Article

Evaluation of Printability and Thermal Properties of 3D Printed Concrete Mixed with Phase Change Materials

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Abstract: Three-dimensional (3D) printed concrete has recently received considerable research attention. In buildings, phase change materials (PCMs) with excellent thermoregulatory properties and thermal storage capacity can improve the insulation capacity of external walls and reduce energy consumption. In this study, microencapsulated paraffin was added to a 3D printable material and a 3D printed phase-change concrete was developed, resulting in good printability and buildability. The compressive and flexural strengths were declined maximally by 44.6% and 37.5%, respectively, with 20 wt% PCM mixed. Results from 3D printed room models proved the thermo-regulated performance by regulating the room temperature when mixed with 20 wt% PCM. With the addition of PCM, 3D printed facilities can have sufficient thermal comfort.

Keywords: 3D concrete printing; phase change concrete; printability; buildability; thermophysical properties

1. Introduction

Three-dimensional printing is an emerging construction technology for building structures by stacking bondable materials layer-by-layer in a computer-planned path. It is now widely used in various fields, such as aerospace, medicine, and chemicals. Three-dimensional concrete printing (3DCP) has gained attention in the last decade [1]. 3DCP is a highly digital technology that allows the principle of “what you see is what you get” unlike the traditional manufacturing technologies. The printable “ink” is the core component in 3DCP. Thus, it is judicious to study concrete, the most widely used building material, as the printing material [2]. For example, the Contour Craft, invented at the University of Southern California in 2003, realized hollow curved walls without a mold. The emergence of 3DCP has promoted the development of moldless, high-precision, and digitalized manufacturing in the construction field. In addition, 3DCP has various advantages, such as saving materials, reducing labor, and shortening the construction period. Over the past two decades, the number of studies using 3DCP in construction has grown exponentially [1].

Compared with traditional material research, 3D printing requires materials to be successfully printed before testing the performance of the final outputs. Lim [3] proposed pumpability, printability, buildability, and open time to evaluate the performance of 3D printable material. Pumpability means the ability of a material to be transmitted through a delivery system, such as a pipe. Printability implies that the material can be extruded in a specific shape from the printhead. Buildability requires that the printing material has sufficient strength to withstand the weight of the upper layers to ensure structural stability. The open time requires printing materials to maintain good workability throughout the printing process. Admixtures, such as thixotropic agents [4] and thickeners [5], can improve the printability and buildability of materials.

3DCP has been used in many applications. For example, Mazhoud [6] added cellulose ether to cement mortar as an anti-scouring admixture to develop underwater 3D printed...
cement mortar, which can be used to construct offshore underwater structures. In addition, printed porous materials can be used for biodiversity research in coastal areas [7]. Mixing construction waste in 3D printing materials has achieved good application results in resource reuse [8], such as mixing desert sand in printing materials, reducing freeze–thaw damage in 3D printed structures while reducing the costs and increasing structural compactness. Printed materials mixed with steel fibers can be used for 3D printed construction of large-scale facilities [5]. They can improve the toughness, interlayer strength, and fire and heat resistance of printed structures [9]. Assaad [10] proved that styrene-butadiene rubber (SBR) is more effective than an air-entraining agent (AEA) in improving the frost resistance of 3DCP structures. Blended SBR or AEA increased the concrete interface strength by 18–34%. They provided a wealth of data for the standard development of frost resistance in 3D printed structures and promoted the application of 3DCP in frigid climates. In summary, combining functional materials with 3DCP can extend the application of the original materials using additive manufacturing techniques.

