

Enhancing heat transfer in concrete thermal energy storage using TPMS fins: Experimental and numerical study

Liuhui Tu, Guillermo A. Narsilio, Tuan Nguyen¹

Department of Infrastructure Engineering, The University of Melbourne, VIC 3010, Australia

Abstract

Concrete thermal energy storage (CTES) is a promising technology for large-scale renewable heat storage due to its low cost, durability, and thermal stability. However, the low thermal conductivity of concrete material limits CTES performance, leading to slow charging and discharging and an uneven temperature distribution. This study presents an integrated experimental and numerical investigation for improving the heat transfer efficiency of CTES system through the incorporation of innovative fin designs. Four CTES prototypes were tested, including configurations with Triply Periodic Minimal Surface (TPMS) fins (Primitive and Gyroid topologies). Thermal cycling tests were conducted at temperatures up to 300 °C, and a coupled thermo-mechanical numerical model was developed and validated against experimental observations. The model accurately captured temperature evolution, strain development, and crack formation during repeated charge–discharge cycles. The results highlight that TPMS fins significantly improve temperature uniformity and reduce local thermal gradients compared to the conventional CTES configuration without fins. Specifically, the average temperature of the TPMS-enhanced sample increased by 25.9% relative to the control specimen, demonstrating a substantial enhancement in heat transfer performance. Despite the development of surface cracking, the thermal performance over five charge–discharge cycles remained stable, attributed to the heat transfer pathway and radiative heat transfer across crack interfaces. The findings demonstrate the potential of TPMS fin structures to improve the efficiency and durability of CTES systems, providing a practical pathway for advancing sustainable and cost-effective thermal energy storage technologies for renewable energy applications.

Keywords

Concrete thermal energy storage (CTES); Heat transfer enhancement; Triply Periodic Minimal Surface (TPMS) fin; Numerical modelling; Coupled thermal-mechanical simulation

¹ Corresponding author. E-mail address: tuan.nguyen@unimelb.edu.au (Tuan Nguyen).

1. Introduction

Renewable energy sources such as solar and wind play a pivotal role in reducing carbon emissions and achieving Net Zero targets by 2050. However, their intermittent nature results in fluctuations in energy supply, thereby intensifying the need for reliable energy storage systems [1]. Thermal Energy Storage (TES) technologies enable the capture and retention of heat from renewable sources for subsequent use in residential, industrial, and concentrated solar power applications [2, 3]. TES can be categorised into three main types based on the storage mechanism: Sensible Heat Thermal Energy Storage (SHTES), Latent Heat Thermal Energy Storage (LHTES) and Thermochemical Thermal Energy Storage. Extensive research has been performed to investigate the performance of LTES systems in the literature [4, 5]. While LTES has a relatively higher storage density, LTES systems face challenges of poor thermal conductivity and high-cost nature of phase change materials [6-8].

Considering the challenges of LTES system, STES systems have been investigated in the field of renewable energy storage due to their favourable economics and relative simplicity [9-11]. Among various TES materials, concrete has emerged as a promising medium for sensible heat storage, with early investigations dating back to 2004 [12]. A typical concrete thermal energy storage (CTES) system consists of concrete matrix as sensible storage media and a number of pipes acting as heat exchangers (Figure 1) [13]. In recent years, research on CTES has gained considerable momentum, driven by the global imperative for a sustainable energy transition [14, 15]. A notable commercial implementation includes EnergyNest [16], which employ a propriety concrete storage system to convert and retain renewable energy as high-temperature heat. Concrete offers several advantages because it is cost-effective, non-toxic, non-flammable, easy to cast, and thermally stable at operating temperatures up to 400 °C [17]. However, many studies have concluded that efficient heat transfer is essential for optimising energy storage and retrieval in CTES, as it directly influences heating charge/discharge times, thermal efficiency, and overall system performance. To this end, researchers have extensively investigated various concrete mixtures to improve the thermal conductivity and heat capacity of concrete in the literature [14, 15]. Siliceous aggregates [18], steel fibre [19], supplementary cementitious materials [20], and phase change materials [21-23] can be used to increase the thermal properties and stability of concrete at room and elevated temperatures. In general, the literature reveals that optimal concrete mixtures could achieve the thermal conductivity of 2.0-2.5W/(m·K) and heat capacity of 3.0-3.2 MJ/(m³·K) [24]. A thorough literature review on the thermal properties of concrete for CTES applications can be found in Wang et al. [14].

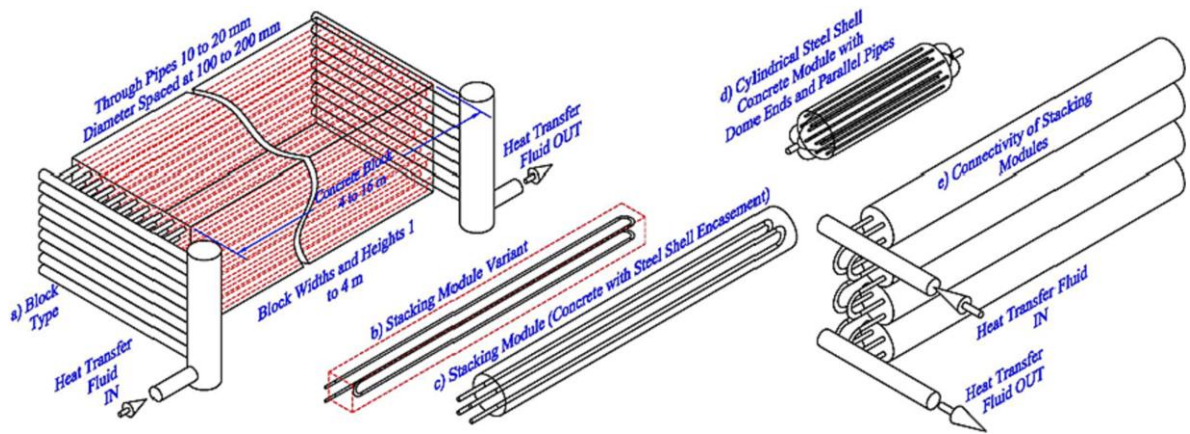


Figure 1 An example of CTES system from the literature, showing concrete storage medium and a number of pipes as heat exchanger [14]

While improving the intrinsic thermal properties of concrete can enhance CTES performance, the extent of this improvement is often limited. In this context, Liu and Nguyen [25] recently conducted a comparative study using three-dimensional numerical simulations to evaluate the performance of CTES systems incorporating various fin designs. The results demonstrated that incorporating fin design, especially Triply Periodic Minimal Surface (TPMS), could significantly enhance the efficiency of CTES, outperforming strategies that focus solely on improving the intrinsic thermal properties of concrete. In fact, their study showed a CTES system incorporating TPMS design, even with a relatively low concrete thermal conductivity of $1 \text{ W/m}\cdot\text{K}$, significantly outperformed a conventional tube configuration without fins (Figure 1) using concrete with a higher thermal conductivity of $2.0 \text{ W/m}\cdot\text{K}$. This finding confirms the critical role of fin-based design for enhancing CTES performance, which corroborate the findings of a great deal of the previous work in improving the heat transfer efficiency of phase change material using fin design [26–28]. In another study of fin-based design CTES, Prasad and Muthukumar [29] performed a numerical investigation on a 10 MJ CTES system incorporating conventional straight fins and reported reductions in charging time of 35.4% and 41.4% for configurations with four and six fins, respectively. Building on this work, Aswin, Karthik and Muthukumar [30] examined the optimisation of fin geometry, specifically rectangular and trapezoidal shapes, for a 170 MJ CTES prototype. Their results showed that the incorporation of fins reduced charging and discharging times by 36.9–48.1% for rectangular fins and 36.9–45.6% for trapezoidal fins. Liu and Yang [31] developed a numerical model to examine and optimise the thermal behaviour of CTES under various geometrical and operational parameters. They concluded that the geometrical parameters of 22 tubes and 4

straight fins was optimal to maximise the thermal performance of CTES. Skinner et al. [32] conducted experiments to examine the behaviour of concrete subjected to elevated temperatures ranging from 400 to 500 °C. To enhance heat transfer performance, a helical fin configuration was introduced; however, experimental results indicated that this modification led to pronounced crack formation localised around the fin regions [32].

