

Article

Effects of PVA Fibers on the Mechanical and Thermal Properties of Microencapsulated Phase Change Material Mortar

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Abstract

Microencapsulated phase change material (MPCM) can be used in place of sand in mortar to obtain phase change construction materials; however, this will degrade the mortar's mechanical qualities. To address this challenge, a novel synergistic approach was proposed: phase change materials were used in mortar to enhance its thermal properties, while polyvinyl alcohol (PVA) fibers were uniquely incorporated to counteract the mechanical degradation caused by MPCM. Twenty different types of mortar were created and produced. Tests were conducted on the mortar's micro properties, consistency, compressive strength, thermal conductivity, and specific heat capacity. The findings indicate that adding 0.4% PVA to the mortar optimally strengthened it, compensating for mechanical loss, while replacing sand with MPCM had a negative impact on consistency. The thermal conductivity of the PVA-MPCM mortar ranged from 0.75 to 1.2 W·m⁻¹·K⁻¹, decreasing by up to 34.45% when the MPCM substitution rate reached 4%. Furthermore, as the MPCM substitution rate rises to 4%, the peak value of specific heat capacity increased by 195.28% during the heating process, and replacing sand with MPCM had a negative impact on consistency. The thermal conductivity of the PVA-MPCM mortar ranged from 0.75 to 1.2 W·m⁻¹·K⁻¹, indicating that adding MPCM to the mortar had a significant impact on thermal conductivity. As the MPCM substitution rate rises, so does the peak value of specific heat capacity.

Keywords: microencapsulated phase change material; mortar; polyvinyl alcohol (PVA) fiber; thermal conductivity; specific heat capacity; strength; consistency



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1. Introduction

Temperature regulation is one of the main energy consumption in buildings. At present, energy conservation and emission reduction have become the development goals of the world; in this context, the design concept of green buildings is gradually respected. Optimizing energy saving and emission reduction in buildings is one of the effective ways of green buildings. Improving the insulation performance of the enclosure structure without reducing people's quality of life can reduce the building energy consumption.

Reducing the thermal conductivity of the enclosure structure is one of the important means to reduce building energy consumption and improve comfort. The development of this technology has led to a large number of scientific research and engineering applications, which belong to a passive temperature regulation means. Nowadays, they are no longer satisfied with passive temperature regulation, especially in some areas with large temperature

differences between day and night, and large temperature differences play a great negative role in comfort. For this reason, some scholars proposed adding phase change materials to building materials to reduce the temperature change inside buildings through heat storage and release caused by the phase transition of phase change materials, and this strategy can improve comfort and reduce energy consumption at the same time [1]. Cuadri et al. [2] successfully manufactured novel form-stable bitumen/paraffin-wax/polymer composite binders that can be used as energy-efficient building materials with thermal energy storage and thermoregulation functions. Cunha et al. [3] explored the use of waste paraffin wax from the foundry industry as a substitute, preparing cement-based mortars with different contents (25%, 50%, and 75%). The results showed that all mortars achieved the CSIV mechanical strength classification, and with a 75% wax content, the cooling demand was reduced by more than 10% under all analyzed scenarios. Jeong et al. [4] evaluated the feasibility of applying low-cost phase change materials in an electric radiant flooring heating system through three steps: analyzing the thermal performance of three types of paraffin-based PCMs, developing an activated carbon composite PCM that increased the latent heat by 50%, and mixing it with n-octadecane to verify the enhanced heat transfer performance and time-lag effects, demonstrating its potential for use in energy-efficient systems.

The acceptable phase change temperature of building materials is in the range of 20 to 30 °C, so paraffin wax has become the first choice for building phase change materials; however, paraffin wax can not be directly mixed with traditional building materials, mainly because paraffin wax is easy to overflow after liquefaction. For this purpose, it is considered to wrap paraffin in microcapsules to form microencapsulated phase change material (MPCM) [5].

To comprehend how phase change microcapsules (MPCMs) dictate the mechanical, thermal, and physical behaviors of mortar, numerous researchers have conducted in-depth investigations. For instance, Rebelo et al. [6] evaluated PCM-integrated mortar by assessing its microstructural features, workability, and mechanical strengths. They established the material's thermal profile using differential scanning calorimetry (DSC) and applied the hot box method to determine the steady-state thermal efficiency of these mortars when used as lightweight interior coatings. In parallel, Djamaï et al. [7] combined thermophysical, mechanical, and Fourier transform infrared (FTIR) analyses to reveal that the strength reduction in PCM composites is driven by both the inherent weakness of the PCM particles and a compromised hydration process. Furthermore, the utilization of form-stable PCMs for indoor climate regulation was systematically examined by Gencel et al. [8], who detailed the physical, mechanical, and thermal storage capacities of these modified cementitious mortars.

Investigating temperature extremes, Cunha et al. [9] incorporated raw, unencapsulated PCMs into a matrix of cement and fly ash. Their study indicated that this direct addition enhanced freeze–thaw resistance while sustaining high-temperature performance comparable to standard reference mortars.

Addressing the limitations of MPCMs, Naveen et al. [10] tackled the poor thermal conductivity of conventional polymer shells, such as melamine. They synthesized a Cu-TiO₂ hybrid nanocomposite to coat nano-MPCMs, which, upon integration into cement mortar, drastically improved the material's overall heat conductivity. On a practical application level, Abbasi et al. [11] explored the efficacy of shape-stable PCMs within the external masonry walls of traditional Iranian architecture. Their findings confirmed that these thermal energy storage elements effectively mitigate indoor temperature fluctuations and suppress peak thermal loads.

The thermal energy storage and release of MPCM have a wide application prospect in the thermal insulation performance of industrial and civil buildings in the area of large

temperature difference between day and night. However, most studies have shown that although the addition of MPCMs can improve the thermal storage capacity of mortar, it has a negative impact on the mechanical properties of mortar. To improve the mechanical properties of mortar, many scholars have proposed adding fibers to mortar [12], including basalt fiber mortar [13], coir fiber mortar [14], PVA fiber mortar [15], etc. Specifically, Xu et al. [13] evaluated the geometric parameters of basalt fibers and concluded that an optimized aspect ratio (specifically, a length of 6 mm and a diameter of 7 μm) provided the highest interfacial bond strength and significantly enhanced the tensile toughness of asphalt mortar. Schiavon et al. [14] investigated chemically treated natural coir fibers in cement–lime mortars, revealing that 2% oxalic acid-treated fibers altered the internal pore structure and boosted the compressive and tensile strengths by up to 8% and 22%, respectively. Furthermore, Chen et al. [15] found that the addition of 1 vol% PVA fibers fundamentally upgraded the cracking tolerance of cement mortars, contributing to a 44.8% increase in initial impact energy absorption by building a resilient fiber-bridging network.