Concrete structures mixed with phase-change materials (PCMs) exhibit thermal regulation performance in conventional concrete preparation. PCM releases/absorbs energy to exotherm/cool down during a phase change. By mixing PCMs in concrete, a phase-change concrete can be prepared to store a large amount of thermal energy when the ambient temperature rises and release it when the temperature decreases, thereby maintaining the concrete structure within the appropriate temperature range. The application of PCMs can improve the thermal comfort of houses and save energy by releasing the thermal energy (green energy) stored at high temperatures when required (low temperatures). Papadaki [11] estimated the environmental performance of a house model with PCMs using life cycle analysis methodology. He found that PCMs have the advantage of requiring lower energy inputs to maintain a thermally comfortable in-home environment. These energy savings lead to a 57% lower environmental footprint than the reference house during a 25-year life span. Therefore, the importance of PCMs in the field of building energy-saving determines that they have considerable development prospects [12]; and research on PCMs applied to concrete structures has developed rapidly in the past two decades. PCM has been mixed in the cement proportions as aggregates after being encapsulated in the form of steel spheres [13], ceramic granules [14], or microcapsules [15] with variable sizes. Cui et al. [15] introduced the mixing of phase-change microcapsules in concrete and achieved excellent temperature regulation ability in room model experiments.

Few studies combining 3DCP with PCMs have been conducted. Yang [16] used finite element simulation analysis to verify that incorporating shape-stabilized PCM (SSPCM) in 3D printed concrete could improve the thermal performance of printed building facades and significantly reduce the building energy consumption. However, this study only included a simulation analysis and lacked printing tests. In addition, studies incorporating PCM materials directly into concrete printing materials have not yet been reported. Combined with the advantages of energy-efficient and moldless 3D printing technology, 3D printed phase change concrete has excellent research value and application prospects. As a green material, the application of PCM in 3D printed buildings can further enhance the environmental potential of 3DP. Additionally, the combination of 3D printing technology and PCM is an attempt to achieve a low carbon footprint for the entire lifespan of the structure, i.e., from construction to service, which is also in line with the significant energy strategy of carbon neutrality in China.

This study utilized a laboratory-scale 3D concrete printer for the PCM concrete printing experiments. New characterization methodologies are proposed to quantify the printability and buildability of 3D printable material. PCM was introduced in the 3D printing technology to reveal its influence on printable materials, including the mechanical properties and thermal regulation performance of 3D printed results, by mixing 10% and 20% PCM into a developed printable material.
2. Materials and Devices

2.1. Materials

The printable cementitious mixture used in this study was previously developed in our laboratory, as listed in Table 1, with Ordinary Portland Cement (OPC) (42.5 R, purchased from Foshan, China) as the basic material. Glass beads (GB) with mean particle size of 60–250 µm and density of 0.60 g/cm³ were used to increase the compressive strength as fine aggregates, lower the density of the final product compared to that of fine sand, and increase the extrusion efficiency because of their smooth appearance, instead of fine sands. Admixtures of fly ash (FA) with a fineness of 43 µm, density of 2.7 g/cm³, the specific surface area of 0.36 m²/g, and water content of 0.5%, and silica fume (SF) with a density of 2.2 g/m³, the average particle size of 0.1–0.3 µm, and specific surface area of 20–28 m²/g were chosen to improve the workability of the mortar. Polycarboxylic acid superplasticizer was chosen as the high range water reducing agent (HRWR). Hydroxypropyl methylcellulose (HPMC) was chosen as the thickening water-retaining agent to improve the printability of the paste by improving its viscosity. A plasticizer was used as the plastic agent (PA) to improve the plasticity of the fresh paste. Lithium carbonate was used as an accelerator (AR) to accelerate hydration. Magnesium aluminum silicate (MgAl₂(SiO₃)₄) was chosen as the thixotropic agent (TA) to increase the fluidity of the paste during extrusion. In addition, a defoaming agent (DFA) was used to decrease the air bubbles generated during the mixing and extrusion processes.

