive strength when PVC drainage pipe waste was added. Initially, flexural strength increased with 5%, 10%, and 15% replacement levels, showing improvements of 17.05%, 37.11%, and 20.77%, respectively. However, at replacement levels of 20%, 25%, and 30%, flexural strength decreased by 9.05%, 18.43%, and 37.98%, respectively. The reasons for these variations are similar to those that explain the compressive strength results. These findings align with Kaur's study [39], which reported that plastic aggregates enhance flexural strength up to 15%. Even at a 20% replacement, the flexural strengths ranged from 4 to 9 MPa, exceeding standard strength requirements. Similarly, another study [40] found that flexural strength reduced with higher amounts of waste PET in the mixture, except for the 5% PET mix, which showed a 16% increase. They explained this behavior by the flexibility and unique shape of PET particles, which promote interlocking at reduced substitution levels (up to 5%) and enhance flexural strength. However, at higher replacement levels, the reduction in strength is likely due to the lack of strong adhesion between the plastic waste and cement paste. This is caused by water being trapped around the PET particles, as plastic waste is hydrophobic in nature. On the other hand, Silva et al.[41] also noted that PET flakes reduce mortar flexural strength by approximately 30-40% when replaced by 10-15%.

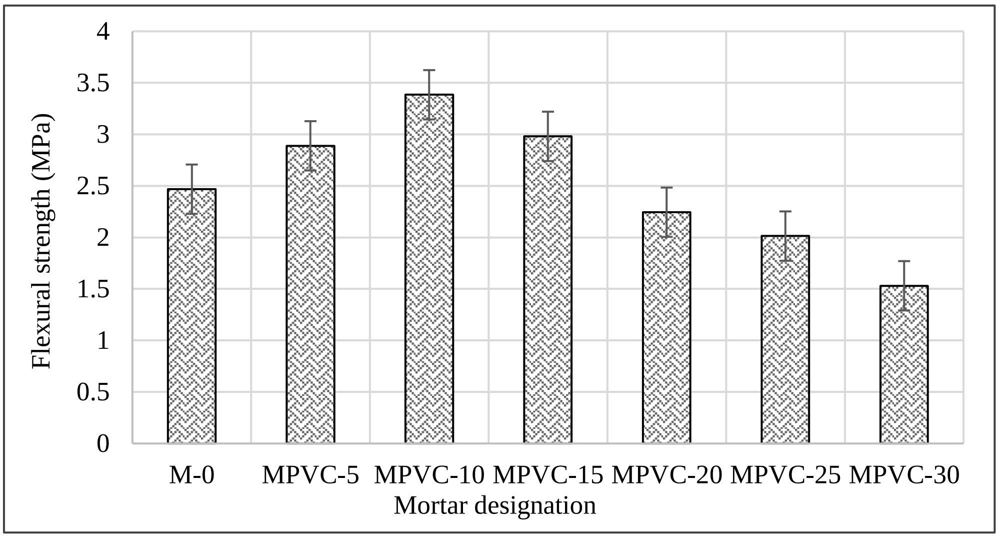

Fig. 13: Results of flexural strength at different replacement levels.

3.2 Thermal characterization

3.2.1 Thermal conductivity

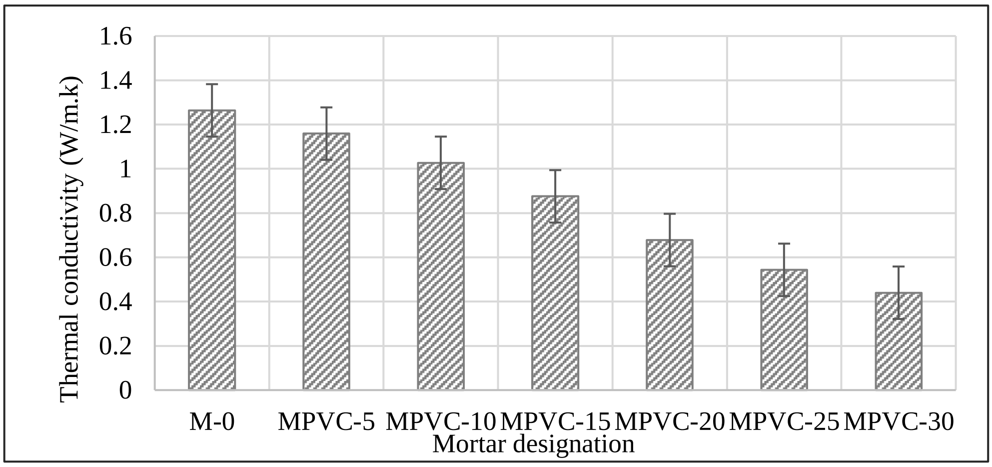

Fig. 14: Results of thermal conductivity at different replacement levels.

