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Mechanical and Thermal Properties of Hybrid Fiber Reinforced Concrete Containing Microencapsulated Phase Change Materials

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***Abstract*— Traditional concrete is prone to thermal stress under significant temperature fluctuations or extreme climatic conditions, leading to cracking and structural degradation. To address this issue, researchers have increasingly incorporated phase change materials (PCM) into concrete to improve its thermal performance and freeze resistance. However, while PCM can significantly enhance the thermal properties of concrete, their direct addition may adversely affect mechanical strength. Therefore, this study combines steel fibres and polypropylene fibres as hybrid fibres with microencapsulated phase change materials (MCPM) to optimize the performance of concrete. Experimental results indicate that the incorporation of MPCM reduces the compressive strength of concrete, whereas the addition of hybrid fibre enhances both the ductility and compressive strength of phase change concrete. The inclusion of microencapsulated PCM also decreases the splitting tensile strength of concrete; however, the addition of hybrid fibres significantly improves the splitting tensile strength, with this enhancement being more pronounced than the increase in compressive strength. Moreover, when the level of microencapsulated PCM is relatively high, the positive effect of hybrid fibres on the mechanical properties of phase change concrete becomes more significant. Additionally, the inclusion of MPCM reduces the thermal conductivity and thermal diffusivity of concrete while increasing its specific heat capacity, whereas the addition of hybrid fibres has minimal influence on thermal conductivity and thermal diffusivity but slightly reduces the specific heat capacity of phase change concrete.**

***Keywords*—Phase Change Material, Fiber Reinforced Concrete, Hybrid Fiber, Mechanical Properties, Thermal Properties.**

I. INTRODUCTION

Concrete is widely used in the construction industry due to its abundant raw materials, low cost, and excellent durability [1]. However, traditional concrete is susceptible to thermal stresses under significant temperature fluctuations or extreme climatic conditions, which leads to cracking and structural degradation. In recent years, with increasing demand for energy efficiency and durability, extensive research has focused on incorporating phase change materials (PCM) into concrete to enhance its thermal performance and freeze resistance [2-6].

PCM are widely used in building materials to achieve temperature stability and improve energy efficiency, as they can store and release a large amount of thermal energy during phase transitions. PCMs are mainly classified into organic, inorganic, and eutectic types, with organic PCM (such as paraffin) being widely applied due to their high thermal stability and suitable phase transition temperatures [7, 8]. However, direct incorporation of PCM can lead to leakage issues. To address this, researchers have commonly adopted microencapsulation techniques to prevent PCM leakage and ensure material stability [9-11]. Yuan et al. [12] used hollow steel balls containing PCM to replace part of the coarse aggregate in concrete, discovering that the optimal PCM content significantly enhanced freeze-thaw durability by reducing mass loss, strength degradation, and porosity growth. Anupam et al. [13] investigated the use of encapsulated PCM in concrete pavements to reduce urban heat island (UHI) effects, focusing on the long-term cooling performance of two organic PCM, OM35 and OM42. It was found that PCM integration consistently lowered pavement temperatures. Sharifi et al. [14] used COMSOL modeling and Guarded Longitudinal Comparative Calorimetry (GLCC) tests to evaluate PCM in concrete, finding that PCM with melting points near comfort zones smooth indoor temperature profiles, while those near freezing points reduce freeze-thaw cycles in pavements, extending their service life.

Although the addition of PCMs to concrete can significantly enhance thermal performance, showing potential for antifreeze applications and urban heat island mitigation, it may negatively impact the mechanical strength of concrete [15-18]. Therefore, many scholars are dedicated to improving the mechanical properties of PCM-enhanced concrete [19,20]. Studies have shown that the use of hybrid fibers can

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effectively optimize the mechanical properties of concrete [21-24]. Shan et al. [25] conducted mechanical tests on hybrid steel-polypropylene fiber-reinforced concrete (HSPFRC), analyzing different volume fractions and aspect ratios of fibers. The results indicated that the hybrid combination of fibers significantly enhanced the compressive, split tensile, and axial tensile properties compared to using each type of fiber individually. Mahto et al. [26] noted that incorporating steel fibers and polypropylene fibers significantly improved the mechanical properties and durability of concrete, with optimal performance achieved at 0.85% steel fibers and 0.15% polypropylene fibers. Li et al. [27] developed a hybrid fiber-reinforced concrete by integrating steel fibers and three distinct polypropylene fibers into concrete. They investigated the mechanical properties and microstructural characteristics of concrete across various fiber combinations and concentrations to determine the optimal hybrid fiber composition.