PVA fiber is a synthetic fiber processed with a high polymerization degree of polyvinyl alcohol, which has high elastic and high strength material properties, good affinity with cement, non-toxic and pollution-free properties, etc. Adding PVA fiber into cement mortar can effectively improve the mechanical properties of cement mortar. Several studies have documented the benefits of PVA fibers in cementitious composites. For instance, previous research has shown that PVA fibers significantly enhance the toughness and crack resistance of mortars due to their high tensile strength and strong interfacial bonding with cement hydration products. Furthermore, early trials combining various fibers (such as polypropylene or steel fibers) with phase change materials indicated that fiber networks could restrict the volumetric expansion of PCMs during melting and limit strength degradation. However, comprehensive investigations specifically pairing PVA fibers with MPCM remain scarce.

The referenced publications generally concluded that fibers predominantly enhance the flexural and tensile capacities by bridging cracks. While fiber reinforcement typically targets flexural strength, this study primarily evaluated compressive strength because the replacement of rigid silica sand with soft, compressible MPCM directly compromises the primary load-bearing skeleton of the mortar under compression.

Although previous studies have explored various fibers, there remains a critical research gap regarding the synergistic application of flexible polymer fibers and microcapsules in mortar. Many conventional fibers suffer from poor dispersion or weak interfacial bonding with cementitious matrices in the presence of MPCM. PVA fiber was specifically selected for this study because it is a synthetic fiber with a high degree of polymerization, possessing high elastic modulus, excellent tensile strength, and superior hydrophilicity. These characteristics ensure exceptional affinity and chemical bonding with cementitious materials, which is crucial for bridging the micro-cracks induced by the weak interfacial transition zones around MPCM particles. To improve the mechanical properties of phase change mortar, this study tries to incorporate PVA fiber into the mortar. First, mortars with various mixes, considering different fiber content and different MPCM replacement rates, were designed and manufactured. Second, key properties of the mortar, such as microscopic properties, consistency, strength, and thermal conductivity, were tested. The influence of fiber and MPCM on the properties of mortar was also analyzed. The purpose of this research was to provide technical and theoretical support for the application and popularization of phase change building materials.

2. Materials and Test Methods

2.1. Raw Materials

2.1.1. PVA Fiber

The PVA fiber used in this study is produced by Shanghai Chenqi Chemical Technology Co., Ltd. (Shanghai, China), and the performance indexes are shown in Table 1. Figure 1a shows PVA fiber in its natural state.

Table 1. Properties of PVA fiber.

Item	Length (mm)	Diameter (μm)	Elongation (%)	Tensile Strength (MPa)	Initial Modulus (GPa)	Density (g/cm^3)
Value	9	15.09	6.9	1830	40	1.29

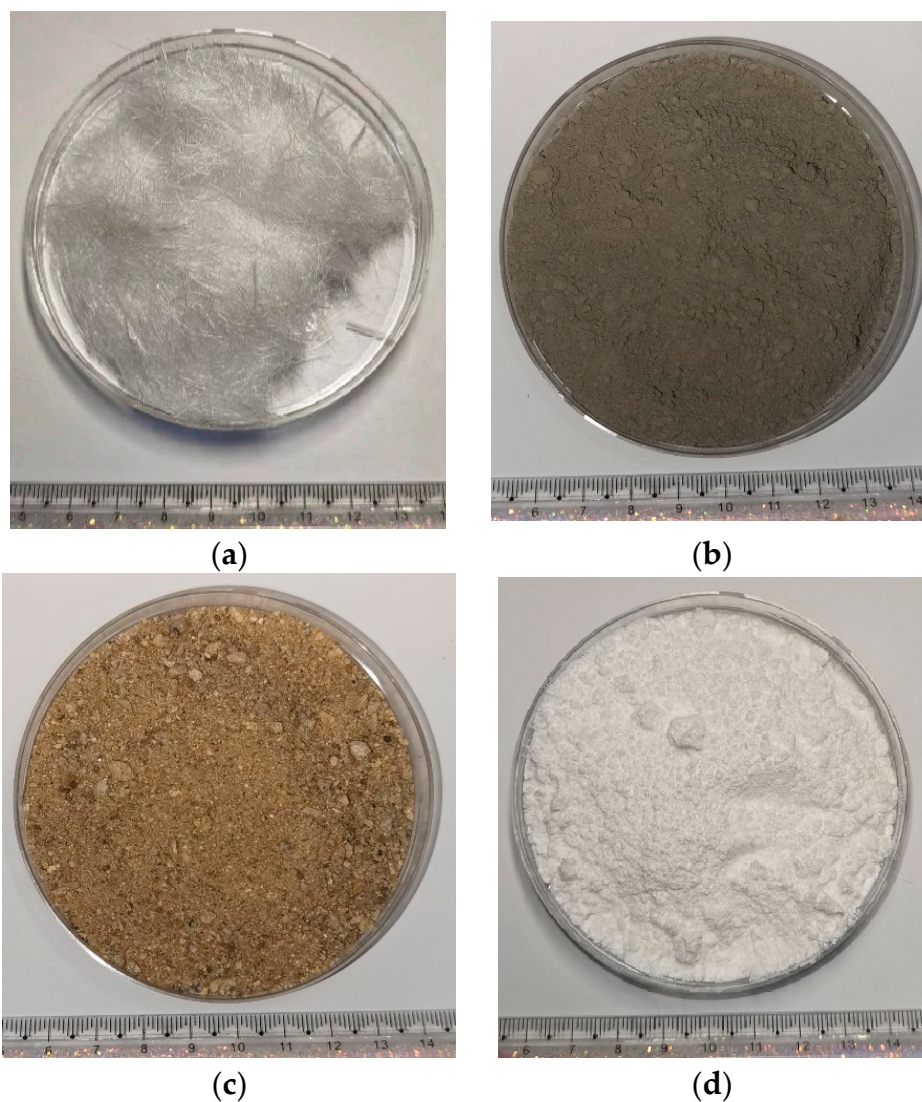


Figure 1. Raw material: (a) PVA fiber; (b) cement; (c) river sand; (d) MPCM.