Table 1. Mix proportions of the printable MPCM (unit: gram).

|   | Water | OPC | GB | MPCM | FA | SF | HRWR | PA | AR | HPMC | TA | DFA |
|---|-------|-----|----|------|----|----|------|----|----|------|----|-----|
| MIX-00 | 1680 | 4000 | 800 | 0 | 588 | 212 | 8 | 40 | 30 | 12 | 60 | 2 |
| MIX-10 | 2400 | 4000 | 800 | 400 | 588 | 212 | 8 | 40 | 30 | 12 | 60 | 2 |
| MIX-20 | 2880 | 4000 | 800 | 800 | 588 | 212 | 8 | 40 | 30 | 12 | 60 | 2 |

OPC: Ordinary Portland Cement; GB: glass beads; MPCM: micro-capsuled phase change materials; FA: fly ash; SA: silica fume; HRWR: high range water reducing agent; PA: plastic agent; AR: accelerator; HPMC: hydroxypropyl methylcellulose; TA: thixotropic agent; DFA: defoaming agent.

Large aggregates cannot be extruded through the printing nozzle. The PCM, purchased from Shanghai, was made of paraffin wax encapsulated with microcapsules (poly-methyl methacrylate), namely micro-capsuled PCM (MPCM), as the sample image shown in Figure 1a. The differential scanning calorimetry (DSC) tests were conducted on MPCM over a temperature range of 0–60 °C under nitrogen at a flow rate of 40 mL/min and a heating/cooling rate of 2 °C/min. The results are shown in Figure 1b.

Figure 1. MPCM: (a) MPCM sample and SEM image, the microcapsules shrinking due to vacuum operation before SEM tests and (b) DSC curve of the MPCM.
- Phase change temperature: 23.6 °C.
- True density: 0.8 × 10^3 kg/m³.
- Particle size: 2–10 µm.
- Latent heat value: 133.84 J/g.

Three mix proportions were used based on mix percentages of 0, 10, and 20 wt%, named MIX-00, MIX-10, and MIX-20, respectively, as listed in Table 1. The water–cement ratios were 0.42, 0.60, and 0.72, for MIX-00, MIX-10, and MIX-20, respectively, to balance the workability and printability of the mixtures because the MPCM absorbs free water owing to its small particle size and large specific surface area.

2.2. The 3D Concrete Printing System

A gantry-type 3D printer, as shown in Figure 2a, was designed and built using an open-source 3D printing control motherboard with a mechanical accuracy of 0.1 mm in three alignments of X-, Y-, and Z-axes. The printer had a maximum movement speed of 100 mm/s in the XY-plane, with a maximum printing size of 60 × 60 × 1000 cm. The resolution of the motion system was 0.1 mm, which is acceptable for concrete printing operations. The printer control unit was based on the RepRap open-source project, ensuring precise motion positioning and stable execution for a smooth printing process. As shown in Figure 2b, the printing head involves a material storage bin and printing nozzle. The material bin is commonly V-shaped. It worked as a material cache/buffer. It commonly stores 1–3 kg of mixed material, and feeds the extruder to maintain continuous printing, with a large screw blade to feed the material into the extruding nozzle. The small nozzle screw extruded the material from the nozzle tip. The gantry-type motion system carries the nozzle moving in 3D dimensions to fulfill the “print” fabrication with the printable material.

![Figure 2](image-url)  
**Figure 2.** The 3D concrete printer; (a) gantry-type printing device; (b) extruding nozzle design.

3. Experimental Program

3.1. Basic Testing Methodologies

The fluidity of fresh mortar was evaluated using a flow table test according to ASTM C230. Because there were interfaces among the printed layers [17], the microstructure of the interfaces was observed using SEM. Software ImageJ.exe was used to measure the layer height with accurate digital image processing referencing the real ruler similar to the image.
3.2. Printability

In this study, printability was the first essential parameter to guarantee printing success. The fresh cement was manipulated in a three-dimensional space over X-, Y-, and Z-axes and the printing nozzle. The nozzle fulfills this printing operation with material extruding and 3D movements. The moving speed exhibits acceleration and deceleration at the starting and ending points of one printing segment. Extrusion speed requires the fabrication of a filament with a consistent width and height. Thus, printability should involve two conditions: extrudability and layout ability.