Based on the literature on PCMs and hybrid fibers, steel fibers and polypropylene fibers are selected as the hybrid fibres and microencapsulated phase change materials. This study aims to investigate the mechanical and thermal properties of hybrid fiber-reinforced concrete containing microencapsulated PCMs, with the goal of contributing to the development of sustainable, high-performance building materials that meet the needs of modern infrastructure.

II. Experimental materials and methods

A. Experimental Materials

The following raw materials were utilized in this study. P·O42.5 cement was utilized as cement. The gravel with a particle size ranging from 5mm to 16mm was utilized as the coarse aggregate, and the natural river sand with apparent density of 2610 kg/m3, which belonged to well-graded medium sand, was utilized as the fine aggregate. Sand and gravel could be purchased at the local market in Changchun, Jilin Province, China. As shown in Table 1, the hooked-end steel fibres with a length of mm were utilized as the steel fibres, which were supplied by Hengshui Shengying Metal Products Co., Ltd. (Hengshui, China). The polypropylene fibres with a length of 19 mm were utilized, which were supplied by Changsha Ningxiang Building Materials Co., Ltd. (Changsha, China), as shown in Figure 1 and Table 2. As shown in Figure 2 and Table 3, The MPCM were utilized as PCM, which were supplied by Shanghai Runsong Industrial Co., Ltd. (Shanghai, China). The MPCM used paraffin as the phase change core material, and the phase transition temperature was about 28 ℃. A high-efficiency polycarboxylate-based water-reducing agent was utilized as the water-reducing agent. The water utilized was locally supplied tap water.

FIGURE 1 POLYPROPYLENE FIBRES

FIGURE 2 MPCM

According to Chinese standard JGJ55-2011, the benchmark mix ratio of concrete was designed, as shown in Table 4, and the design compressive strength grade of concrete was C40. On the basis of the benchmark mix, referring to the existing research literature on phase-change concrete and the Chinese standard JG/T472-2015, the MPCM equivalent volume replacement sand was added to the concrete, and 0.85% steel fiber and 0.15% polypropylene fiber were added according to the volume level. In the Table 4, the concrete labeled as PC referred to plain concrete. The concrete labeled as M4C, M7C, and M9C represented phase change concrete with MPCM volume level of 4%, 7%, and 9%, respectively. The concrete labeled as FRM0C was fiber-reinforced concrete containing 0% MPCM, 0.85% steel fiber, and 0.15% polypropylene fiber by volume. The concrete labeled as FRM4C, FRM7C, and FRM9C was fiber-reinforced phase change concrete with MPCM volume level of 4%, 7%, 9%, respectively, combined with 0.85% steel fiber and 0.15% polypropylene fiber.

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TABLE 1 BASIC PROPERTIES OF STEEL FIBERS

Shape	Length (mm)	Diameter (mm)	Aspect ratio1/d	Tensile strength(MPa)	Density (g/cm^3)
Hooked end	35	0.55	64	1050	7.85

TABLE 2 BASIC PROPERTIES OF POLYPROPYLENE FIBERS

Density (g/cm^3)	Diameter（mm）	Length (mm)	Elastic Modulus(MPa)	Tensile Strength(MPa)	Melting point(℃)
0.91	32.7	19	4236	469	169

TABLE 3 BASIC PROPERTIES OF MPCM

Phase transition point (℃)	Latent heat value(kJ/kg)	Density (kg/m^3)	Thermal conductivity(W/m.k)
28	170	850	0.25

TABLE 4 MIX RATIO OF CONCRETE TEST

Test group	Water (kg/m^3)	Cement (kg/m^3)	Sand (kg/m^3)	Gravel (kg/m^3)	Water reducing agent(kg/m^3)	Steel fiber (kg/m^3)	Polypropylene fiber (kg/m^3)	MPCM (kg/m^3)
PC	185	440.5	707	1017.5	3.524	0	0	0
M4C	185	440.5	602.6	1017.5	3.524	0	0	34
M7C	185	440.5	524.3	1017.5	3.524	0	0	59.5
M9C	185	440.5	472.1	1017.5	3.524	0	0	76.5
FRM0C	185	440.5	707	1017.5	3.524	66.725	1.365	0
FRM4C	185	440.5	602.6	1017.5	3.524	66.725	1.365	34
FRM7C	185	440.5	524.3	1017.5	3.524	66.725	1.365	59.5
FRM9C	185	440.5	472.1	1017.5	3.524	66.725	1.365	76.5