2.1.2. Cement

The cement used in the test was grade P.O. 42.5 ordinary Portland cement produced by Jinniu Cement Co., Ltd. (Jiangsu, China), as shown in Figure 1b, and the chemical composition of the cement is shown in Table 2.

Table 2. Chemical composition of cement.

Chemical Composition	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	CaO	MgO	SO ₃	Na ₂ O
Proportion (%)	22.92	6.12	4.40	64.65	1.12	0.31	0.48

2.1.3. Fine Aggregate

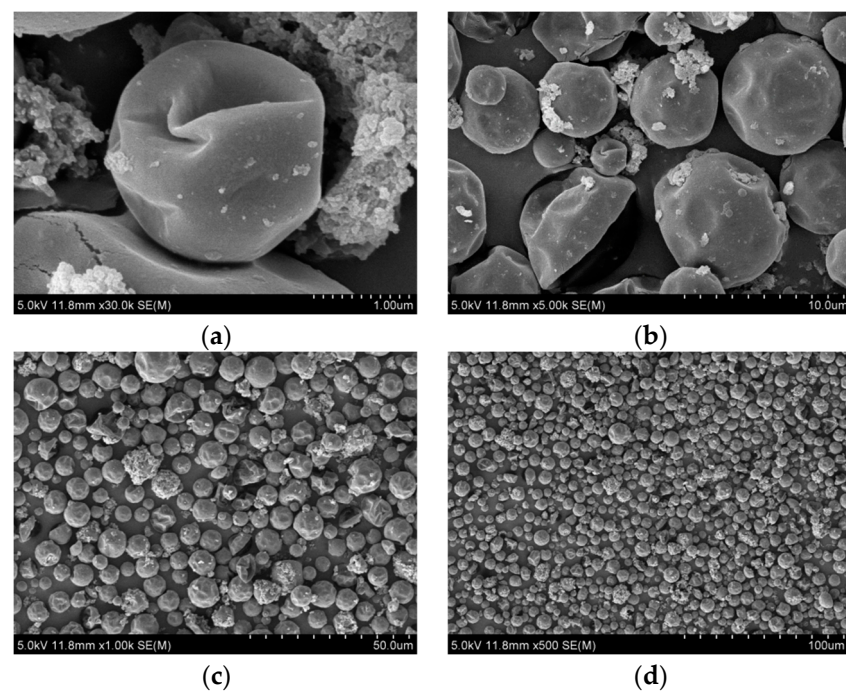
The fine aggregate used was local natural river sand, as shown in Figure 1c. River sand was screened by a screening machine, and its particle gradation is shown in Table 3. According to the guideline JGJ52-2006 [16], this sand was grade II sand.

Table 3. Grain gradation of river sand.

Screen Size (mm)	Residual Mass (g/500 g)	Grading Screening Residual Rate (%)	Cumulative Screening Rate (%)
5	0	0	0
2.5	25	5	5
1.25	72	14.4	19.4
0.63	135	27	46.4
0.315	146	29.2	75.6
0.16	120.5	24.1	99.7

2.1.4. Microencapsulated Phase Change Material (MPCM)

MPCM, as shown in Figure 1d, was produced by Hefei Xinneng Phase Change New Materials Co., Ltd. (Hefei, China), using n-octatetane as core material and melamine-formaldehyde resin as wall material. The synthesis process adopted the interfacial polymerization method, and the ratio of core to wall was 4:1, and the density was 0.8 g/cm³. The microstructure of MPCM is shown in Figure 2. It can be seen that the MPCM are spherical and have some depressions, and the diameter of the microcapsules is between 15 µm and 80 µm.

**Figure 2.** Microstructure of MPCM: (a) 1.0 µm; (b) 10.0 µm; (c) 50.0 µm; (d) 100.0 µm.

A differential scanning calorimeter (DSC) was used to characterize the basic thermal properties of MPCM at a temperature range of 5–50 °C, and the melting/freezing rate was 3 °C/min. The results are shown in Figure 3. During the melting and freezing processes, the phase transition temperature ranged from 22.67 °C to 32.42 °C and 25.67 °C to 17.55 °C, the peak phase transition temperature was 28.18 °C and 21.27 °C, and the latent heat of melting and freezing was 141 J/g and 102.3 J/g, respectively. To ensure the representative nature of the DSC testing, given the small chamber size, the MPCM powder was extensively homogenized using a mechanical micro-mixer prior to sampling. A micro-spatula was used to extract a randomized 5 mg sample from different depths of the bulk powder batch for characterization.

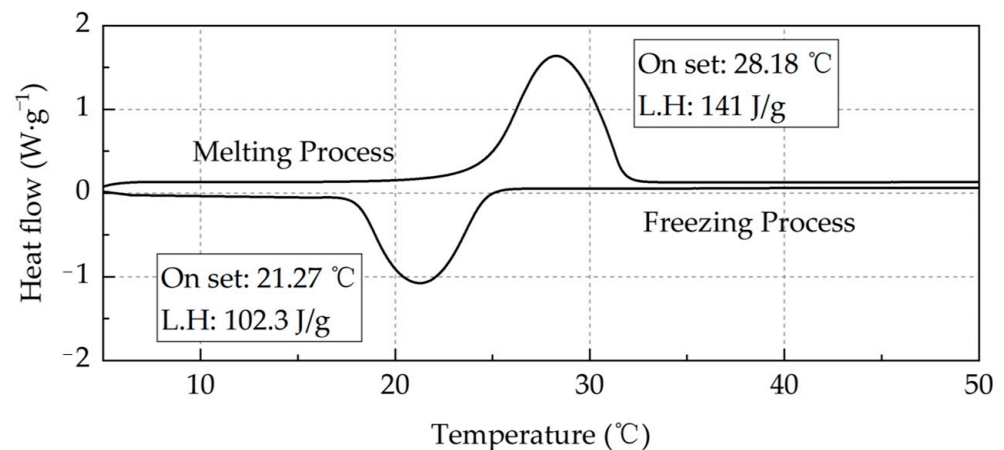


Figure 3. Phase change characteristics of MPCM.

2.2. Mix Proportion

A full factorial design approach was utilized for the experiment to comprehensively evaluate the interactive effects of the two independent variables (PVA fiber volume and MPCM replacement rate). This method was chosen over fractional designs to ensure that the synergistic or antagonistic interactions between every level of PVA fiber and MPCM replacement rate could be directly observed without confounding factors. To systematically analyze the effects of PVA content and MPCM replacement rate on the performance of mortar, twenty kinds of mix proportions were designed, as shown in Table 4.