Extrudability is the controlability of the extrusion; the cement extruding speed \( v_e \) (gram per second, g/s) should have a stable corresponding function \( f \) to the motor rotating speed \( v_r \) (rounds per minute, rpm) within the operational time duration, as in Equation (1). In this case, the printer could control the extrusion speed by adjusting the rotation speed of the screw motor, as shown in Figure 2b.

\[
v_e = f(v_r)
\]

A zigzag printing path, as shown in Figure 3a, was designed to obtain \( f \), with the speed configurations. The extruding speed \( v_e \) was measured as the average weight \( m_n \) of the 40 mm long filaments at different rotating speeds; while the moving speed was consistent as \( v_n = 40 \text{ mm/s} \). In each segment, three 40 mm long filaments were cut, weighed, and marked as \( m_{na/b/c} \) as dash-framed in red in Figure 3a. Then, \( m_n = (m_{na} + m_{nb} + m_{nc})/3 \). Eventually, \( v_n \) could be derived from Equation (2) and \( f \) could be obtained from the fitted curve of the discrete dots.

\[
v_e = \frac{m_n}{40/v_n} = \frac{(m_{na} + m_{nb} + m_{nc})/3}{40 \text{ mm}/(40 \text{ mm/s})} = \frac{m_{na} + m_{nb} + m_{nc}}{3 s |v_n}
\]

Figure 3. Zigzag paths for printability characterization: (a) extrudability test (the cutting tool had two blades fixed at a distance of 40 mm to guarantee the precision cutting operation; red dotted line in the figure indicates the interception position and spacing of the 40 mm long filaments); (b) layout ability test.

The layout ability indicates that the printed filaments have no distinct discontinuity, crack, or fracture under a certain extrusion speed \( v_e \) and nozzle moving speed \( v \). In a printing process, if \( v_e \) is fixed, then, the higher the \( v \), the more likely the failure of the printed filament is; and if \( v \) is fixed, the lower the \( v_e \), the more likely the printing failure is. Thus, there must be a minimum speed ratio \( r_{min} \).

\[
r_{min} = \frac{v_e}{v}
\]
The unit of \( r_{\text{min}} \) was determined as g/cm, meaning that the material weight was distributed on one unit of length. The printing configuration should be larger than the \( r_{\text{min}} \).

The layout ability was observed under different moving speeds and consistent extrusion speeds, and a slower moving speed was found to calculate the \( r_{\text{min}} \). This is similar to other studies, where researchers assessed printability by examining blockages, discontinuities, and other apparent failures qualitatively and visually [18,19].

### 3.3. Buildability Tests

Buildability defines the geometry-keeping/layer-stacking ability, which is the second essential parameter in this study. The extruded filaments should have a fast setting and sufficient green strength to bear their self-weight and weight of the upper layers and low slump to maintain their designed geometry (by the nozzle tip). Unfortunately, to date, there is no uniform and reliable method to evaluate buildability. Most studies evaluated buildability based on the number of layers printed or the height achieved in a single printing process without failure [20–23]. Ma and Li [24] determined the factor as the ratio of vertical deformation of the 20 stacked layers to the optimal height. Arunothayan et al. [5] defined good buildability as no vertical distortion, layer failure, or excessive deformation in the lower layers in a seven-layer printing test. Rahul and Santhanam [25] evaluated buildability by measuring the height reduction in the bottom layer in a two-layer printed specimen.

However, material slump cannot be avoided because material hardening is a progressive hydration process. To achieve good buildability, Wolfs et al. [26] suggested the use of printing materials with a low-to-zero slump. The material slumping property is significant for printing success. Therefore, the testing methodology for the slump of the extruded filaments is essential because it is not suitable to use the traditional slump test, which is conducted on a large amount of mixed material, approximately 10 kg in weight and 300 mm in height.