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B. *Test methods*

1) Compressive strength test:

The compressive strength was performed on the cubes prepared of size 100mm×100mm×100mm. A total of 24 specimens were prepared, and each mix ratio variant was repeated 3 times to assess the compressive strength. To determine compressive strength, follow specification GB/T 50081-2019 [28]. Use Yaw-2000 pressure testing machine to continuously and evenly load at the speed of 0.5 MPa/s. When the specimen was crushed, the failure load reading shown by the pressure testing machine was recorded. Since a non-standard cube was used in the test, the obtained compressive strength value should be adjusted by multiplying it with a dimensional correction factor of 0.95.

2) Splitting tensile strength test:

The splitting tensile strength was performed on the cubes prepared of size 100mm×100mm×100mm. A total of 24 specimens were prepared, and each mix ratio variant was repeated 3 times to assess the splitting tensile strength. The test was performed in accordance with specification GB/T 50081-2019. The special steel mold for the determination of splitting tensile strength was adopted. The test equipment was YAW-2000 pressure testing machine, and the pad was made of 160mm×20mm×4mm ordinary plywood. The loading speed of the specimen was 0.05MPa/s. The splitting load reading from the pressure testing machine was recorded when the specimen was splitting. Since a non-standard cube was used in the test, the resulting value should be adjusted by multiplying it with a dimensional correction factor of 0.85.

3) Thermal parameters test:

The TPS2500S thermal constant analyzer was utilized in this experiment, as shown in Figure 3. Using transient plane source method, the instrument can simultaneously measure the thermal conductivity, thermal diffusion coefficient and specific heat capacity of the sample. The sample size for this experiment was 100mm×100mm×18mm, as shown in Figure 4.

4) SEM micromorphology test:

The JSM-6700F scanning electron microscope was utilized in this experiment. Procedure: (1) Select the massive crushing material after the mechanical test as the sample, the sample size was about 10mm×10mm×5mm; Put the sample into the oven to dry; (2) Fix the sample on the sample bearing platform with special conductive tape; (3) The sample was sprayed with gold, and then the instrument with the sample was pumped to vacuum; (4) By adjusting magnification, focal length, color contrast and other parameters, in order to obtain the ideal microscopic structure.

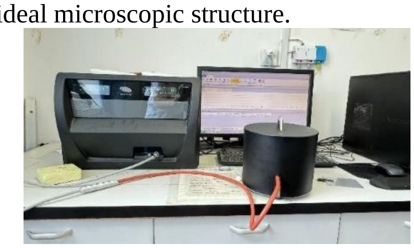

FIGURE 3 THE TPS2500S THERMAL CONSTANT ANALYZER

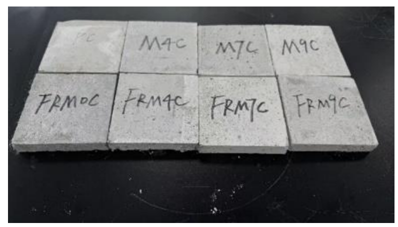

FIGURE 4 IMAGE OF THERMAL PARAMETER TEST SAMPLE

III. TEST RESULTS AND ANALYSIS

A. *Compressive strength of cube*

As shown in Figure 5, plain concrete and PCM exhibit brittle failure modes. With the increase of MPCM level, the damage of concrete becomes more and more serious. When the specimen of PC is damaged, the outer concrete around the test block is only slightly peeled, and the inner core remains relatively intact, indicating that the damage is mild. When the sample of M9C is damaged, the outer concrete around the test block has been completely removed, and the remaining part shows an hourglass shape, indicating serious damage. This is because the phase change material in the phase change concrete changes the internal microstructure of the concrete, affects the bonding force between the cement slurry and the aggregate, and makes the concrete produce microcracks.

As shown in Figure 6, the failure mode of fiber reinforced concrete and fiber reinforced phase change concrete changes from brittle failure to ductile failure. The concrete was relatively intact after damage, no obvious spalling of concrete was seen, and only a small amount of concrete fragments fell off. This is because hybrid fibers play a bridging role in the concrete matrix. When the concrete is cracked by external forces, the fibers can cross the cracks and transfer the stress, thus inhibiting the further expansion of the cracks. This bridge action significantly improves the ductility of concrete.