The specimen notation is defined as M-Fx-Py, where “F” represents PVA fiber, “x” represents its volume percentage, “P” stands for MPCM, and “y” represents its mass replacement rate. The PVA volume content range (0% to 1.2%) was selected based on preliminary trials indicating that fiber contents beyond 1.2% lead to severe agglomeration and unworkable mixtures. The MPCM replacement rates (0% to 4% by total mass) were chosen to strike a balance between achieving a meaningful enhancement in thermal mass and avoiding an unacceptable loss of structural integrity.

Table 4. Mix proportion of mortar.

No.	Number of Mortar	Cement (kg/m ³)	River Sand (kg/m ³)	Water (kg/m ³)	MPCM (kg/m ³)	PVA (%)
1	M-F0-P0	450.0	1350.0	203.0	0.0	0.0
2	M-F0.4-P0	450.0	1350.0	203.0	0.0	0.4
3	M-F0.8-P0	450.0	1350.0	203.0	0.0	0.8
4	M-F1.2-P0	450.0	1350.0	203.0	0.0	1.2
5	M-F0-P1	450.0	1288.1	203.0	19.8	0.0
6	M-F0.4-P1	450.0	1288.1	203.0	19.8	0.4

Table 4. Cont.

No.	Number of Mortar	Cement (kg/m ³)	River Sand (kg/m ³)	Water (kg/m ³)	MPCM (kg/m ³)	PVA (%)
7	M-F0.8-P1	450.0	1288.1	203.0	19.8	0.8
8	M-F1.2-P1	450.0	1288.1	203.0	19.8	1.2
9	M-F0-P2	450.0	1226.3	203.0	39.6	0.0
10	M-F0.4-P2	450.0	1226.3	203.0	39.6	0.4
11	M-F0.8-P2	450.0	1226.3	203.0	39.6	0.8
12	M-F1.2-P2	450.0	1226.3	203.0	39.6	1.2
13	M-F0-P3	450.0	1164.4	203.0	59.4	0.0
14	M-F0.4-P3	450.0	1164.4	203.0	59.4	0.4
15	M-F0.8-P3	450.0	1164.4	203.0	59.4	0.8
16	M-F1.2-P3	450.0	1164.4	203.0	59.4	1.2
17	M-F0-P4	450.0	1102.5	203.0	79.2	0.0
18	M-F0.4-P4	450.0	1102.5	203.0	79.2	0.4
19	M-F0.8-P4	450.0	1102.5	203.0	79.2	0.8
20	M-F1.2-P4	450.0	1102.5	203.0	79.2	1.2

Note: F0.4 means that the PVA fiber content accounts for 0.4% of the total volume, and P1 means that the mass replacement rate of MPCM is 1%, and the rest are similar.

2.3. Specimen Preparation

PVA fiber was in bundle shape, which had good hydrophilicity, and the undispersed fiber was easy to cluster when it encountered water. Therefore, before making the specimen, the PVA fiber needed to be evenly disassembled to ensure that the fibers were evenly distributed in the mortar mix. In the natural state of MPCM, there were some local agglomerations, and a small crusher was used to break MPCM evenly before placing it to ensure that the material was evenly distributed in the mix.

Figure 4 illustrates the preparation sequence for the test specimens. Initially, the cement and fine aggregates were dry-blended in a mixer for 2 min to achieve a uniform distribution. Following this, the MPCM was gradually introduced, and the blending continued for another 2 min. Subsequently, PVA fibers were slowly dispersed into the dry mix with an additional 2 min of stirring. Once all solid components were thoroughly homogenized, water was steadily poured into the mixer, initiating a final 3 min wet mixing phase. Upon completion, a fraction of the fresh mixture was extracted to evaluate its consistency. The remaining batch was then cast into molds, mechanically compacted on a vibrating table to remove entrapped air, and ultimately leveled using a trowel to obtain a smooth surface. The curing method was conducted in a standard curing room with a controlled temperature of 20 ± 2 °C and a relative humidity of over 90%, and the curing time was 28 days.

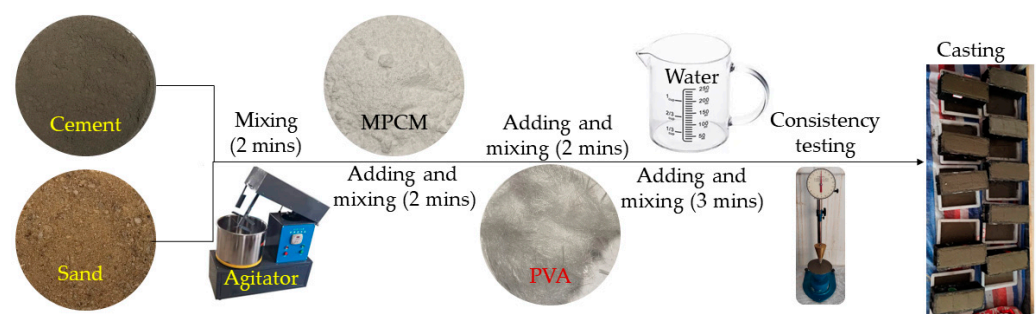


Figure 4. Preparation sequence for the test specimens.

2.4. Test Method

2.4.1. Consistency Test

The consistency test was strictly carried out according to the standard JGT/T70-2009 [17]. Due to the standardized batch-mixing volume, the consistency measurement was performed on a single representative fresh mixture sample for each mix design.

2.4.2. Compressive Strength

Compressive strength test standards were carried out according to standard JGT/T70-2009. Three replicate cubes with a side length of 70.7 mm were made for each mix proportion to ensure statistical reliability. The final reported strength is the mean value of the three samples, and standard deviation bars were added to the results to evaluate data dispersion. The cube compressive strength test was carried out after 28 days of curing. After confirming that the test block had no defects, the surface was wiped, and the size of the specimen was measured. When the difference between the measured size and the nominal size was less than 1 mm, the bearing area of the specimen could be calculated according to the nominal size. Loading was carried out through the mechanical property testing machine. In the test, the loading speed was set at 0.1 mm/s until the test block was destroyed, and the maximum load could be recorded. The compressive strength of the mortar cube is as follows,

$$f_{m.cu} = K \frac{N_u}{A} \quad (1)$$

where N_u denotes the ultimate force that the mortar block can bear; A denotes the area of the pressure surface; K is the coefficient, and it equals 1.35.