The thermal conductivity evaluation revealed a consistent decline as the PVC content in the mortar increased, as illustrated in **Fig. 14**. For replacement of 5%, 10%, 15%, 20%, 25%, and 30%, the thermal conductivity was reduced by 8.3%, 18.75%, 30.73%, 46.35%, 57%, and 65.18% respectively as compared to the standard mortar. These findings can be associated with the lower thermal conductivity of PVC relative to natural sand, as well as the presence of voids, often filled with air, a poor heat conductor with a thermal conductivity of 0.024 W/m.K, leading to a drop in the overall thermal conductivity of the mortar. Similar findings were documented by Herrero et al. [8], who observed that thermal conductivity decreased to one-third of its original value when 20% plastic waste (PVC or PVC + PE) was added to the mortar. Additionally, Senhadji et al. [22] demonstrated that replacing 50% and 70% of natural aggregates with recycled PVC particles resulted in reductions in thermal conductivity of 56% and 74%, respectively, compared to the conventional mortar sample. These results emphasize the considerable positive impact of incorporating PVC particles on the thermal insulation properties of the modified mortars.

3.2.2 Volumetric heat capacity

The results of thermal capacity have demonstrated a non-linear relationship with respect to the rates of PVC drainage pipes replacement level as shown in **Fig. 15**. Volumetric heat capacity increased up to 15%. For 5%, 10%, and 15%, it increased by 12.85%, 25.61%, and 28.32%, respectively. Then, the rate of increase began to decrease slightly, yet remained exceeding that of the standard mortar, by 19.09%, 14.57%, and 0.72% for 20%, 25%, and 30%, respectively. This variation can be ascribed to the inclusion of plastic waste, which initially enhanced the thermal capacity of the mortar, as plastic waste has a higher thermal capacity compared to sand. However, as the plastic content continues to increase beyond a certain limit, this can lead to a drop in the overall density of the mortar, which in turn can decrease its thermal capacity [42]. Záleská et al. [43] reported a decrease in volumetric heat capacity with a higher concentration of integrated plastic waste. This trend was linked to the reduced volumetric heat capacity of PP aggregate relative to silica sand. Overall, high thermal capacity contributes to better insulation as it enables the material to store heat during warmer periods and release it gradually during cooler times, thereby regulating indoor temperatures more effectively.

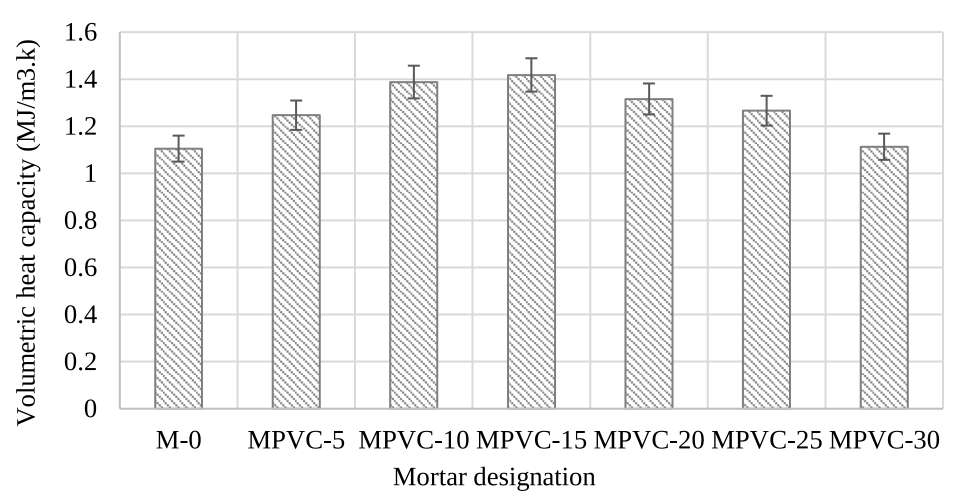

Fig. 15: Results of volumetric heat capacity at different replacement levels.