As seen from Figure 5 and Figure 6, with the increase of MPCM level, more cracks and damages appear after the concrete is damaged under pressure, which leads to the aggravation of the spalling of the concrete surface. The gradual development from small local spalling to large area of massive spalling makes the concrete compression damage more serious.

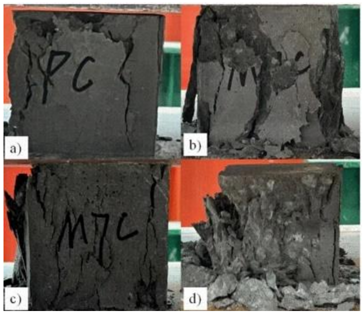

FIGURE 5 CUBE COMPRESSIVE FAILURE PATTERN OF CONCRETE WITH A) 0% MPCM LEVEL, B) 4% MPCM LEVEL, C)7% MPCM LEVEL AND D) 9% MPCM LEVEL

FIGURE 6 CUBE COMPRESSIVE FAILURE PATTERN OF FIBER REINFORCED CONCRETE WITH DIFFERENT MPCM LEVEL: A) 0%, B) 4%, C) 7%, D) 9%

The results of the cube compressive strength test are presented in a line chart, as shown in Figure 7. The analysis is as follows:

The cube compressive strength decreases with the increase of MPCM level. For the test group without fiber, when the level of MCPM was 4%, 7% and 9%, the compressive strength was reduced by 29.3%, 54.5% and 67.2% compared with PC, respectively. When hybrid fiber was added, the compressive strength of the specimen was significantly improved compared with that of the specimen without fiber. For the specimens with 4%, 7% and 9% MPCM level, the compressive strength of the doped fiber can be increased by 6.5%, 8.3% and 32.7%, respectively, compared with that of the unadded fiber. For the hybrid fiber test group, when the level of MPCM was 4%, 7%, 9%, the compressive strength was reduced by 24.6%, 50.7%, 56.4% compared with PC, respectively.

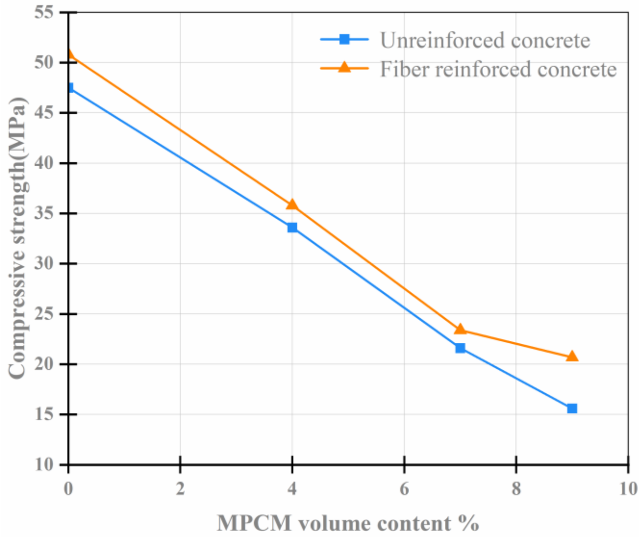

FIGURE 7 COMPRESSIVE STRENGTH RESULTS OF PHASE CHANGE CONCRETE

B. *Splitting tensile strength*

The failure mode of the splitting tensile test is shown in Figure 8. After reaching the breaking load, the undoped concrete formed an obvious crack in the center, which ran through the whole specimen, resulting in the specimen being split into two parts, displaying characteristics of brittle failure. When the concrete mixed with fiber reaches the ultimate load, it will not suddenly split into two parts, but there are many micro-cracks along the main cracks near the middle line, which makes the whole test block always maintain a certain integrity during the failure process, which is manifested as ductile failure. This is because the bridging effect of fibers can effectively prevent the further expansion and penetration of cracks. When the concrete reaches the ultimate tensile strength value, the binding effect of fibers on the matrix prevents the concrete from being split in two.