2.4.3. Thermal Conductivity

To evaluate the thermal conductivity of the mortar, a pair of cuboid specimens measuring 200 mm × 200 mm × 20 mm was cast for each mixture design. The thermal conductivity was determined based on a single steady-state measurement per mixture using the paired blocks. Prior to the measurement, all samples were thoroughly dried. The evaluation was conducted relying on the thermal steady-state method. During the procedure, a constant temperature gradient of 5 °C was established across the opposite surfaces of each specimen. Once the target temperatures were achieved, this thermal condition was maintained for one hour to ensure that the heat flux completely stabilized without any further fluctuations. The calculation method of thermal conductivity is as follows,

$$T_c = \frac{qt}{\Delta T} \quad (2)$$

where T_c denotes thermal conductivity, and the unit is W/m·°C; q_{ave} denotes the average heat flux on both sides of the block, and the unit is W/m²; d is the depth of the block, and the unit is m; ΔT is the temperature difference between the two sides of the test block, and the unit is °C.

2.4.4. Specific Heat Capacity

Defined as the amount of thermal energy required to alter the temperature of a unit mass by one degree, specific heat capacity serves as a fundamental metric for evaluating the performance of phase change materials (PCMs). To master the phase change performance of PVA-MPCM mortar, one cuboid test block with the size of 200 mm × 200 mm × 20 mm was made for each group of mix proportion respectively, to test the specific heat capacity of PVA-MPCM mortar, and the test block was put into the drying box to dry after 28 days, and then the specific heat capacity of the test block was tested.

The test device is shown in Figure 4, which is composed of a water circulation incubator, heat exchanger, adiabatic foam board, heat flow sensor and thermocouple. The specific heat capacity of 5~45 °C was measured according to the dynamic heat flux meter method, and heating and cooling processes were both tested. The temperature change rates were 0.2 °C/min. Sensors were set on both sides of the test block to collect the heat flux and temperature on both sides of the specimen. The specific heat capacity can be obtained as follows,

$$S_H(T) = \frac{Aq(T)}{m \cdot R_T} \quad (3)$$

where $S_H(T)$ denotes the specific heat capacity at temperature T , and the unit is J/kg·°C; A is the area of test specimen, and the unit is m²; $q(T)$ is the sum of heat flux on both sides of the specimen at a temperature T , and the unit is W/m²; m is the mass of tested specimen, and the unit is kg; R_T is the rate of change in temperature with time.

3. Results and Discussions

3.1. Microscopic Property

The microscopic photos of the M-F0.8-P2 mortar sample are shown in Figure 5. It can be seen that PVA fiber is closely combined with the mortar matrix, and PVA fiber has high toughness and tensile strength, which provides a foundation for the enhancement of the mortar's mechanical properties. Spherical MPCM has more pores around it, indicating slightly inadequate dissolution or bonding with the surrounding cementitious hydrates. No obvious MPCM shell rupture or extensive phase change core leaching was identified, confirming the structural survivability of the microcapsules during mixing.

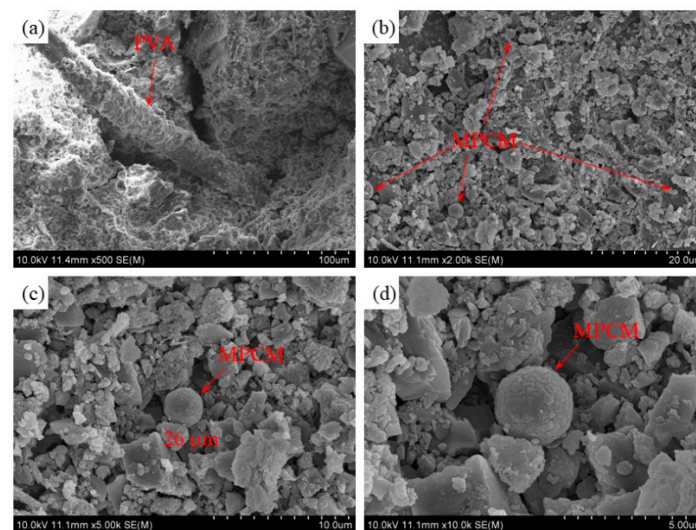


Figure 5. SEM image of PVA-MPCM mortar. (a) PVA, (b–d) MPCM.

3.2. Consistency

Figure 6 illustrates the mortar consistency variations, which range between 17 mm and 37 mm, depending on the PVA fiber dosage and MPCM substitution level. Overall, incorporating more MPCM consistently reduces the mixture's flowability. For the control group without PVA fibers (0%), gradually raising the MPCM proportion up to 4% yields consistency reductions of 5.56%, 13.89%, 22.22%, and 25.00%, respectively. The inclusion of PVA fibers further magnifies this workability loss. At a fiber fraction of 0.4%, the corresponding declines across the same MPCM addition levels are 8.82%, 20.59%, 29.41%, and 44.12%. Similarly, when the PVA content is elevated to 0.8%, the consistency drops by 12.90%, 19.35%, 25.81%, and 45.16%. Finally, at the maximum PVA dosage of 1.2%,

scaling up the MPCM replacement results in decrements of 7.41%, 18.52%, 25.93%, and 40.74%. In general, with the same PVA fiber content, the consistency of mortar decreases with the increase in MPCM replacement rate, indicating that replacing sand with MPCM has a negative effect on the consistency of mortar. This is because MPCM has certain water absorption and a large specific surface area, and it can adsorb more water than sand, and with the increase in MPCM replacement rate, the consistency of mortar decreases.

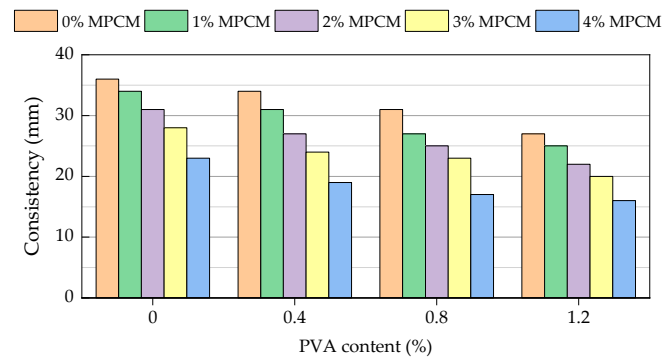


Figure 6. Consistency of PVA-MPCM mortar.