Although the effectiveness of fin designs in enhancing CTES performance has been widely demonstrated in the literature, most studies have been limited to numerical simulations. Therefore, this paper presents an integrated experimental and numerical investigation to evaluate heat transfer enhancement in CTES systems through the use of innovative fin designs. Four CTES configurations are examined, incorporating a conventional straight fin, a tree-branched fin, and two Triply Periodic Minimal Surface (TPMS) fins (Primitive and Gyroid topologies) within a simplified CTES setup. The key contributions of the paper are:

- 1) A comprehensive experimental programme was conducted to systematically evaluate and compare the heat transfer performance of four distinct fin designs for CTES applications.
- 2) Repeated thermal cycling tests were undertaken to assess the impact of thermally induced damage on the thermal performance and durability of CTES specimens.
- 3) A coupled thermal–mechanical numerical model was developed and validated against experimental data, providing a reliable tool to support the future design and optimisation of CTES systems.

The structure of the paper is as follow. Section 2 presents the experimental program. The numerical modelling is developed in Section 3. Sections 4 and 5 presents the experimental and numerical results, respectively. Finally, Section 6 outlines the conclusions of the study.

2. Experimental Program

This section summarises the experimental program undertaken and the rationale behind the design of each specimen, the materials and preparation methods and the overall testing setup. The experimental results are presented in the following section and also used for validation of a detailed coupled numerical model.

2.1 Specimen Design

In CTES systems, heat is transferred between the heat transfer fluid (HTF) and the concrete matrix via embedded pipe networks (Figure 1). To enhance the thermal conductivity of the system, metallic fins are often attached to or integrated with the pipes. These fins increase the effective heat-exchange surface area, thereby accelerating both charging and discharging processes. As illustrated in Figure 2a, heat transfer in fin-enhanced CTES systems occurs simultaneously through the embedded pipes and the attached fins. To reduce experimental complexity while preserving the essential thermal characteristics of the system, an elementary section of the CTES module was developed for this study. A section of the full-scale module, comprising a segment of the pipe, fin, and surrounding concrete, was selected, wherein the HTF was substituted with a direct heat source applied to the pipe surface (Figure 2b). Leveraging both geometric and thermal symmetry of the fin and concrete domains, the model was further reduced to a quarter-section configuration for experimental testing (Figure 2c). To facilitate the fabrication of the CTES specimen for testing, the cylindrical geometry is finally employed as shown in Figure 2c. This strategic simplification enabled the fabrication and testing of a smaller, more manageable CTES unit, significantly reducing material usage and fabrication effort while maintaining a consistent heat transfer pathway.

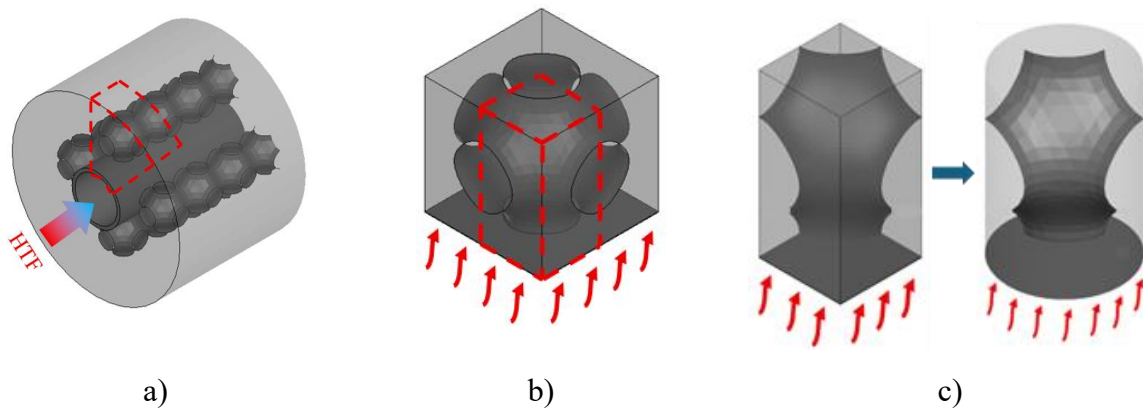


Figure 2 The simplification of elementary section in this study: a) A CTES unit with fins; b) A section of CTES unit with heat applied directly to the pipe; and c) A simplified, symmetric structure to examine CTES performance

In this study, various fin configurations were employed and compared to a CTES sample without fin design (C-0). The fin configurations include a standard normal fin (C-N), a tree-branched fin structure (C-T); and two types of TPMS fins (C-TP/C-TG). Figure 3 illustrates the geometry and dimension of the C-T, C-TP and C-TG fins in this study. Readers are

encouraged to refer to our previous study [25] for the details on the geometry of the tree-branched fin and TPMS fins.

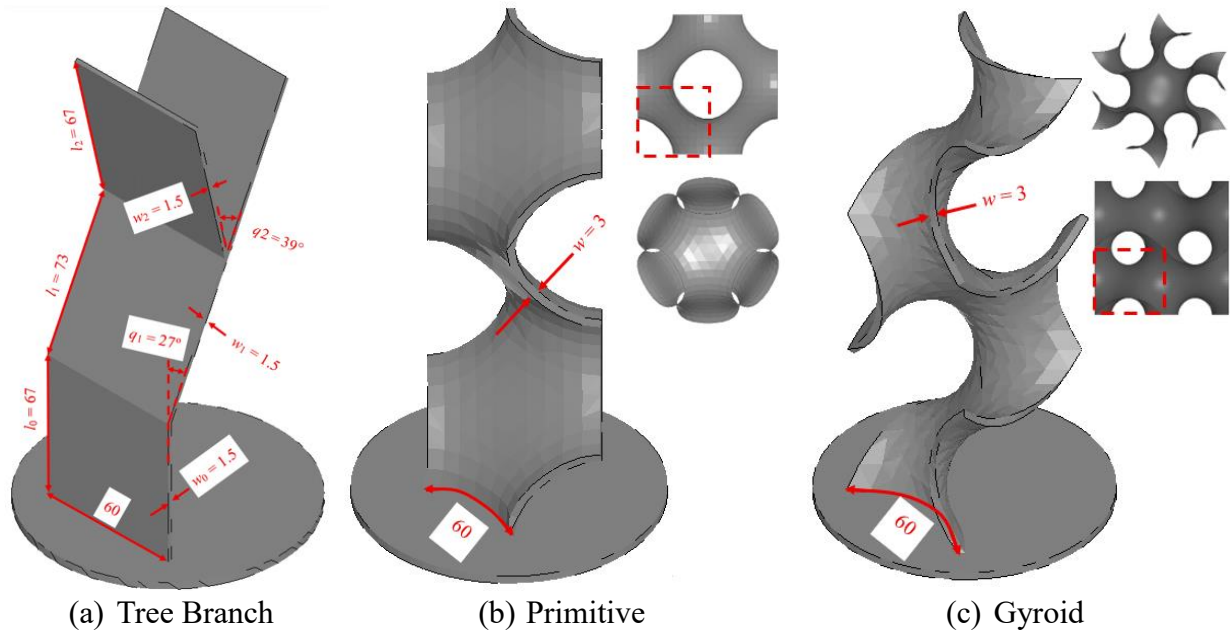


Figure 3 The geometry and dimension (in mm) of tree-branched fin (C-T) and TPMS fins (C-TP and C-TG)