3.2.3 Thermal diffusivity

Thermal diffusivity results indicated a decrease as the replacement ratio increased, as shown in **Fig. 16**. Reductions of 18.74%, 35.31%, 46.02%, 54.95%, 62.47%, and 65.44% were observed for substitution levels of 5%, 10%, 15%, 20%, 25%, and 30% when contrasted with the control mix. This could be linked to the significant plastic waste content in the mortar, which effectively diminishes the speed at which heat propagates within it. Additionally, Aattache et al. [44] assert that thermal diffusivity is directly proportional to conductivity, thus exhibiting a similar decay trend. Abd Allah Abd Elaty et al. [45] observed that thermal diffusivity declined remarkably by an average of 32.6 %, 40.7 %, and

51.1 % when replacing 10%, 20%, and 30% of crumb rubber for sand, respectively. The decline in thermal diffusivity as the plastic replacement rate rises suggests a slower traverse of heat flux through the material's thickness. Specifically, it will take considerably more time compared to the standard mortar, leading to an increased phase shift. This property is highly desirable, especially in summer, as it helps prevent the penetration of solar radiation energy and dissipates it during the night.

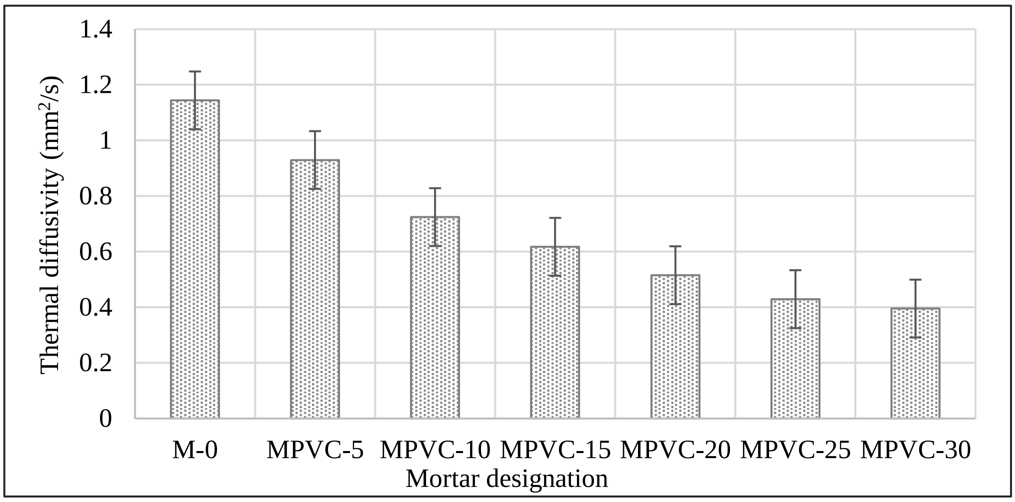

Fig. 16: Results of thermal diffusivity at different replacement levels.

3.3 Numerical simulation and energy efficiency findings

Both low thermal conductivity and high thermal capacity are preferred properties in insulating materials [46]. However, determining which has a greater influence on energy consumption in a simulated office building requires a comparative study. For this purpose, Experimental investigations have been undertaken to assess the thermal behavior of the new mortar incorporating different percentages of PVC drainage pipes (0%, 5%, 10%, 15%, 20%, 25%, and 30%). Based on the findings, two scenarios will be simulated using the TRNSYS software: one with high thermal capacity (i.e., 15% of replacement) and the other with low thermal conductivity (i.e., 30% of replacement). Additionally, a control mix will be utilized for comparison. This evaluation will allow us to assess the potential reduction in heating requirements for Ifrane City and cooling needs for Er-rachidia City. **Table 3** illustrates the properties required for the simulation.