3.3. Compressive Strength

Figure 7 shows the failure mode of some mortar test blocks. Observation of the failure modes revealed that ordinary mortar failed in a typical brittle manner with major diagonal shear cracks. In contrast, the failure mode of the PVA-MPCM mortar exhibited enhanced ductility. Due to the bridging effect of the PVA fibers, the macroscopic cracks were finer and more thoroughly distributed, preventing explosive spalling and keeping the fractured block relatively intact even after reaching the ultimate stress peak.

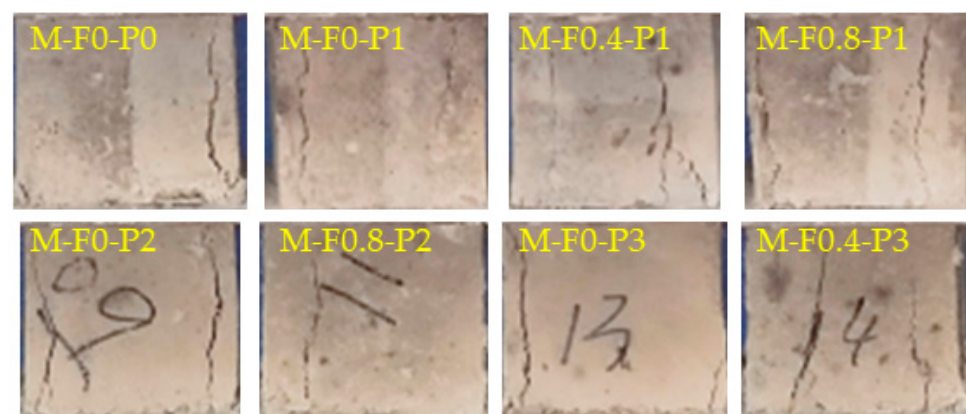


Figure 7. Compressive failure modes of PVA-MPCM mortar block.

Figure 8 shows the mean compressive strength of PVA-MPCM mortar (each value represents the average of three identical samples, with standard deviations ranging from 0.4 to 1.2 MPa, ensuring high data reliability). When PVA fiber is not added, and MPCM replacement rate increases from 0% to 4%, the compressive strength decreases by 9.30%, 12.98%, 20.16% and 23.47%, respectively. For the mixture incorporating 0.4% PVA fibers, raising the MPCM substitution level from 0% to 4% resulted in successive compressive strength reductions of 2.61%, 8.33%, 10.79%, and 15.22%. Meanwhile, escalating the fiber dosage to 0.8% under the same MPCM addition gradient yielded more pronounced strength drops of 7.74%, 13.26%, 15.40%, and 21.30%, respectively. When the replacement rate of MPCM increased from 0% to 4% with 1.2% PVA fiber, the compressive strength decreased by 6.36%, 12.65%, 18.33% and 18.62%, respectively. The reason for this phenomenon is

that the strength of MPCM is weaker than that of fine aggregates, and the MPCM are not well combined with the cement slurry, and there are more pores around the microcapsules, resulting in a decrease in compressive strength when the fine aggregates are replaced by MPCM.

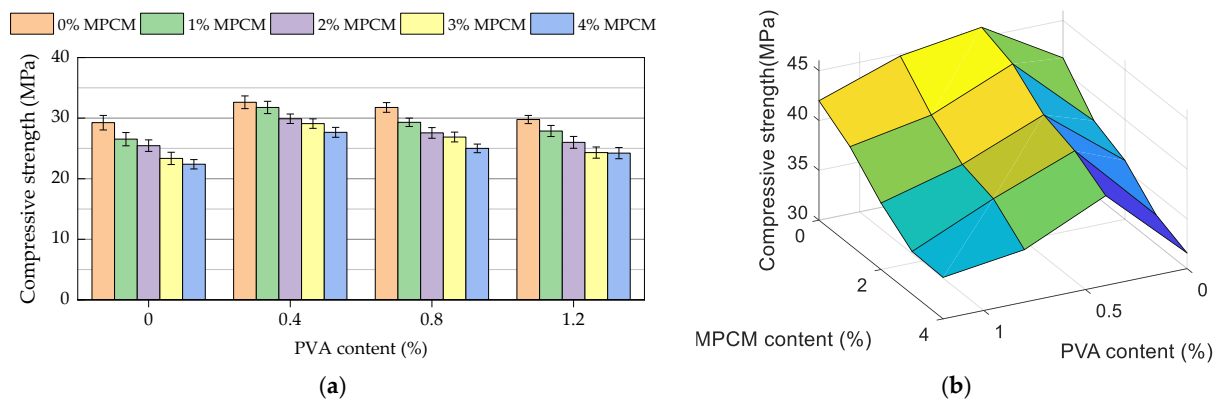


Figure 8. Compressive strength of PVA-MPCM mortar: (a) bar chart; (b) 3D performance map.

PVA content has a positive contribution to compressive strength. When MPCM is not added, and PVA fiber increases from 0% to 1.2%, the strength increases by 11.51%, 8.62% and 1.78%, respectively. When the MPCM replacement rate was 1%, and PVA fiber increased from 0% to 1.2%, the strength increased by 19.74%, 10.49% and 5.08%, respectively. When the MPCM replacement rate was 2%, and PVA fiber increased from 0% to 1.2%, the strength increased by 17.46%, 8.27% and 2.15%, respectively. When the MPCM replacement rate was 3%, and PVA fiber increased from 0% to 1.2%, the strength increased by 24.59%, 15.09% and 4.11%, respectively. When the MPCM replacement rate was 4%, and PVA fiber increased from 0% to 1.2%, the strength increased by 23.54%, 11.70% and 8.23%, respectively. In general, when the fiber content increases from 0 to 1.2%, the compressive strength increases first and then decreases, and the compressive strength reaches the maximum when the fiber content is 0.4%.

The reason for these phenomena is that PVA fiber has a good affinity with cement, which effectively enhances the bonding performance between cement substrates. The fiber fills the void between the particles, binds each substrate particle tightly, and forms a fiber skeleton structure, which enhances the compressive strength of the cement substrate. However, with the increase in fiber content, the contribution of PVA fiber to strength decreases, mainly because the increase in fiber reduces the fluidity of mortar (see Section 3.2), resulting in inadequate hydration reaction in mortar. The optimal peak of mechanical performance is strictly localized at the 0.4% PVA coordinate along the fiber axis, regardless of the MPCM content. Beyond this optimal fiber threshold, the benefits of fiber-bridging are counteracted by the loss of matrix homogeneity, leading to a downward trend in the 3D performance map.