As shown in Figure 4a,b, 14 layers were printed to evaluate the overall height reduction. Each layer was 5 mm high and 150 mm long. The total height \( h \) was measured 20 min after the printing was completed. Height reduction ratio (HRR)

\[
\text{HRR} = \frac{(H - h)}{H}
\]

where \( h \) is the measured height and \( H \) is the designed height. Thus, it is clear that the smaller HRR value means better buildability.

![Figure 4. Buildability tests: (a) illustrations of HRR and height accumulation and (b) actual buildability test.](image)

A frame with dimensions 200 (Length) \( \times \) 200 (Width) \( \times \) 200 mm (Height), which was the same size as the room models, was designed to characterize the buildability of the three mixtures. The height of each layer was measured, and the cumulative height was plotted.
Additionally, the better the fitted linear line, the better the buildability, which means that the layer height is distributed evenly for all layers. Let \( h \) be the designed layer height, and \( h_n \) stands for the actual layer height. Then the total layer-height error can be:

\[
h_{\text{error}} = \frac{\sum |h_n - h|}{n}
\]

Then, the lower of the \( h_{\text{error}} \), the better the buildability.

3.4. Mechanical Experiments

Beams with dimensions 240 mm × 50 mm × 50 mm were printed in a 100% zigzag filling mode, as shown in Figure 5, cured at room temperature and 100% humidity for 28 d, and cut and milled to dimensions 40 × 40 × 160 mm. Three-point bending and compressive tests were conducted to obtain flexural and compressive strengths in the three mixtures, with loading along the Z-axis. The control samples were cast directly with dimensions 40 × 40 × 160 mm. Each group had six samples prepared for casting and printing the three mixtures.

![Figure 5. Illustration of the 3D printed beams for flexural strength tests.](image)

3.5. Thermal Performance

Thermal regulation performance was tested to determine the feasibility of 3D printed phase change concrete in building construction applications. Thermal conductivity, which is one of the most important thermophysical properties, determines the energy storage capacity of a material. Therefore, the thermal conductivity of three 3D printed phase change concrete needs to be tested to verify if it can be used as an insulating energy storage material. Specimens, 3 cm in diameter and 2 cm in height, were made for each group of materials. The thermal conductivity of the materials was tested using a TC-3000 thermal conductivity measuring instrument (Xi’an, China) based on the transient hot-wire method. Because the printing process fabricated a layer-wise structure, the printed specimens for the thermal conductivity tests were directly cut from the printed room models, as illustrated in Figure 6.

Three room models were printed with mixers MIX-00, MIX-10, and MIX-20, as illustrated in Figure 7a, with dimensions 235 × 235 × 210 mm, as shown in Figure 7b. Each room model was set up with a polystyrene board door with dimensions 50 × 100 × 15 mm and thermal conductivity of 0.0337 W/m·K. The joints of the components were sealed with waterproof glue and the surface of the room model was covered with waterproof paint to ensure the airtightness of the interior of the house. The spacing between the room models was 500 mm, with the doors facing south. As shown in Figure 7c, a temperature logger collected the temperature data. One K-type thermocouple was placed at the center of each room model. A wooden stick (as shown in orange in Figure 7b) ensured that the sensor
was located at the center of the room model. The wires passed through the gap between the door and room composite.

![Figure 6](image)

**Figure 6.** Thermal conductivity tests: (a) CAD sketch of the printed room; (b) testing specimen from the room model; (c) printed specimen tested with TC-3000; and (d) cast specimen tested with TC-3000.

![Figure 7](image)

**Figure 7.** CAD of the room model for the thermoregulation test: (a) size of the room model, (b) finished room model and the inner thermal sensor, and (c) the temperature logger TOPRIE-TP700 and the outer thermal sensor.