2.2 Specimen Preparation

In this study, an AlSi10Mg alloy has been used via 3D printing technology (selective laser melting) to fabricate the TPMS fins due to their complex geometry. The same material and method were used for the normal fin (C-N) and tree-branched fin (C-T) to assure the consistency and comparability. The AlSi10Mg alloy material is commonly utilised in die-castings that necessitate high corrosion resistance, strong performance at elevated temperatures, and resistance to hot cracking [33]. The melting point is approximately 570-590 °C due to the presence of about 10% silicon and trace amounts of magnesium [34], which is sufficient for the current temperature range of CTES applications. The relative thermal expansion ($\Delta l/l_0$) of the 3D-printed Al alloy was measured along the three principal orientations (x, y, and z) relative to the build platform using a Dilatometer DL801. As shown in Figure 4, all directions exhibited a nearly linear increase in expansion with temperature up to 300 °C. The calculated average coefficients of thermal expansion were $\alpha_x = 2.27 \times 10^{-5}/K$, $\alpha_y = 2.19 \times 10^{-5}/K$, and $\alpha_z = 1.97 \times 10^{-5}/K$. Using a Hot Disk TPS2500, the measured thermal conductivity values at ambient temperature were 94.50 W/(m·K), with a corresponding volumetric heat capacity of 2.00 MJ/(m³·K). These properties of the 3D-printed Al alloy were used in the numerical

simulation in this study. Figure 5 shows the 3D printed fins in this study. The fins have an overall height of 200 mm and a base diameter of 100 mm.

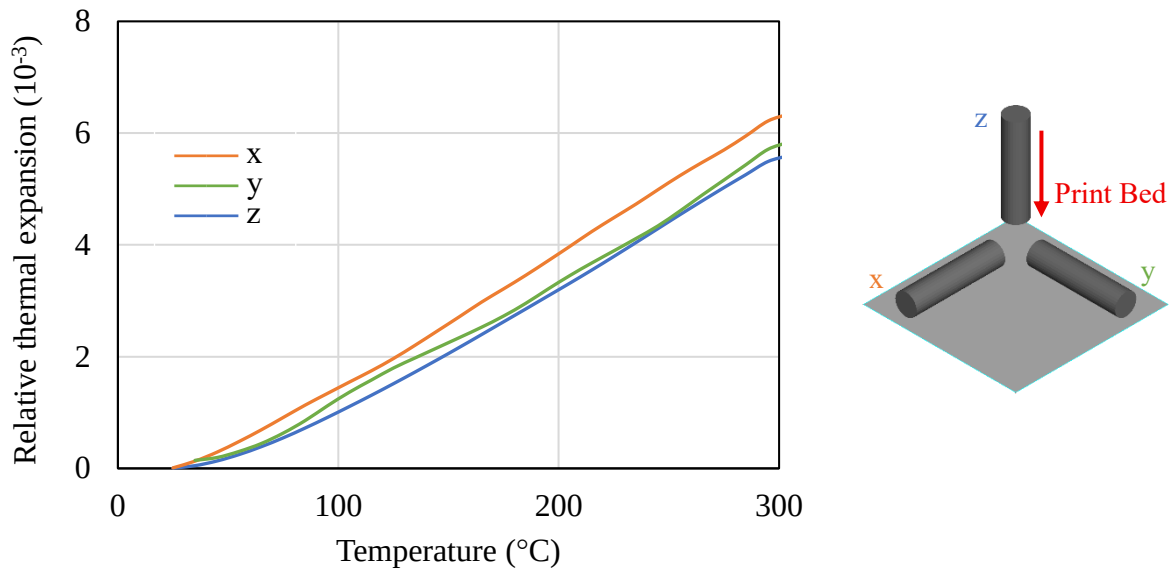
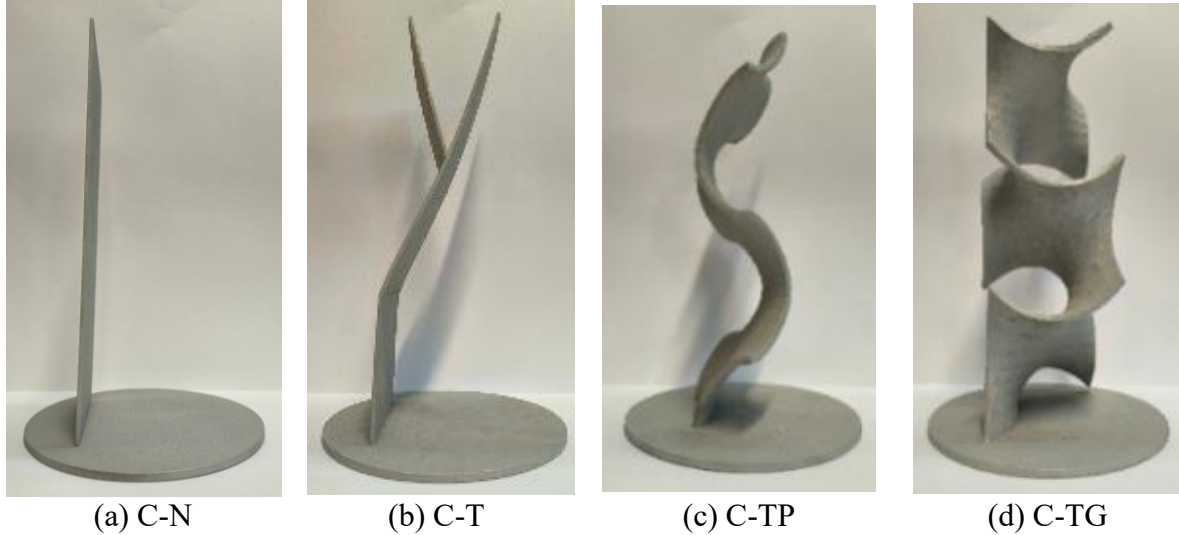


Figure 4 Relative thermal expansion ($\Delta l/l_0$) of 3D printed Al alloy used for the fin fabrication in this study



(a) C-N (b) C-T (c) C-TP (d) C-TG
Figure 5 The 3D-printed fins for enhancing the CTES performance in this study

The concrete material used in this study was a normal concrete mixture using locally available cement, sand, and aggregate with the compressive strength of 46 MPa. The ingredients were mixed for five minutes to ensure homogeneity before casting into 100 x 200 mm cylindrical moulds with embedded fins. Extra concrete samples were cast for measuring the thermal properties using the Hot Disk TPS 2500. In this study, the thermal conductivity and volumetric heat capacity of concrete are 1.95 W/(m·K) and 1.90 MJ/(m³·K), respectively.

2.3 Test Setup

Figure 6a illustrates the setup and sensor configuration used in the experimental testing. Each cylindrical concrete specimen ($\Phi 100 \text{ mm} \times 200 \text{ mm}$) was placed on a steel base plate ($\Phi 110 \text{ mm} \times 5 \text{ mm}$) that was heated using a hot plate equipment to provide a uniform bottom heat source. Initially, the specimens were placed on top of the hot plate, which was set to 100°C for 10 minutes, then to 200°C for another 10 minutes, and finally to 300°C . After thermally charging for 180 min, the hot plate was turned off, allowing the module to cool naturally for 120 min through natural convection. The testing temperature regime is presented in Figure 6b.