The splitting tensile strength test results are shown in Figure 9. Similar to the trend of compressive strength, the splitting tensile strength decreased with the increase of MPCM level. For the test group without fiber, when the MCPM level was 4%, 7% and 9%, the splitting tensile strength was reduced by 17.1%, 30.4% and 39.0% compared with PC, respectively. When hybrid fiber was added, the splitting tensile strength was significantly improved compared with the specimens without fiber. For the samples with 4%, 7% and 9% MPCM level, the splitting tensile strength of the doped fiber can be increased by 17.2%, 33.7% and 52.7%, respectively, compared with that without the added fiber. For the experimental group with hybrid fiber, for MPCM 4%, 7% and 9%, the splitting tensile strength is reduced by 2.8%, 6.9% and 6.9% compared with PC, respectively, indicating that the splitting tensile strength of fiber-reinforced phase change concrete tends to be stable when the level of MPCM is higher.

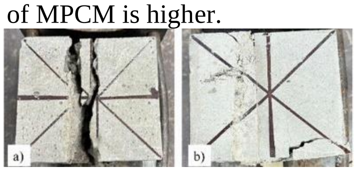

FIGURE 8 CUBE CLEAVAGE DAMAGE PATTERN. A) UNREINFORCED CONCRETE, AND B) FIBER REINFORCED CONCRETE

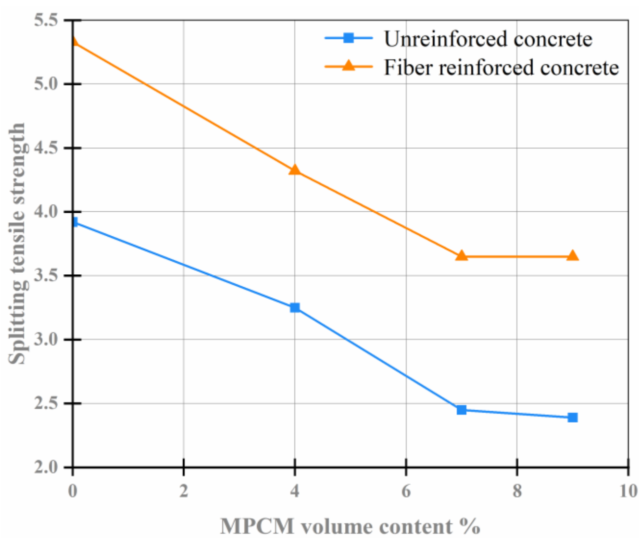

FIGURE 9 SPLITTING TENSILE STRENGTH OF PHASE CHANGE CONCRETE

C. Thermal parameters

The results of the thermal performance parameters are shown in the figure below. From Figure 10, it can be concluded that the addition of MPCM reduces the thermal conductivity of concrete, and the thermal conductivity of concrete decreases as the MPCM level increases. For the test group without fibers, when the level of MCPM is 4%, 7% and 9%, the thermal conductivity decreases by 7.1%, 21.6% and 39.2%, compared to plain concrete (PC), respectively. After adding hybrid fibers, the thermal conductivity increases compared to the specimens without fiber. For the samples with MPCM level of 4%, 7% and 9%, the thermal conductivity increases by 0.7%, 1.3% and 1.0%, respectively, compared to those without fibers. For the experimental group with hybrid fibers, when the MPCM level is 4%, 7%, and 9%, the thermal conductivity decreases by 6.5%, 20.6%, and 38.6%, respectively, compared to PC.