### 4. Results and Discussion

#### 4.1. Fresh Properties

The fluidities of the three mixtures are listed in Table 2. All were in the acceptable range for smooth printing, as concluded by Tay and Qian [27]. MIX-10 achieved a fluidity of 160 mm, which was higher than that of MIX-20 (130 mm) and MIX-0 (125 mm). The water–cement ratio of MIX-20 was increased to 0.60. However, the fluidity was lower than that of MIX-10 because the MPCM particles can absorb free water owing to their high specific surface area and small particle size and density (as listed in Section 2.1).
Table 2. Fluidity test results.

| Mixture   | MIX-0 | MIX-10 | MIX-20 |
|-----------|-------|--------|--------|
| MPCM ratio| 0%    | 10%    | 20%    |
| Water–cement ratio | 0.35  | 0.50   | 0.60   |
| Fluid diameter (mm) | 125   | 160    | 130    |

4.2. Printability

Extrudability: The printed zigzag is shown in Figure 8a at different rotating and moving speeds. According to Equation (2), the rotating speed and material extrusion speed are plotted in Figure 8b. All three mixtures had linear relationships, proving a stable extruding ability and consistent with the research [28], where there was a linear relationship between the nozzle traveling speed (mm/s) and the material extrusion speed (mL/s).

![Figure 8a](image1.png)

![Figure 8b](image2.png)

![Figure 8c](image3.png)

![Figure 8d](image4.png)

Figure 8. Tests and results of extrudability and layout ability: (a) extrudability test, (b) graphed data of the rotating speed vs. extruding speed, (c) layout ability test, and (d) high-definition image of the layout ability test.

Layout ability: as shown in the images in Figure 8c,d, the extruded filaments had non-consistent width, and fracture owing to the lack of material extruded in the first three segments and had smoother morphology when the extruding speed reached 7.2 g/s, at the fourth segment. The lowest material distribution obtained was 2.4 g/cm, according to Equation (3). Therefore, the printing operation should configure at least 2.4 g/cm material distribution to guarantee smooth printing. Lowering the material distribution causes fractures, significant gaps in the printed outputs, and printing failures. Additionally, the extrusion operation was tested for 2 h by refilling the extruded material into the
printing nozzle. The extruding speed had no significant change (less than 1%) in the data immediately after the material was mixed.

These findings indicate that the materials (MIX-0/10/20) had good printability and that the MPCM did not diminish their printability. It can be explained that the MPCM particles were spherical and did not affect the fluidity and viscosity; further studies regarding rheology are worth conducting.

Compared to [28], where the widths of the extruded filament were measured to characterize printing consistency, we chose weight per second as the parameter for extrusion speed. Two conditions guaranteed the weight measurements. First was the cutting tool, which had two wallpaper blades fixed in parallel on a 40 mm steel plate, and each cutting operation could obtain 40 mm of filament precisely. The second was that the cutting position should be in the middle of a filament line. The moving speed was stable because it was accelerated and decelerated at two points on one segment.

4.3. Buildability

The HRR data were 0.01, 0.00, and 0.00 for MIX-0, MIX-10, and MIX-20, respectively, 20 min after printing, indicating that the overall height of the printed output barely had any slump. The $h_{\text{error}}$ data were 0.30, 0.38, and 0.34 mm for MIX-0, MIX-10, and MIX-20, respectively. Figure 9b shows the accumulated heights of the stacked layers in the three mixtures shown in Figure 9a. All three sets of data showed good linearity, with similar data of slope and $R^2$. This means that all layers had a consistent height. No slumping occurred in the lower layers under the load, which was the self-weight and weight from the upper layers. All three mixtures exhibited the same phenomenon. The HRR, $h_{\text{error}}$ data, and accumulated height data proved that the printed outputs had a low-to-zero slump in each layer and integral outputs. The addition of MPCM did not diminish the buildability of the origin mixture. Thus, it was promising to print a room model to study the thermal regulation capability further.

![Figure 9](image-url)

**Figure 9.** Buildability tests: (a) printed frame for layer accumulating test of MIX-0 and (b) the graphed data of the accumulated layer height of MIX-0/10/20.