A two-way ANOVA statistical analysis revealed that the negative impact of MPCM replacement on compressive strength was highly significant ($p < 0.01$), and the positive moderating effect of PVA fiber content (up to 0.4%) was also statistically significant ($p < 0.05$), proving that the combination can be mathematically modeled to predict optimal mixture designs for future applications.

It must be acknowledged that this study solely evaluated compressive strength to isolate the structural skeleton degradation caused by soft MPCMs. The omission of flexural and tensile strength testing represents a distinct limitation of the current work, given that crack-bridging under tension is the primary mechanism by which PVA fibers

improve composite performance. Future studies will systematically incorporate these mechanical indices.

3.4. Thermal Conductivity

Figure 9 shows the thermal conductivity of PVA-MPCM mortar. The thermal conductivity of PVA-MPCM mortar is in the range of $0.75\text{--}1.2\text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$. The MPCM replacement rate has a great influence on the thermal conductivity of PVA-MPCM mortar, which shows that the thermal conductivity decreases with the increase in MPCM replacement rate.

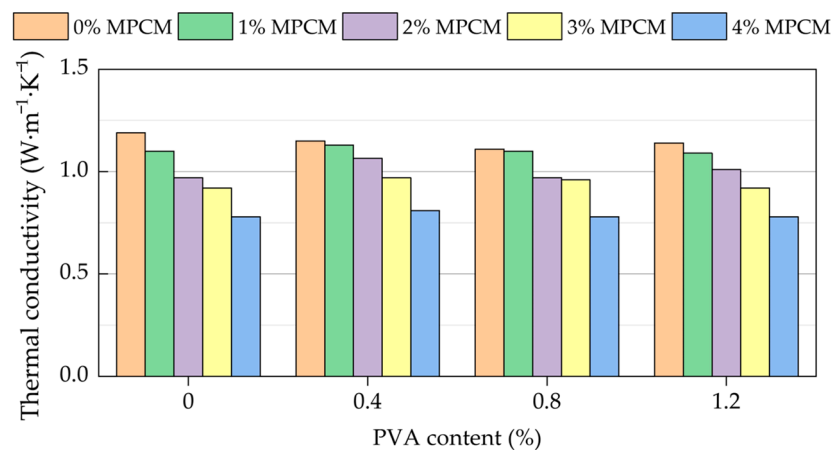


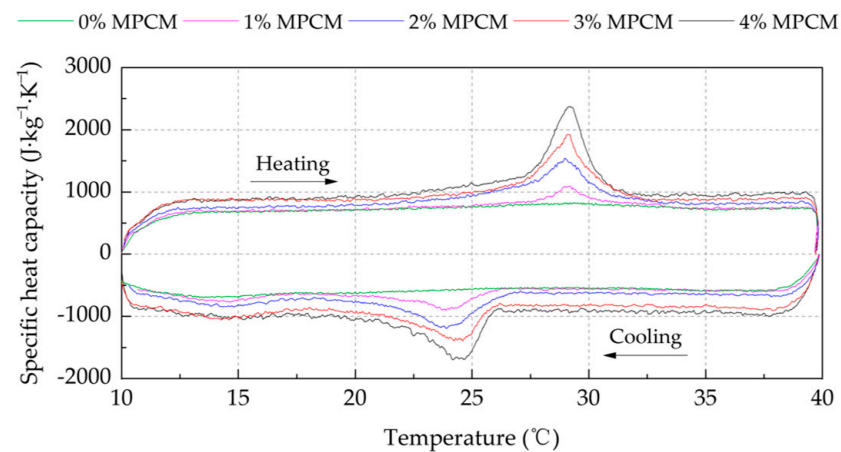
Figure 9. Thermal conductivity of PVA-MPCM mortar.

When PVA fiber is not added, and MPCM replacement rate increases from 0% to 4%, thermal conductivity decreases by 7.56%, 18.49%, 22.69% and 34.45%, respectively. When 0.4% PVA fiber is added, and the MPCM replacement rate increased from 0% to 4%, the thermal conductivity decreased by 1.74%, 7.39%, 15.65% and 29.57%, respectively. When 0.8% PVA fiber is added, and the MPCM replacement rate increased from 0% to 4%, the thermal conductivity decreased by 0.90%, 12.61%, 13.51% and 29.73%, respectively. When 1.2% PVA fiber is added, and MPCM replacement rate increases from 0% to 4%, thermal conductivity decreases by 4.39%, 11.40%, 19.30% and 31.58%, respectively. The reason for this phenomenon is that the thermal conductivity of microcapsules is lower than that of fine aggregates. Secondly, the addition of MPCM increases the porosity and decreases the overall bulk density of the mortar, creating more air voids that act as thermal insulators. However, systematic tracking of bulk density and quantitative porosity data was not conducted in this study, which represents a limitation that warrants further investigation to map precise phase-property correlations. Consequently, a strong correlation exists between the density reduction caused by MPCM and the decline in thermal conductivity.

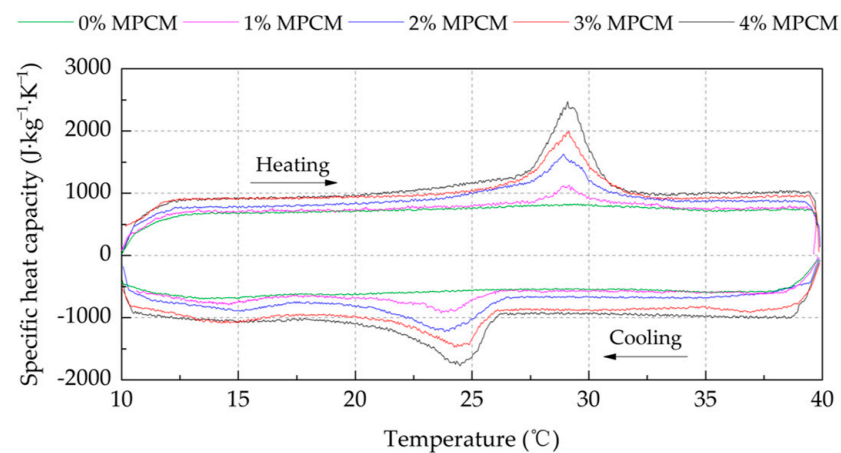
Compared with the MPCM replacement rate, PVA content has little effect on thermal conductivity and no obvious rule. This is mainly because, despite the addition of PVA fiber, its content is relatively small compared to other materials, with a maximum volume rate of only 1.2%, which has a limited impact on thermal conductivity.