Table 3: Thermal properties required for numerical simulation

Mix ratio	Density ($\mathrm{kg/m^3}$)	Thermal conductivity (W/m.k)	Volumetric heat capacity ($\mathrm{MJ/m^3.k}$)
M-0	1065.495	1.264	1.105
MPVC-15	951.692	0.875	1.418
MPVC-30	781.291	0.440	1.113

Fig. 17 depicts the results of three simulated scenarios for external walls to evaluate the heating demand for the model office located in Ifrane City and the cooling needs for the model in Er-rachidia City. The annual heating demand was 3320.77kwh, 3231.01kwh, and 2961.78kwh for M-0, MPVC-15, and MPVC-30, respectively. In particular, the MPVC-30 mix, characterized by its low thermal conductivity, exhibits a drop in heat demand of approximately 11% when contrasted to the conventional mix. Similarly, for Er-rachidia city, the total yearly requirement for air conditioning was 6723.45kwh, 6609.03kwh, and 6256.37kwh for M-0, MPVC-15, and MPVC-30, respectively. Specifically, MPVC-30 demonstrates a decrease in cooling demand of around 7% as compared to the reference mix. Based on the findings, it's evident that as thermal conductivity decreased, the energy requirement for both heating and cooling decreased. However, it's crucial to consider the mechanical attributes of this mortar, as plastic waste content rose, mechanical strength diminished. Notably, MPVC-30 exhibits compressive strength exceeding 3.5 MPa and thermal conductivity below 0.75 W/m.k. As stated by Rilem [47], this mortar could serve as a structural and insulating material. Utilizing this proposed material offers economic savings and environmental benefits, as reduced energy consumption correlates with

decreased CO_2 emissions. Numerous studies have demonstrated that incorporating insulating materials into external walls leads to lower energy consumption [48, 49].

The thickness of the mortar requires careful consideration, as increasing its thickness typically results in higher energy gains [50]. When considering insulating a wall using alternative insulation materials, it’s advisable to opt for a single layer of this new mortar while increasing its thickness. However, such a decision requires thorough studies, taking into account the associated costs.

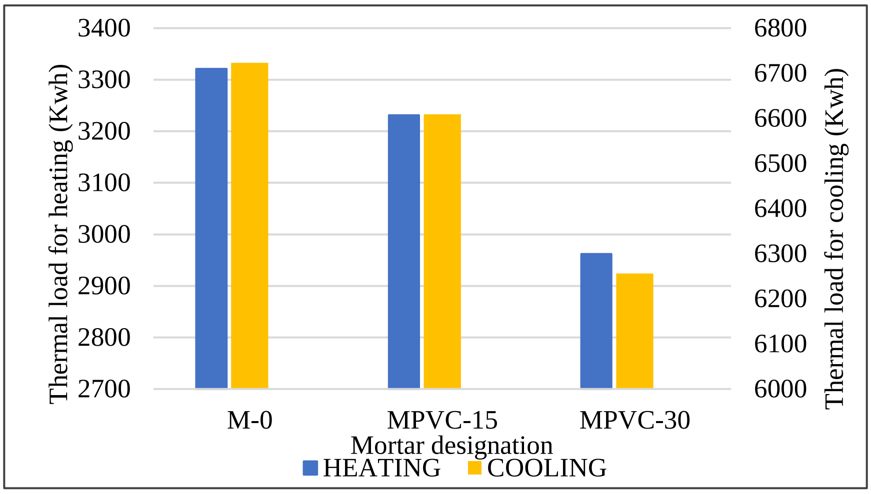

Fig. 17: Thermal load for heating and cooling in the three investigated scenarios.

The numerical simulation was performed using specimens with 30% PVC waste, chosen based on the RILEM classification for its low thermal conductivity and acceptable mechanical strength. To further validate this selection and determine the optimal trade-off between thermal and mechanical performance, a multi-objective optimization approach is displayed in the following section.

4 Multi-objective optimization for mix design

4.1 Problem statement

The utilization of PVC waste as a partial sand substitute in mortar presents a complex relationship between mechanical and thermal properties. Experimental results have shown that compressive strength, flexural strength, and thermal conductivity exhibit a nonlinear variation with increasing PVC content. While higher PVC substitution enhances thermal insulation, it generally reduces mechanical strength. Multi-objective optimization is a mathematical approach used to solve problems where multiple conflicting objectives must be optimized simultaneously [51]. It consists of finding a set of Pareto optimal solutions, where no single objective can be improved without negatively affecting another, allowing for trade-offs between competing performance criteria. This approach is widely applied in engineering applications to balance different requirements, ensuring an optimal compromise between conflicting objectives.