Buildability defines the geometry-keeping ability. The extruded filaments should have a fast setting and sufficient green strength to bear self-weight and weight from the upper layers and a low slump to maintain their designed (by the nozzle tip) geometry. HPMC and MPCM increased the viscosity and yield stress of the fresh cement and minimized the material slump to approximately zero. Both high yield stress [29] and a low slump [26] increase the printability of the mixture. Furthermore, MPCM remarkably decreases the material density, which could help improve the printability, according to [30].
4.4. Microscopic Characterization

The SEM results show that the MPCM particles were small balls surrounded by cement, as indicated by the red circles in Figure 10a,b. The large balls were the glass beads. There are cracks visible in Figure 10c and microcracks in Figure 10d among the printed interfaces during the layer-stacking operations. Buswell concluded that cracks occurred when the layer was stacked after the initial setting time [31] because long time intervals between the layers led to low moisture on the layer surface. Thus, the printing speed should be increased to shorten the time interval. In contrast, the rotating blades in the nozzle stir, cut, shear, and extrude fresh cement. This may have caused tiny interfaces in the mixture.

![Figure 10](image)

**Figure 10.** Printing results under microscopic and mesoscopic observations: (a) SEM of the GB and MPCM in the composite, (b) high-definition image of the MPCM particle, (c) visible gaps in yellow circles, and (d) micro gaps.

4.5. Mechanical Properties

The compressive and flexural strengths are graphed in Figure 11a,b, respectively. The compressive strength of the printed samples decreased as the MPCM content increased, by declining ratios of 23.9% and 43.6% and flexural strengths of 4.3% and 39.1% for MIX-10 and MIX-20 to MIX-0, respectively. Consistent with the other printing studies [32,33], all the testing results of the printed samples were lower than those of the cast samples. The interfaces and cracks among the printed cement are the first reason. The vibrating compaction helped the cast sample become denser than the printed ones.

There were interfaces between the stacked composite layers, which are the weaknesses of the printed structure [34]. The bonding of the interfaces was the weakness zone [34] or worse contact [35] and is significant to the final mechanical properties [17]. Furthermore, the better the bonding, the better are the mechanical properties. As mentioned in Section 3.4, a quick printing speed would shorten the time interval and obtain better bonding strength [36]. Contrarily, the compressive and flexural strengths of the specimens decreased significantly using MPCM [37] owing to the weak bonding between the MPCM particles and cement or MPCM leakage [38]. The compressive strength dropped by 18.5% for cast MIX10-C compared with cast MIX0-C; and the printed MIX0-P was 13.3% less than the cast MIX-0; comprehensively, 10% of MPCM and printing methods reduced the compressive strength of MIX10-P by 33.8% from MIX0-C. This phenomenon shows that MPCM decreased the compressive strength more effectively than the printing methods used in this study. Fiber like short steel fibers [39] or basalt fibers [40] can enhance mechanical properties, both for casting and printing. Concrete slurry [41] can be used to glue the adjacent layers. Additionally, it is possible to optimize the printing speed and toolpath [42] to increase the fabrication time.
4.6. Thermophysical Properties of Cement/MPCM Composites

The phase-changing material can absorb the heat; thus, reducing the heat transfer efficiency. Figure 12 shows the thermal conductivity of the cement with and without the PCM. The thermal conductivities of the MIX-10 and MIX-20 series decreased with increasing MPCM content. Specifically, the thermal conductivity of the composite decreased from MIX0-C to MIX10-C and MIX20-C, by 24.2% and 31.7% with the addition of 10 wt% and 20 wt% PCM, respectively, when the samples were prepared by casting. For printed samples from MIX0-P to MIX10-P and MIX20-P, MPCM decreased the thermal conductivity by 24.5% and 24.6%, respectively.

The interfaces between the printed strips were the worse contact [35] and slightly decreased the thermal conductivity by approximately 8% for MIX-0 and MIX-10. There was a slightly higher value (1.6%) for printing than for casting in MIX-20. This was the data variation, which proves that the interface contributed less to the effect of the large volume of MPCM.