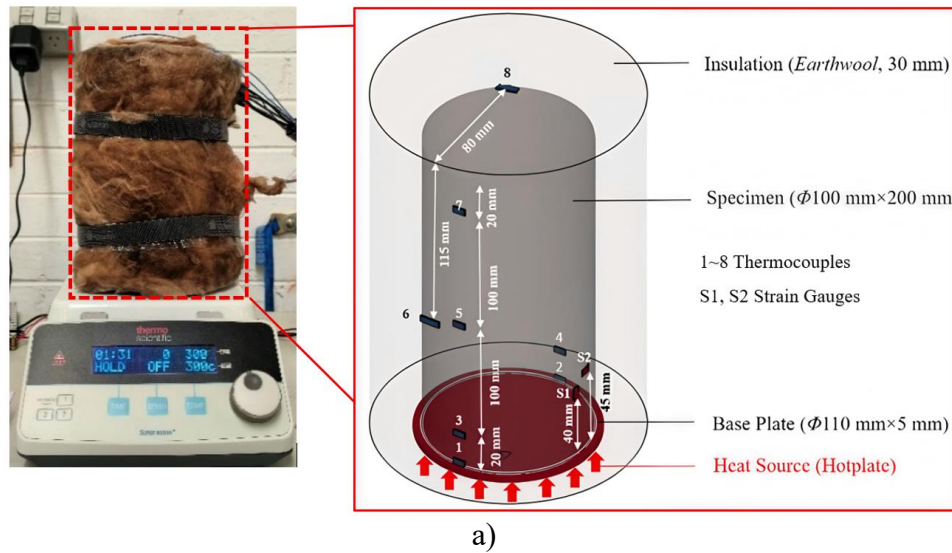
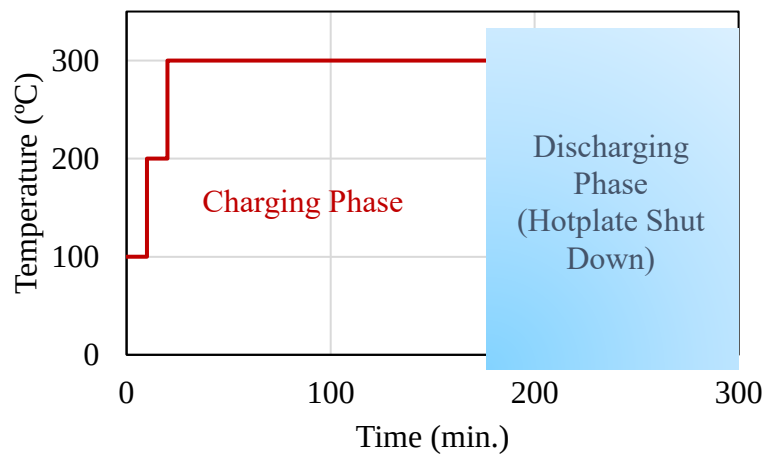


Figure 6 a) The test setup and temperature and strain sensor placement in the CTES experiment; b) The thermal charging and discharging phase

The surface of the specimen was wrapped with a 30 mm-thick Earthwool ($k = 0.05 \text{ W/(m}\cdot\text{K)}$) insulation layer to minimise heat loss to the surroundings [35]. Eight thermocouples (TC 1~8) were embedded along the specimen height to record the temperature distribution. High-temperature thermocouples (JXWRN-XYQ, up to 900°C) with glass fibre insulation (PB-HH), supplied by Taizhou Suou Electric Heating Appliance Co., Ltd. (Taizhou, China), were used for temperature monitoring. TC 1, 2, 3, 4, 5, and 7 were positioned on the concrete surface, while TC 6 and 8 were placed on the insulation surface as depicted in Figure 6a. Two high-temperature resistance strain gauges (BAM120-3AA-G, up to 200°C), supplied by Chengdu Electrical Measurement Co., Ltd. (Chengdu, China), were attached on the surface to monitor thermal strain responses. The strain gauges S1 and S2 were positioned 40 mm and 45 mm from the bottom of the sample, respectively (Figure 6a).

3. Numerical Analysis

In this study, the finite element package LS-DYNA was employed for the coupled thermo-mechanical analysis owing to its robustness and versatility in handling complex multiphysics problems. It is worth noting that our previous study [25] only developed the transient heat transfer model without considering the thermal-mechanical coupling effect. In this study, LS-DYNA modelling is developed to provide a unified environment in which thermal and mechanical fields are solved consistently [36]. This integration significantly simplifies the modelling process, as temperature-dependent material properties, thermal strains, and structural responses can be defined within a single input deck. Details of such implementation and analysis are provided in the following subsection.

3.1 Governing equations

In LS-DYNA, the governing equations for thermo-mechanical coupling are based on the conservation of energy and momentum, which are solved in a fully integrated framework. Fourier's law governs the transient heat conduction [37]:

$$\rho C_p \frac{\partial T}{\partial t} = \nabla \cdot (k \nabla T) + Q + Q_{mech} \quad (1)$$

where ρ is the density, C_p is the specific heat capacity, T is the temperature, k is the thermal conductivity tensor, Q represents volumetric heat sources, and Q_{mech} represents heat generated from mechanical processes such as plastic deformation, which is negligible in this study.

The mechanical response is modelled using the following equilibrium equation:

$$\nabla \cdot \boldsymbol{\sigma} + \mathbf{f} = \rho \ddot{\mathbf{u}} \quad (2)$$

where $\boldsymbol{\sigma}$ is the Cauchy stress tensor, $\mathbf{f}$ is the body force vector, and $\ddot{\mathbf{u}}$ is the acceleration vector. The thermal and mechanical fields are coupled through temperature-dependent material properties and thermal strain contributions to the constitutive relation as follows [38]:

$$\boldsymbol{\varepsilon} = \boldsymbol{\varepsilon}^e + \boldsymbol{\varepsilon}^p + \boldsymbol{\varepsilon}^T, \boldsymbol{\varepsilon}^T = \alpha(T - T_0)\mathbf{I} \quad (3)$$

where $\boldsymbol{\varepsilon}^e$, $\boldsymbol{\varepsilon}^p$, and $\boldsymbol{\varepsilon}^T$ are the elastic, plastic, and thermal strain, α is the coefficient of thermal expansion, T_0 is a reference temperature, and $\mathbf{I}$ is the identity tensor. This thermal strain is then incorporated into the constitutive equation to determine the thermal stresses [39]:

$$\boldsymbol{\sigma} = \mathbf{D}(\boldsymbol{\varepsilon} - \boldsymbol{\varepsilon}^T) \quad (4)$$

Here, $\mathbf{D}$ is the material constitutive matrix, which defines the relationship between stress and strain. In thermal-mechanical analysis, $\mathbf{D}$ typically only maps mechanical strain to stress, while thermal strain is included separately. In LS-DYNA, these coupled equations are solved simultaneously, with the thermal solver handling heat transfer and the structural solver managing stress-strain response, thereby ensuring consistent exchange of temperature and strain fields within a single computational framework.

3.2 Description of Numerical Modelling

Figure 7 illustrates the schematic of the numerical model in this study, including insulation, concrete and embedded fin domains. The behaviour of the concrete domain was modelled using the Continuous Surface Cap constitutive law, which can accurately capture the nonlinear compressive behaviour, tensile cracking, and volumetric compaction of concrete under both static and dynamic loading conditions [40]. The measured material properties (described in Section 2.2) were used as the inputs in the simulations. For the thermal properties of concrete under elevated temperatures, the standard values from Eurocode 2, Part 1-2 are adopted [41]. The Al alloy fins were modelled as linearly elastic materials. The assumption is appropriate since the fins mainly serve as heat transfer component and it is expected that stresses are well below the material's yield limit during operation. summarises the material definition of the concrete, fins, and insulation in this study.