Given the conflicting nature of mechanical and thermal properties in PVC-modified mortar, a multi-objective optimization approach was implemented to determine the optimal PVC replacement ratio that maximizes both compressive and flexural strength while minimizing thermal conductivity.

The optimization problem was formulated as follows **(2)**:

$$\begin{cases} Maximize\ f_1(x) \\ Maximize\ f_2(x) \\ Minimize\ f_3(x) \end{cases} \tag{2}$$

Where; $f_1(x)$ represents compressive strength depending on x; $f_2(x)$ represents flexural strength depending on x; $f_2(x)$ represents thermal conductivity depending on x; x is the PVC replacement percentage, which is constrained by: $0\% \leq x \leq 30\%$.

4.2 Regression modeling using SVR

To facilitate the optimization process, an analytical formulation of each property as a function of the PVC replacement ratio was required. Support Vector Regression (SVR), a machine learning technique known for its accuracy in nonlinear regression tasks [52], was utilized in MATLAB to develop predictive models for compressive strength $f_1(x)$, flexural strength $f_2(x)$, and thermal conductivity $f_3(x)$. The regression models were trained using the experimental dataset and validated to ensure an accurate representation of the observed nonlinear trends. The obtained mathematical expressions were then integrated into the multi-objective optimization framework, allowing for a continuous evaluation of performance trade-offs across different PVC substitution percentages.

4.3 Optimization resolution using NSGA-II

The optimization problem was structured to determine the optimal PVC replacement ratio that ensures the best balance between mechanical performance and thermal efficiency. Given the nonlinear and conflicting nature of compressive strength, flexural strength, and thermal conductivity, a multi-objective optimization framework was established using the Non-Dominated Sorting Genetic Algorithm II (NSGA-II). NSGA-II is a widely applied evolutionary optimization method that finds optimal solutions by applying Pareto dominance, ensuring that no single objective can be improved without negatively impacting another [53]. The algorithm generates a set of candidate solutions and iteratively refines them, maintaining a diverse population of optimal points.

To implement this optimization process, MATLAB’s gamultiobj function was used. This function applies NSGA-II to generate a Pareto front, providing a set of trade-off solutions where compressive strength, flexural strength, and thermal conductivity are optimized simultaneously. Since gamultiobj is designed for minimization, the objective functions were formulated as follows **(3)**:

$$Minimize\ f(x) = \begin{cases} -f_1(x) \\ -f_2(x) \\ +f_3(x) \end{cases} \tag{3}$$

Where; $0\% \le x \le 30\%$

By iteratively refining candidate solutions and maintaining a diverse set of optimal points, gamultiobj explored PVC replacement ratios between 0% and 30%, allowing for the selection of an optimal substitution percentage based on structural and thermal performance requirements.

Table 4: Optimal PVC replacement percentages and their properties.

Replacement level (%)	Compressive strength (MPa)	Flexural strength (MPa)	Thermal conductivity (W/m.k)
10.1758	23.3824	3.3854	1.0221
10.1475	23.3829	3.3854	1.0229
11.8635	22.4136	3.3178	0.9744
13.3551	20.6337	3.1833	0.9298
17.4734	13.9495	2.5977	0.7769
20.4069	9.9411	2.2110	0.6646
15.4202	17.4349	2.9196	0.8597
19.0089	11.5275	2.3659	0.7151
14.3163	19.2197	3.0712	0.8990
17.4929	13.9169	2.5946	0.7761
16.1331	16.2288	2.8104	0.8316
15.1375	17.9044	2.9610	0.8704
26.1169	7.6388	1.9248	0.5191
30.000	4.7975	1.5328	0.4405

4.4 Optimization results and Pareto front analysis

The findings from the multi-objective optimization generated a set of Pareto optimal solutions, highlighting the trade-offs between compressive strength, flexural strength, and thermal conductivity. The results demonstrate that no single PVC replacement percentage can simultaneously maximize both mechanical properties and minimize thermal conductivity, reinforcing the necessity of a multi-objective optimization approach.