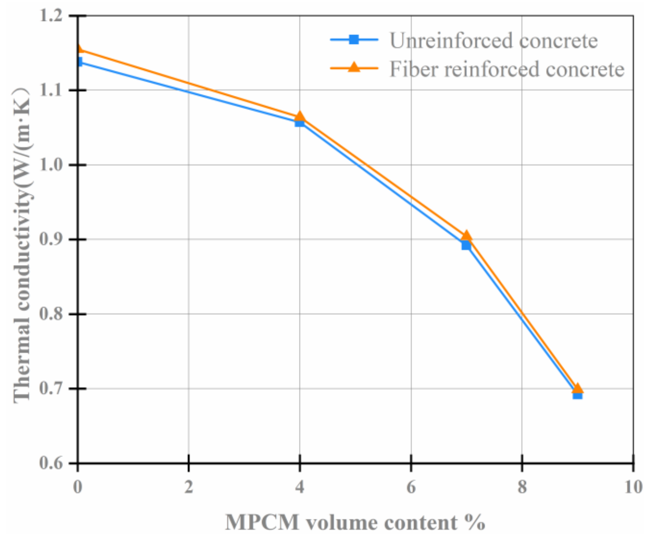

FIGURE 10 THERMAL CONDUCTIVITY OF PHASE CHANGE CONCRETE

From Figure 11, it can be concluded that the addition of MPCM reduces the thermal diffusivity of concrete. With the increase of MPCM level, the thermal diffusivity of concrete decreases. For the test group without fibers, when the level of MCPM is 4%, 7%, and 9%, the thermal diffusivity decreases by 26.0%, 35.9%, and 40.5%, compared to PC, respectively. After adding hybrid fibers, the thermal diffusivity increases compared to the specimens without fibers. For the samples with MPCM level of 4%, 7%, and 9%, the thermal diffusivity increases by 15.6%, 8.3%, and 11.5%, respectively, compared to those without fibers. For the experimental group with hybrid fibers, when the MPCM level is 4%, 7%, and 9%, the thermal diffusivity decreases by 11.5%, 30.5%, and 33.6%, respectively, compared with PC.

The data from Figure 12 indicates that the addition of MPCM increases the specific heat capacity of concrete. Moreover, as the MPCM level increases, the specific heat capacity of the concrete also increases. For the test group without added fibers, when the MPCM level is 4%, 7%, and 9%, the specific heat capacity increases by 21.9%, 25.5%, and 27.8%, respectively, compared to plain concrete (PC). However, after adding hybrid fibers, the specific heat capacity decreases compared to the specimens without fibers. For specimens with MPCM level of 4%, 7%, and 9%, the specific heat capacity with fibers decreases by 16.3%, 15.2%, and 11.3%, respectively, compared to those without fibers. For the experimental group with hybrid fibers, when the MPCM level is 4%, 7%, and 9%, the specific heat capacity

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increases by 2.0%, 6.4%, and 13.4%, respectively, compared to PC.

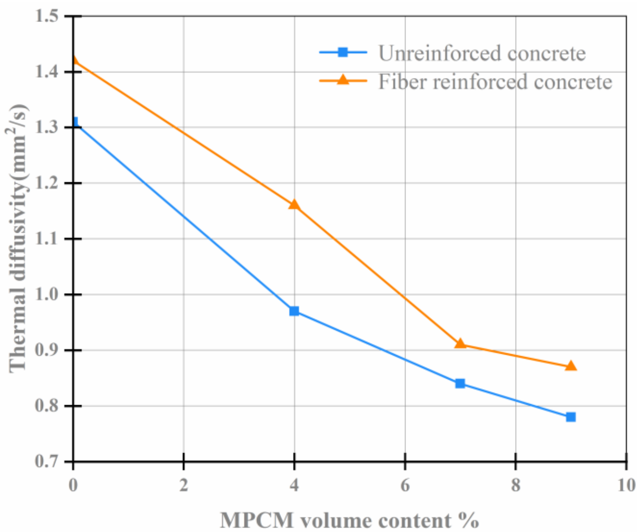

FIGURE 11 THERMAL DIFFUSIVITY OF PHASE CHANGE CONCRETE

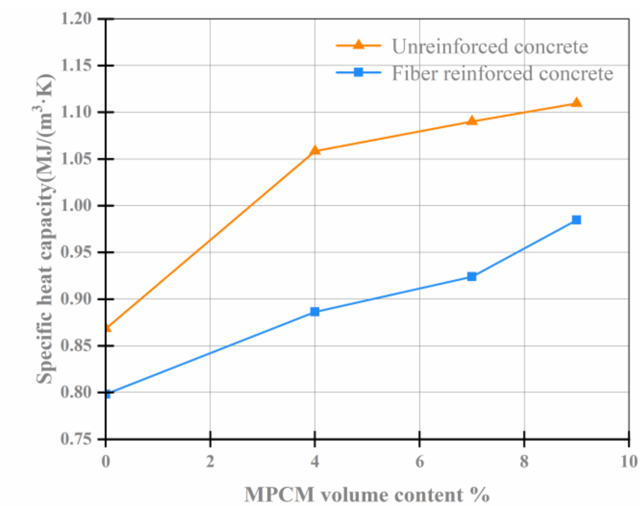

FIGURE 12 SPECIFIC HEAT CAPACITY OF PHASE CHANGE CONCRETE

D. Micromorphology analysis

The images are microscopic views of the samples under a scanning electron microscope. Figure 13 shows the MPCM tightly bonded with the cement matrix. The microcapsules exhibit a spherical appearance with intact walls and good encapsulation. Some microcapsules display noticeable wrinkles, caused by volume shrinkage during the phase transition cycle as the core material changes from a molten to a crystalline state.