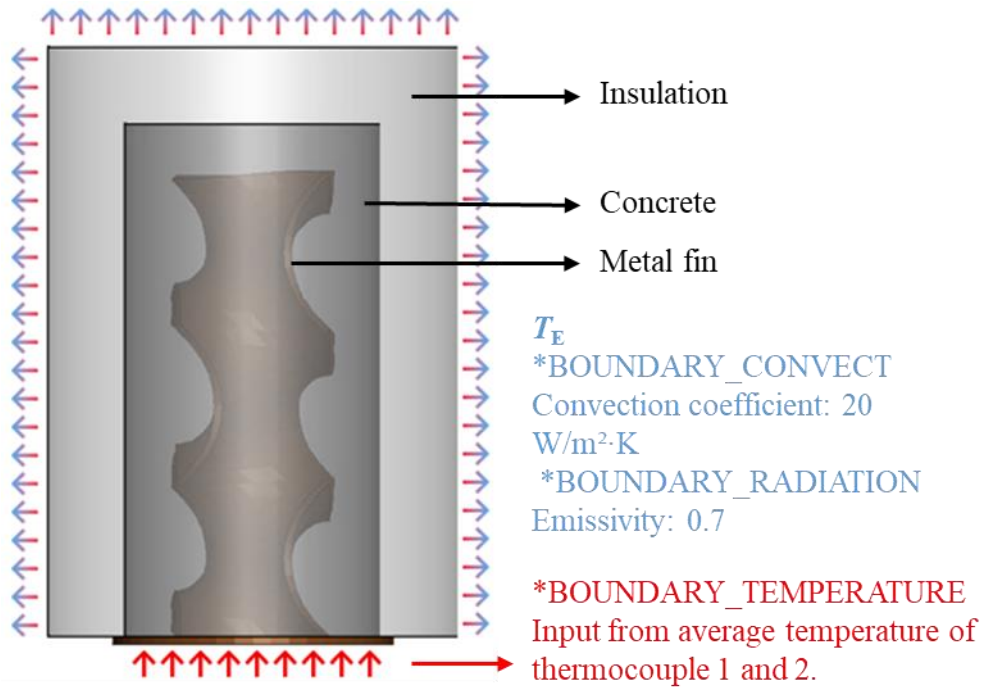


Figure 7 The schematic of numerical model of the CTES samples in this study

Table 1 The inputs of the concrete, fin and insulation materials for the numerical simulation

Material	Input
Concrete	Density: 2200 kg/m ³
	Specific heat capacity: 1.90 MJ/(m ³ ·K)
	Thermal conductivity: 1.95 W/(m·K)
	Compressive strength: 46 MPa
	Coefficient of thermal expansion: 9.0×10 ⁻⁶ /K [41]
Al alloy	Density: 2670 kg/m ³
	Specific heat capacity: 2.0 MJ/(m ³ ·K)
	Thermal conductivity: 94.5 W/(m·K)
	Elastic modulus: 70 GPa [42]
Insulation [43]	Coefficient of thermal expansion: 2.14×10 ⁻⁵ /K
	Density: 128 kg/m ³
	Specific heat capacity: 89.6 kJ/(m ³ ·K)
	Thermal conductivity: 0.05 W/(m·K)

Since the fins were cast with the concrete, a perfect contact is assumed between the fin and concrete domains where the fin and concrete share nodes to prevent slip. This is analogous to the perfect-bond assumption in reinforced concrete modelling [44]. The outer surface of the insulation layer was exposed to ambient environment through convective and radiative heat transfer. As illustrated in Figure 7, convection was modelled with a heat transfer coefficient of 20 W/(m²·K), while surface radiation was represented with an emissivity of 0.7 [41].

Additionally, the bottom surface of the entire specimen is constrained in the vertical direction to represent the physical support condition during the test. The average measured value from thermocouples 1 and 2 in the experiment was used as the temperature boundary condition in the simulation as shown in Figure 7 . The initial temperature of the model is set at the environmental temperature (T_E) measured from the test.

The complex geometry of the model was meshed in Gmsh [45] using tetrahedral elements. To ensure simulation accuracy while optimising computational efficiency, a grid independence study was performed using various mesh sizes and time step intervals. The results indicated that a mesh size of 1 mm is sufficient for the concrete and fin domains, while a 2 mm mesh was adopted for the insulation domain. Additionally, four time steps (5 s, 2 s, 1 s, and 0.5 s) were evaluated, with a 1 s interval found to provide an optimal balance between accuracy and computational cost. For brevity and readability, detailed results of the grid independence study are not included in this paper.

4. Experimental Results

Figure 8 presents the measured temperature evolution of the normal fin sample (C-N) during both the thermal charging and discharging phases. As a reminder, thermocouples (TC) 1, 2, 3, 4, 5, and 7 were positioned on the concrete surface, while TC 6 and 8 were placed on the insulation surface. The results from TC 1 and 2 show a rapid temperature rise during the first 50 minutes, followed by a quasi-steady plateau until the hotplate was switched off at 180 minutes, after which a gradual cooling phase occurred. The temperatures recorded by TC 6 and 8 remained very low, with a maximum of approximately 40 °C, indicating minimal heat loss to the environment. The temperature profiles of TC 3, 4, 5, and 7 follow a similar trend to TC 1 and 2, but with clear evidence of strong vertical gradients, as illustrated in Figure 8. Notably, the temperature difference between TC 1/2 and TC 7 (separated by 200 mm) is approximately 170 °C at peak conditions. This observation aligns the findings reported by Wang et al. [43], who observed a maximum radial temperature difference of approximately 75 °C in a CTES module with a circular cross-section of 82.5 mm in diameter. These results highlight the limited thermal conductivity of concrete, which restricts effective heat transfer via conduction in CTES applications.