3.5. Specific Heat Capacity

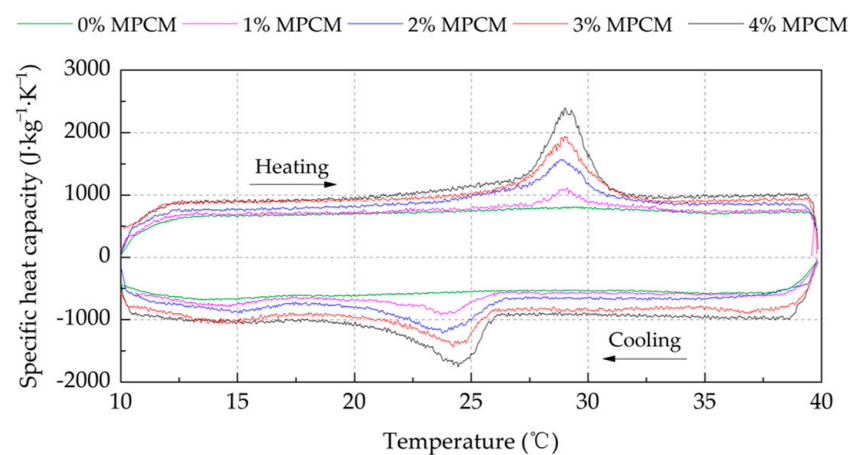
Figure 10 shows the influence of MPCM replacement rate on specific heat capacity of PVA-MPCM mortars under 0%, 0.4%, and 0.8% PVA fiber content. The behavior of the 1.2% PVA group exhibited nearly identical thermal trends to the 0.8% group, further confirming that exceeding a certain fiber threshold does not significantly alter the specific heat capacity profile of the composite.



(a)



(b)



(c)

Figure 10. Specific heat capacity: (a) 0% PVA content; (b) 0.4% PVA content; (c) 0.8% PVA content.

In the heating process, the curve changes obviously when the temperature is in the range of 27 °C to 32 °C, and the cooling is in the range of 26 °C to 22 °C. Combined with DSC of MPCM (see Section 2.1.4), it can be explained that in the process of heating and cooling, the two temperature regions are in the range of phase change temperatures of MPCM, but the phase change temperatures of mortar and MPCM are not completely consistent, which also shows that the MPCM are affected by the encapsulation of cement mortar, resulting in changes in the phase change temperature of PVA-MPCM mortar.

Comparing different replacement rates of MPCM, it can be found that the peak specific heat capacity increases with the increase in the replacement rate of MPCM. Specifically, when the replacement rate of MPCM increases from 0% to 4%, the peak specific heat capacity of heating increases by about 34.53%, 88.20%, 137.89% and 195.28%, respectively. The specific heat capacity of heat release increased by 57.24%, 106.36%, 141.70% and 201.41%, respectively. Comparing the specific heat capacity under different PVA fiber content, it can be found that the influence of PVA fiber content on the specific heat capacity is small, and there is no obvious law. While overlapping the specific heat capacity curves of different PVA contents under the same MPCM rate demonstrates nearly identical trajectory. The overlapped analysis confirms that the incorporation of PVA fibers does not alter the phase-transition enthalpy of the matrix, as the heat capacity curves strictly depend on the mass fraction of MPCM.

3.6. Discussion

Comparing the results of this study with the existing literature highlights the unique contribution of incorporating PVA fibers into PCM mortars. While previous studies, such as Djamai et al. [7], reported an unmitigated 30% drop in compressive strength when incorporating 4% PCMs, our study demonstrated that the introduction of 0.4% PVA fiber could successfully limit this strength degradation to approximately 15.22%. Furthermore, unlike the unencapsulated PCM methods investigated by Cunha et al. [9], which suffered from leakage issues at high temperatures, the MPCM combined with the hydrophilic PVA network in this study maintained excellent thermal stability and material consistency. These comparative findings confirm that the fiber-bridging mechanism effectively compensates for the structural defects introduced by microcapsules, offering a more resilient and functional composite than traditional PCM-only modifications.

4. Conclusions

This study evaluated the synergistic effects of PVA fibers and microencapsulated phase change materials (MPCMs) on the workability, strength, and thermal responses of construction mortars. The primary conclusions are drawn as follows:

- (1) The consistency of PVA-MPCM mortar was between 17 and 37 mm. With the increase in MPCM replacement rate, the consistency of mortar decreased. When the MPCM replacement rate increased from 0% to 4%, the consistency of mortar decreased by 8.67%, 18.09%, 25.84% and 38.76% on average. When the PVA fiber content increased from 0% to 1.2%, the mortar consistency decreased by 12.53%, 19.29% and 28.01% on average.
- (2) Replacing fine aggregate with soft MPCMs decreases the compressive strength from 6.50% to 19.65% due to the weaker microcapsule core and higher porosity. However, adding 0.4% PVA fiber optimally mitigates this loss through crack-bridging actions, transitioning the failure pattern from brittle splitting to ductile matrix integrity. Exceeding 0.4% fiber causes agglomeration, reducing the strength benefits.
- (3) The thermal conductivity of PVA-MPCM mortar was in the range of 0.75 to $1.2 \text{ W} \cdot \text{m}^{-1} \cdot \text{K}^{-1}$. MPCM replacement had a great impact on the thermal conductivity of PVA-MPCM mortar, which was roughly manifested as the thermal conductivity decreased with the increase in MPCM replacement rate, while the PVA content had little effect on the thermal conductivity.
- (4) Dynamic heat flux metrics show substantial specific heat capacity peaks during phase transition zones ($27\text{--}32^\circ\text{C}$ for heating; $22\text{--}26^\circ\text{C}$ for cooling). The peak storage/release capacity scales up by $\sim 195\%$ and $\sim 201\%$ at a 4% MPCM substitution level, unaffected by the fiber dosage.

- (5) For structural–functional building envelopes, a mix proportion combining 0.4% PVA fiber with 1% to 2% MPCM replacement is highly recommended to achieve optimized thermal mass without severely penalizing compressive load bearability.

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Conflicts of Interest: Authors Chuangsheng Cai, Yu Wu, Yongqiang An and Penglin Li was employed by the company China Harbour Engineering Company Limited. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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