In Figure 14, damaged microcapsules of phase change material are observed. The damage may have been caused partly by the compressive testing and partly during the preparation process, though the damage rate is relatively low.

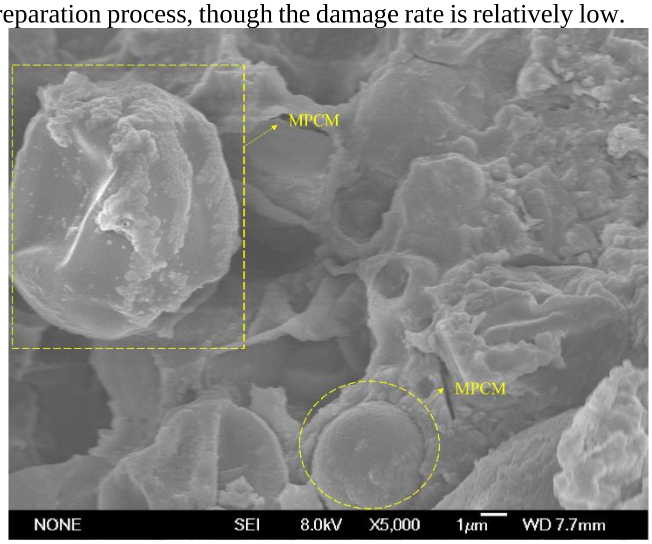

FIGURE 13 MICROSCOPIC IMAGES OF THE MPCM

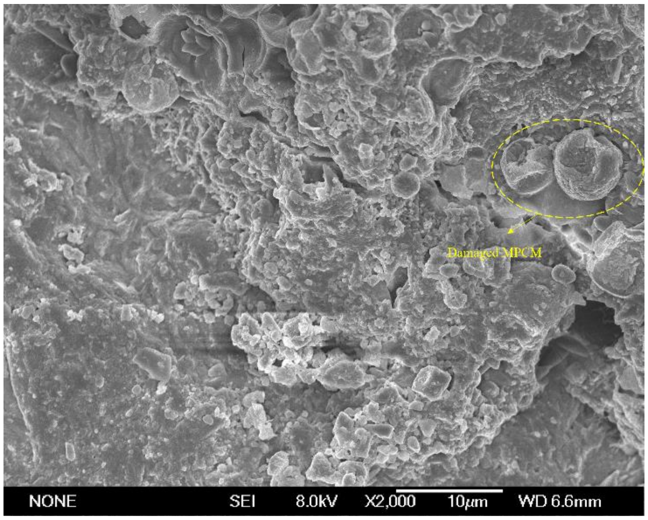

FIGURE 14 MICROSCOPIC IMAGES OF THE DAMAGED MPCM

IV. CONCLUSION

This study examined the impact of microencapsulated phase change materials (MPCM) and hybrid fibers on enhancing concrete performance, providing new insights into the development of sustainable and high-performance building materials that meet the needs of modern infrastructure.

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1. The incorporation of MPCM into concrete reduces its compressive strength. However, when hybrid fibers are added to phase change concrete, both ductility and compressive strength are improved. The addition of MPCM reduces the splitting tensile strength of concrete. In contrast, adding hybrid fibers to phase change concrete increases its ductility and enhances the splitting tensile strength. The improvement in splitting tensile strength due to hybrid fibers is more pronounced than the enhancement in compressive strength. When the level of MPCM is relatively high, the positive effect of hybrid fibers on the mechanical properties of phase change concrete becomes more significant.

2. The inclusion of microencapsulated PCM decreases the thermal conductivity and thermal diffusivity of concrete while increasing its specific heat capacity. The addition of hybrid fibers has minimal influence on thermal conductivity and thermal diffusivity but slightly reduces the specific heat capacity of the phase change concrete.

3. Through micromorphology analysis, the smooth surface of MPCM results in weaker adhesion between MPCM and the cement matrix. Additionally, MPCM undergoes slight volume changes during phase transitions and may break under external forces, releasing phase change materials. These factors collectively contribute to the formation of microcracks and defects within the concrete, thereby reducing its structural strength.

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