The results confirmed that mixes with PVC waste replacement levels between 10% and 30% provided the best trade-off between these properties (**Table 4**). Among these, the 30% PVC waste mix, which was initially selected for the thermal simulation based on RILEM classification, was validated as one of the optimal solutions. This confirmation reinforces the relevance of its choice for the numerical simulation and supports its potential use as an insulating and structural material.

The Pareto front obtained from the optimization process provides a visual representation of the optimal trade-offs between compressive strength, flexural strength, and thermal conductivity, illustrating how improvements in one property often come at the expense of another **Fig. 18**. This distribution of solutions confirms the trade-off between the objectives and allows for a comprehensive analysis of how different PVC replacement levels influence material performance. The determination of the best solution depends on the project's requirements, as the Pareto front presents a range of optimal PVC replacement levels, each offering a different balance between mechanical strength and thermal insulation. Depending on whether structural performance or thermal efficiency is prioritized, different points along the Pareto front can be selected to best meet the specific needs of the application.

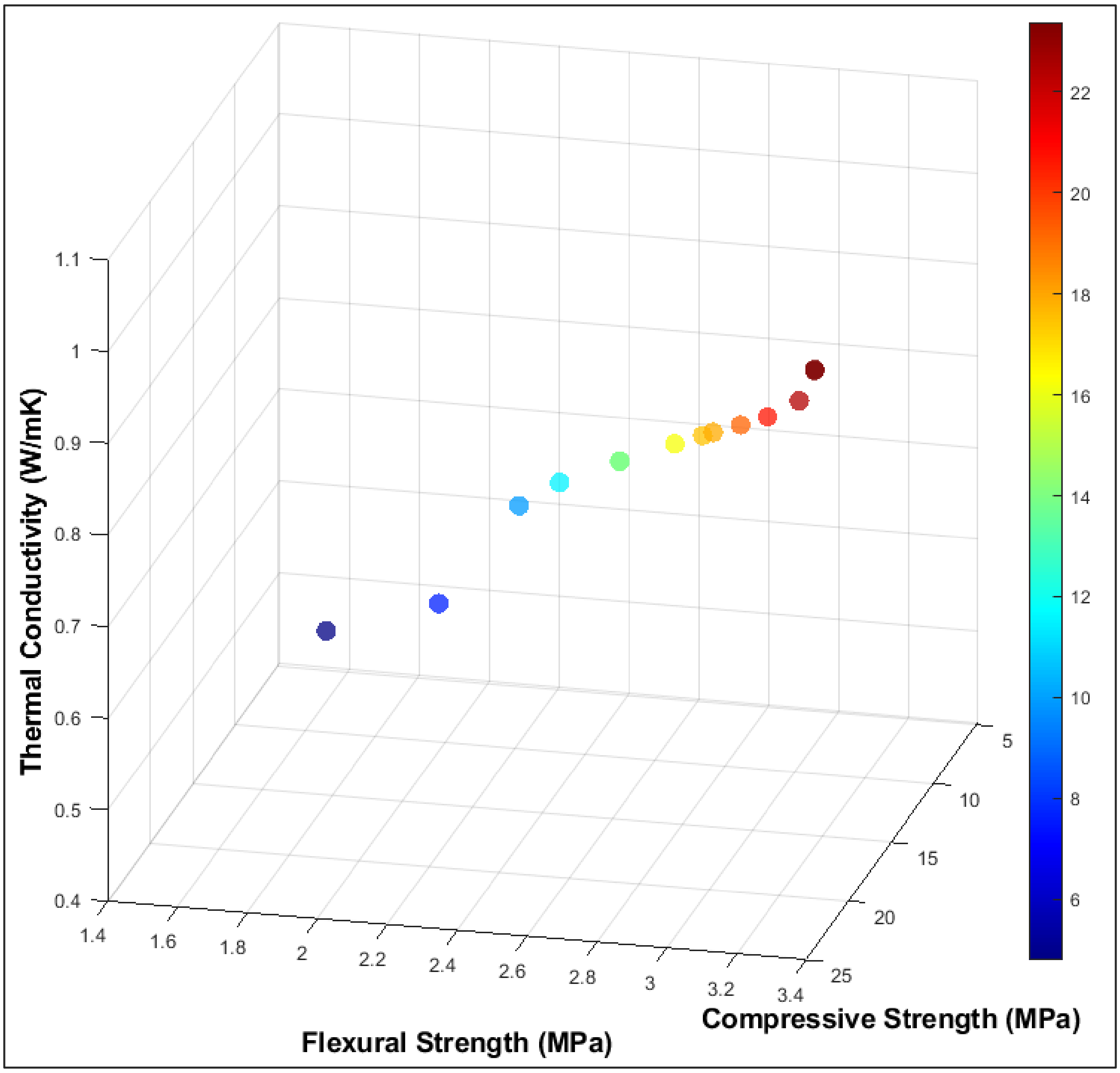

Fig. 18: Pareto front resulting from multi-objective optimization.

5 Conclusions

In this study, the partial substitution of sand with PVC drainage pipe waste in mortar production has yielded promising findings in terms of strength and energy efficiency. A multi-objective optimization was performed to identify the optimal mix design, ensuring a balance between mechanical strength and thermal performance. Thus, optimal utilization could render this material suitable for structural and thermal insulation purposes. Among the notable outcomes that can be highlighted:

- The density of the mortar was lowered as the substitution ratio rose. It decreased by 26.57% for a replacement of 30%. Consequently, this material becomes lighter compared to ordinary mortar.
- The water absorption of the mortar rose as the replacement rate increased. This is ascribed to the higher proportion of fines contained in the plastic. However, the achieved results, typically around 10%, remain within acceptable limits. It is recommended to incorporate admixtures that effectively manage water absorption without compromising the mortar’s strength, especially when using higher proportions of plastic waste.