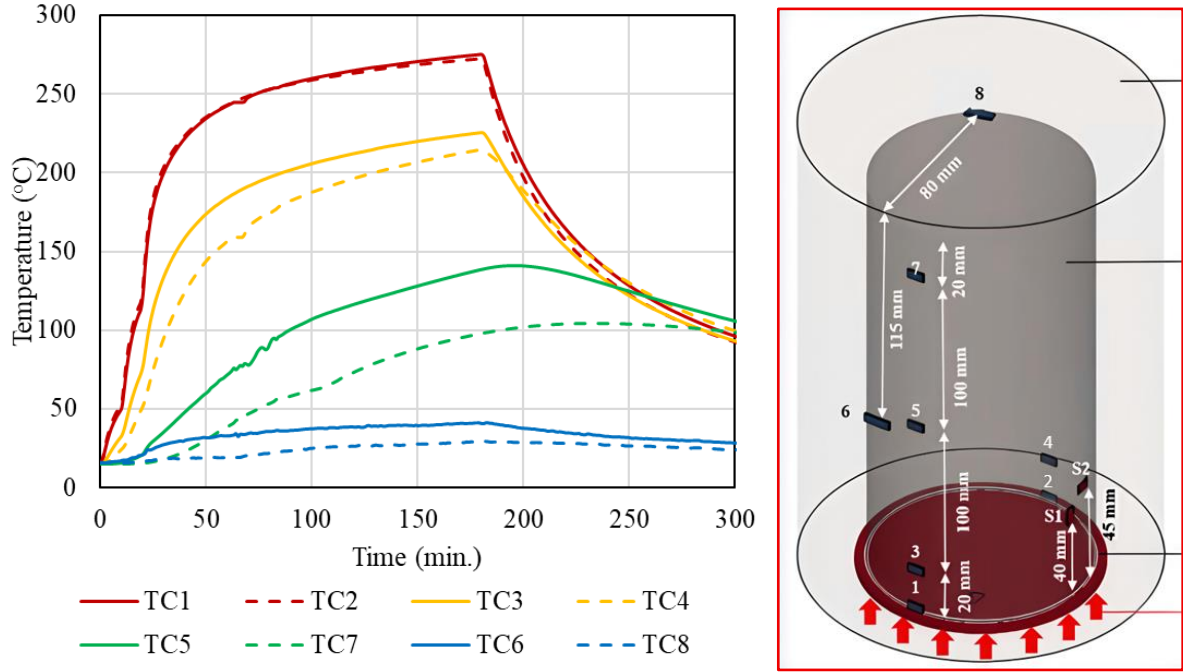
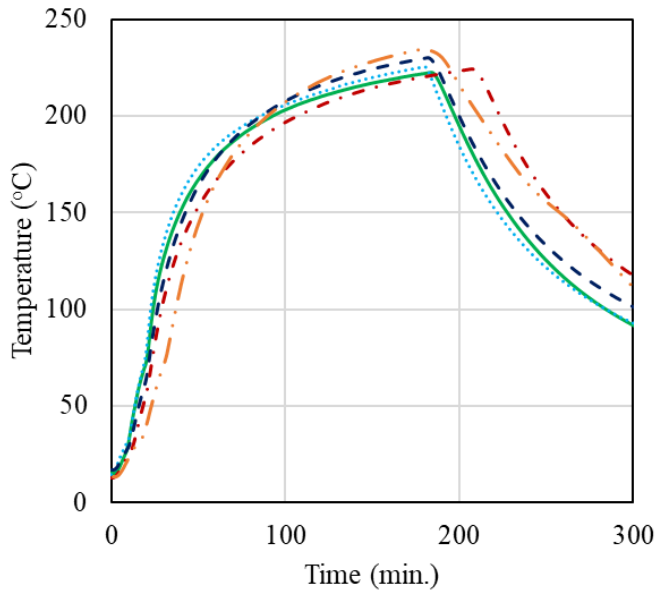
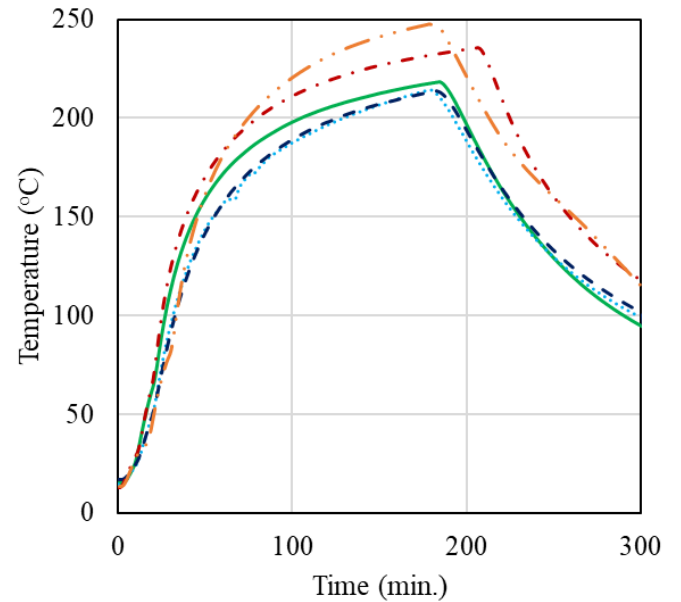


Figure 8 Measured temperature profile of normal fin sample (C-N) during the thermal forced charge and natural discharge cycle

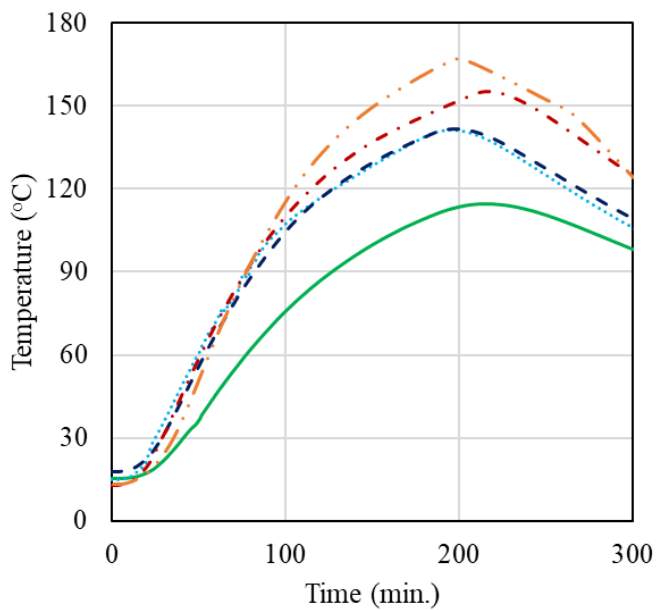
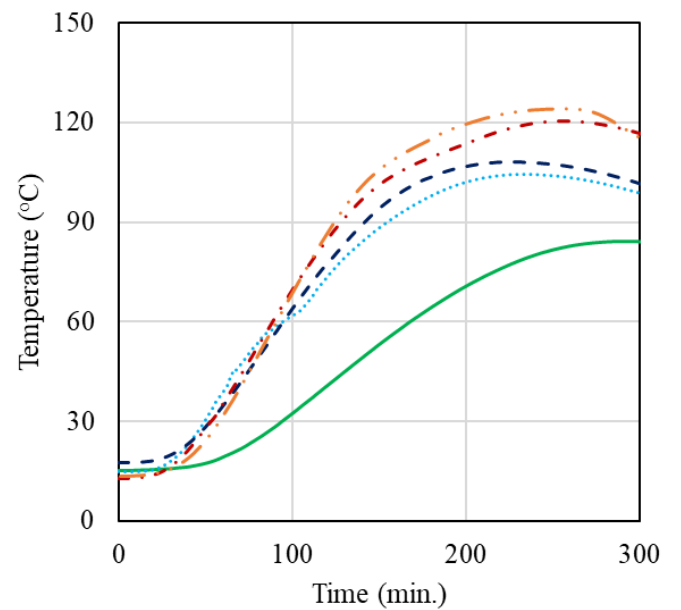
The temperatures recorded by TC 3, 4, 5, and 7 for the various fin designs are presented in Figure 9. The results indicate a similar temperature profile at TC 3 across all configurations, while TC 4 shows slightly higher temperatures for the two TPMS fin designs (C-TP and C-TG). This is expected, as TC 3 and TC 4 are positioned only 20 mm from the bottom of the sample (i.e., the heat source), resulting in minimal variation among the designs at this location. In contrast, the influence of fin design becomes more pronounced at TC 5 and TC 7, where temperatures increase significantly with the inclusion of fins. As shown in Figure 9, the control sample without a fin (C-0) reaches maximum temperatures of only 115 °C (TC 5) and 84 °C (TC 7). The normal fin (C-N) and branched/tree-like fin (C-T) designs produce similar enhancements, achieving peak temperatures of 141 °C and 104 °C at TC 5 and TC 7, respectively, representing an approximate 24% increase compared to the C-0 sample. This increase reflects a reduced temperature gradient within the sample, indicating improved internal heat transfer. The higher temperature increase of TC 5 and 7 means lower temperature gradient in C-N and C-T samples. The most substantial temperature rise is observed for the TPMS fin designs, particularly the C-TG sample, followed by the C-TP sample (Figure 9). The C-TG configuration reaches maximum temperatures of 167 °C (TC 5) and 124 °C (TC 7), corresponding to a 46% increase over the C-0 sample. This improvement can be attributed to the intrinsic geometric characteristics of TPMS structures, which offer a high surface area-to-

volume ratio, facilitating enhanced heat transfer. These results demonstrate that incorporating fin structures, especially TPMS designs, provides a more effective heat transfer pathway within the concrete domain, thereby reducing thermal gradients in CTES systems. However, it is worth noting that the complex structure of TPMS design could lead to high manufacturing costs, as discussed in the authors' previous study [25]



a) TC 3

b) TC 4



c) TC 5

d) TC 7

Figure 9 Comparison of temperature profile for different fin designs at different TC locations