The average results of the three groups were consistent with those by Qian et al. [46] and Ricklefs [47]. The decrease in the thermal conductivity can be attributed to the following reasons. Compared with the cement paste, the thermal conductivity of MPCM is approximately only 0.21 W/m·K in solid state and 0.15 W/m·K in the liquid state [48], which is significantly lower than that of cement composite. In addition, Bao et al. [49] stated that interfacial gaps existed between the MPCM particles and cement paste, which could improve the thermal resistance of the cement matrix, resulting in insufficient thermal conductivity of the cement/MPCM composite. Furthermore, Djamai et al. [50] confirmed that the introduction of MPCM increased the porosity of the cement paste, thereby decreasing the thermal conductivity.
Figure 12. Results of thermal conductivity (experimental temperature 301 K).

The MPCM reduces the heat transfer efficiency of the buildings, thereby improving the thermal comfort in the buildings by stopping the heat gathering indoors during summer and stopping the heat dispersing to the outside of the buildings during winter. However, as discussed earlier, the aim of incorporating MPCM is its heat storage function.

The thermo-regulated performance of cement composites with or without MPCM can be evaluated according to the indoor temperature differences among the room models (as shown in Figure 13a). As shown in Figure 13b, the indoor temperature of the MPCM room models showed a small temperature fluctuation, which became smaller with an increase in the MPCM content. The maximum indoor temperature could be increased up to 43.8 °C for the reference room (MIX-00), while the temperatures were lowered to 37.4 and 35.3 °C when 10 and 20 wt% MPCM were incorporated. Compared with the reference room, the highest indoor temperature in the MPCM room decreased by 6 and 8 °C for 10 and 20 wt% MPCM, respectively. In addition, it is noteworthy that the indoor temperature curve of the MPCM room was delayed, especially for the room with 20 wt% MPCM (MIX-20). This is because the MPCM functions as heat insulation, effectively blocking the heat exchange between the indoor and outdoor environments. Simultaneously, it can also be regarded as a thermal storage battery unit for absorbing and releasing heat based on the demands of the indoor environment. The aforementioned results indicate that the application of MPCM to buildings can play the role of “peak cutting and valley filling” and delay the temperature rise, thereby reducing the building energy consumption and balancing the grid loading.

Studies show that compared with the reference room, the temperatures of the room with 20 wt% MPCM could only decrease by 6.2 °C [51] and 5.6 °C [49]. In other words, the thermo-regulated performance of 3D printed MPCM walls has the same effect as that of cast production. Therefore, we can conclude that it is feasible to fabricate energy-storage houses using 3D printing technology.
5. Conclusions

In this study, MPCM was added to 3D printed concrete. The printability, material slumping, and buildability were studied, before the mechanical properties and thermal regulation performance. The conclusions are as follows.

1. The MPCM did not diminish the material buildability and printability according to the proposed testing methodologies. The minimum material distribution was 2.4 g/cm.

2. The addition of microencapsulated phase-change material influences the mechanical properties of concrete composites. The compressive strength dropped by 44.6% for printed samples with 20% for samples mixed with MPCM. In addition, the flexural strength decreased by 37.5%. Mechanical enhancements, such as fiber reinforcement should be investigated in future studies.

3. The internal temperature of the MIX-0 fluctuated considerably, and the maximum temperature exceeded the ambient temperature by approximately 15 °C. The mixed MPCM flattened the temperature curve, and the maximum temperature difference between the peak indoor temperature of the room model with MIX-20 and peak indoor temperature of the room model with MIX-00 reached 8 °C. The printed room model with MPCM had a better thermal regulation capability.

4. With the addition of PCM, 3D printed facilities can have sufficient thermal comfort. Furthermore, the thermal insulation treatment of the building can be simplified, especially for temporary facilities handling emergencies, such as shelters or isolation wards during the COVID-19 epidemic.

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