- Mechanical strength reached its maximum at a 10% replacement, while the strength at 30% replacement remained acceptable, exceeding 3.5 MPa. This indicates that the material can still be used for structural applications.
- Thermal conductivity exhibited a noticeable reduction in mortar as the content of plastic waste increased. Specifically, a 65.18% decrease was observed at a 30% replacement, resulting in a value below 0.75 W/m.K. This suggests that the material could be considered suitable for use as an insulating material.
- Volumetric heat capacity increased up to 15%, showing a peak of 28.32%. Beyond this point, it begins to decline as the plastic waste fraction increases. This property is beneficial as it allows for heat storage during hot periods and gradual release during cooler times.
- Thermal diffusivity decreased as the plastic content increased up to 65.44% for a 30% replacement. This decrease is particularly desirable, especially during summer, as it aids in blocking the penetration of solar radiation energy and dispersing it during the night.
- The annual heating demand for the model office located in Ifrane was 3320.77kwh, 3231.01kwh, and 2961.78kwh for M-0, MPVC-15, and MPVC-30, respectively. In particular, the MPVC-30 mix shows a decrease in heat demand of approximately 11% as compared to the reference mix.
- The total yearly requirement for air conditioning for the model office located in Er-rachidia city was 6723.45kwh, 6609.03kwh, and 6256.37kwh for M-0, MPVC-15, and MPVC-30, respectively. Specifically, MPVC-30 demonstrates a decrease in cooling demand of around 7% compared to the reference mix.
- The multi-objective optimization approach provided a range of optimal solutions based on project requirements, among which the 30% replacement was identified as an optimal choice, further validating its selection for thermal simulation.

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CRediT authorship contribution statement

Kaoutar Mouzoun: Investigation, Formal analysis, Writing – original draft. **Azzeddine Bouyahyaoui**: Supervision, Writing – review & editing Hanane. **Moulay Abdelali**: Supervision, Writing – review & editing. **Toufik Cherradi**: Supervision, Writing – review & editing. **Khadija Baba**: Supervision, Investigation, Writing – review & editing. **Ilham Masrour**: Investigation, Conceptualization, Writing – review & editing. **Najib Zemed**: Writing – review & editing, Software.

Conflicts of Interest

The authors declare that they have no conflicts of interest to report regarding the present study.

Data Availability Statement

Some or all data, models, or codes that support the findings of this study are available from the corresponding author upon reasonable request.

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