In CTES systems, the brittle nature of concrete, combined with temperature gradients, can lead to damage and cracking during repeated thermal charge–discharge cycles, raising concerns regarding structural integrity and performance consistency [15, 32]. To assess the thermal strain behaviour, two strain gauges (S1 and S2) were installed on the surface of each sample. S1 measured longitudinal strain, while S2 measured circumferential strain, with both positioned 40 mm from the bottom of the sample (Figure 8). The strain evolution of the five sample types during charging and discharging is presented in Figure 10. It is noted that for the C-N sample, S2 malfunctioned during testing and therefore no data were recorded for circumferential strain in this case. The results show a clear correlation between strain development and temperature rise: as temperature increases, strain increases accordingly, followed by a decrease during the cooling phase. Figure 10 shows that all samples incorporating fin designs (C-N, C-T, C-TP, and C-TG) exhibit significantly higher strain responses compared to the control sample without a fin (C-0). This is consistent with the lower temperature development observed in the C-0 sample in Figure 9(c), which results in reduced thermal expansion. Notably, the samples with fins exhibit peak strain values approaching 3000 microstrain, a level comparable to the failure strain of normal concrete under compressive loading. This observation aligns with the cracking patterns observed post-testing, as presented Figure 11. Samples with high recorded strain (C-N, C-T, C-TP, and C-TG) displayed extensive surface cracking, whereas the C-0 sample, which exhibited the lowest strain, showed no visible surface cracks. Furthermore, the crack patterns in the finned samples appear to follow the geometry of the embedded fins (Figure 11), which is similar to the finding reported by Skinner et al. [32]. This can be attributed to the mismatch in thermal expansion coefficients between the metallic fins and the surrounding concrete. During the thermal charging phase, the metallic fins heat and expand more rapidly than the adjacent concrete, generating interfacial stresses that can lead to local debonding. These localised stresses may initiate microcracking at the fin–concrete interface, which can propagate into macrocracks observable on the sample surface, as confirmed by experimental observations.

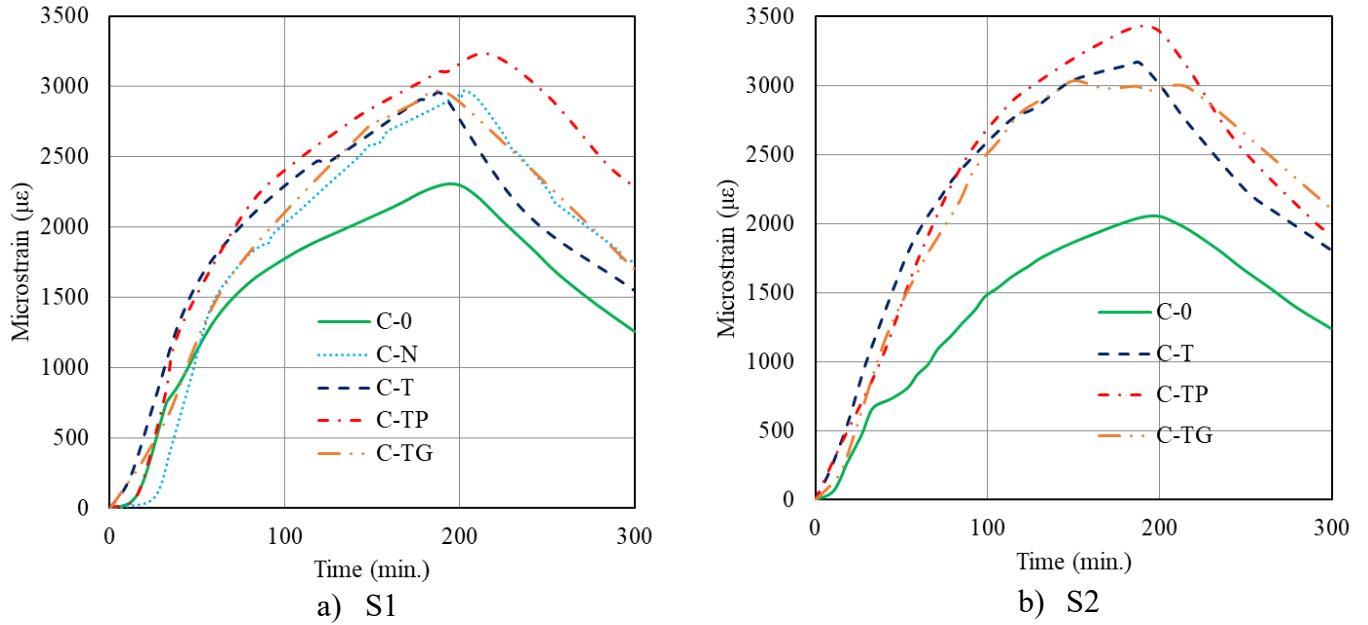


Figure 10 Strain evolution of five CTES samples during charge and discharge

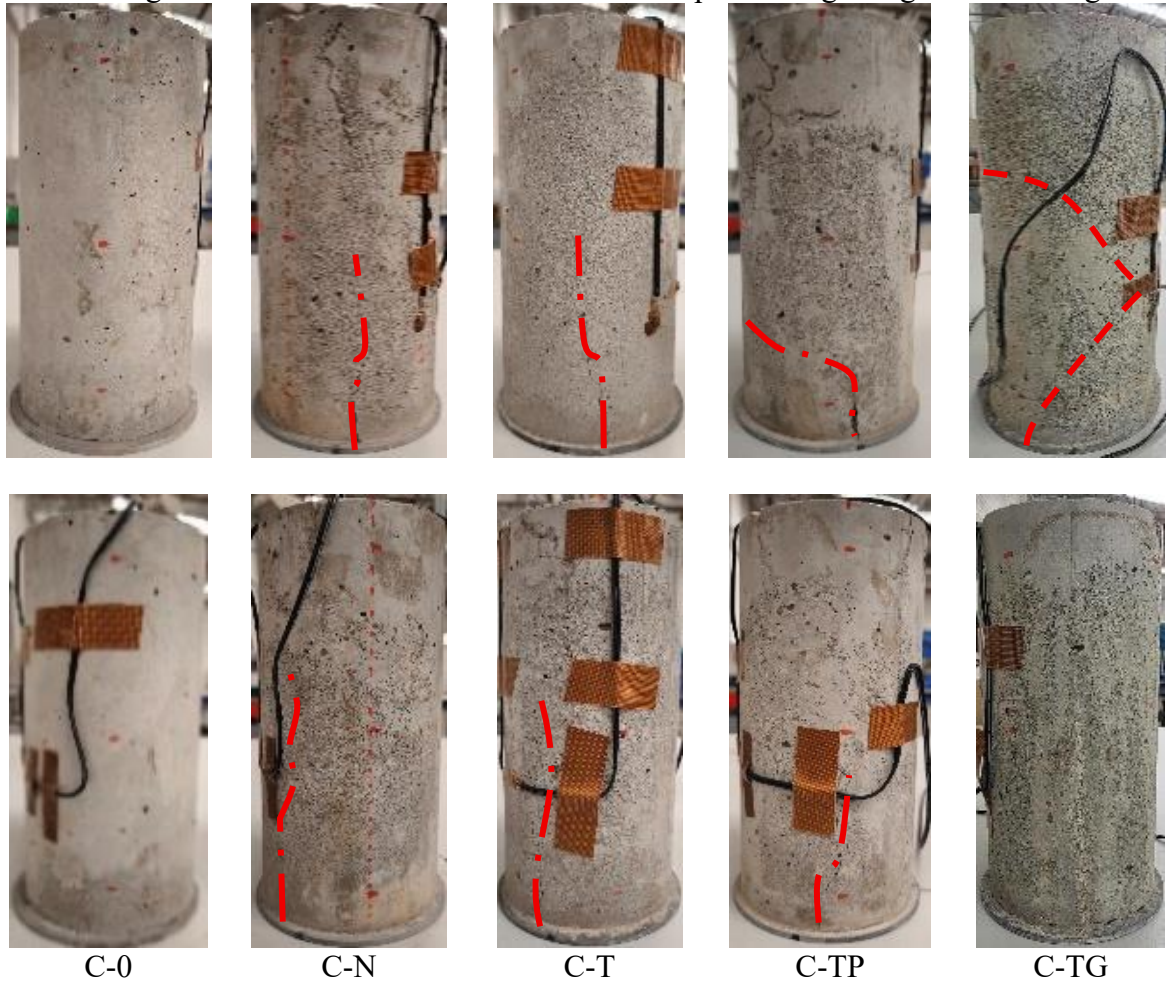
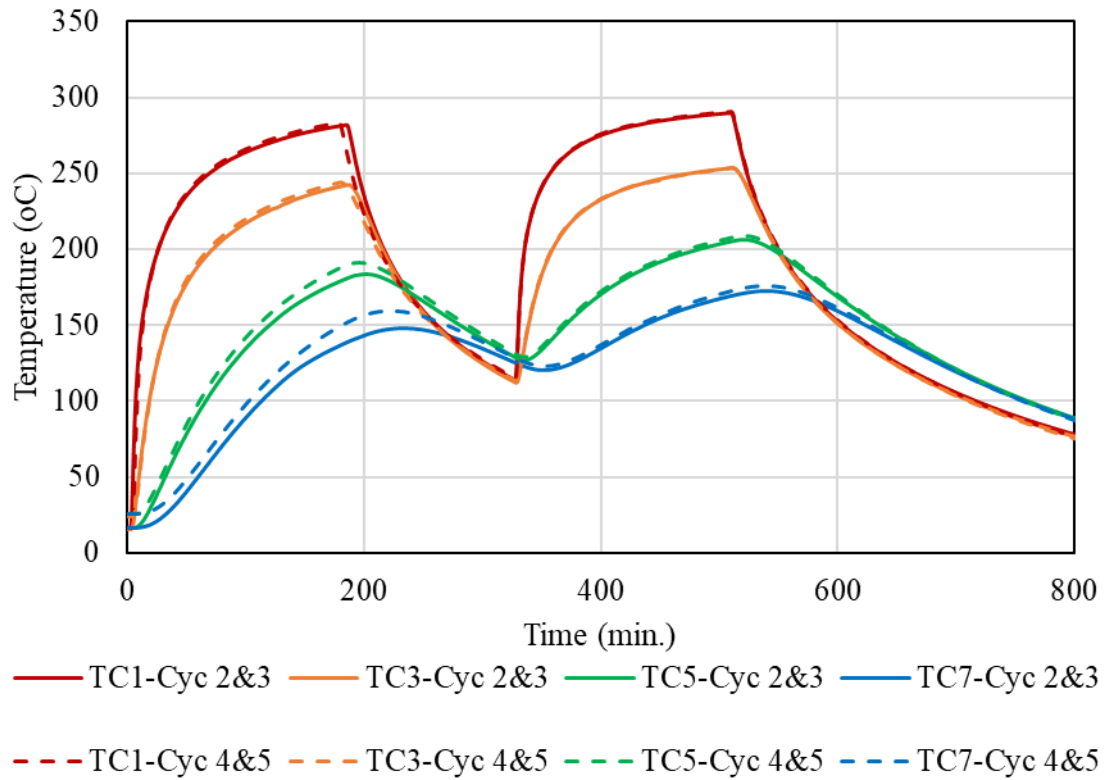


Figure 11 Crack patterns of five CTES samples in this study

The experimental results in this study confirm the potential for crack development in CTES samples incorporating fin designs (Figure 11). To further evaluate the effect of cracking on system performance under repeated thermal cycles, the C-TG sample was subjected to four

additional heating–cooling cycles. This sample was intentionally selected due to its high strain response and pronounced cracking observed during the initial cycle. The second and third cycles were completed on the same day as the first, while the fourth and fifth cycles were conducted the following day. The corresponding temperature and strain data are presented in Figure 12. As shown in Figure 12, the temperature profiles recorded by all thermocouples remained highly consistent across all five cycles, exhibiting near-identical heating and cooling trends. Similarly, the strain data from S2 showed consistent responses between cycles 2–5. One possible explanation for this consistency, despite visible cracking, is the pathway of heat transfer. As seen in Figure 11, the cracks were formed in vertical direction, which does not disrupt the heat transfer pathway (from bottom to top). This could explain the minimal impact of crack on the performance of CTES sample in the cyclic thermal testing. Another possible explanation is the role of radiative heat transfer across the crack interfaces. At elevated temperatures (above 150 °C, as in this study), radiation can act as a thermal bridge, compensating for the loss of conductive heat transfer caused by crack formation [46]. Miao et al. [47], through numerical simulations of CTES systems accounting for concrete cracking, reported a temperature difference of over 200 °C between damaged and undamaged scenarios, concluding that thermally induced damage significantly reduces thermal performance. However, it is important to note that radiative heat transfer was not included in the study by Miao et al. [47]. Other studies, such as those by Gaitero et al. [48] and Barbhuiya et al. [15], frequently cite the work of Skinner et al. [32], which identified cracking as a key concern for long-term CTES performance. Although Skinner et al. [32] provided evidence of extensive cracking in CTES, cyclic thermal testing was not conducted, and thus the impact of cracking on thermal performance was not directly assessed. In contrast, the present study suggests that the initiation and propagation of cracks may have a negligible effect on heat transfer performance during repeated thermal cycling, likely due to the contribution of both the heat transfer pathway and radiative heat transfer across crack interfaces. Nonetheless, it is important to recognise that excessive cracking may still compromise the structural integrity of CTES units, potentially affecting their long-term reliability and safety. Future research should focus on a more comprehensive assessment of CTES systems under extended operational cycling, incorporating both thermal and structural performance metrics to better understand the long-term implications of crack development.



a) Temperature evolution

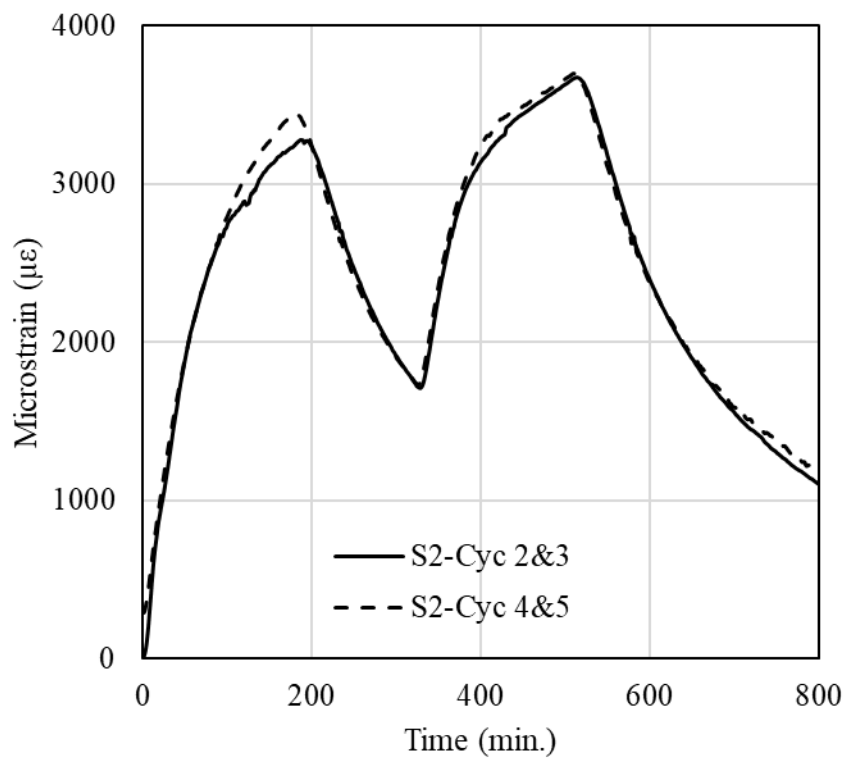
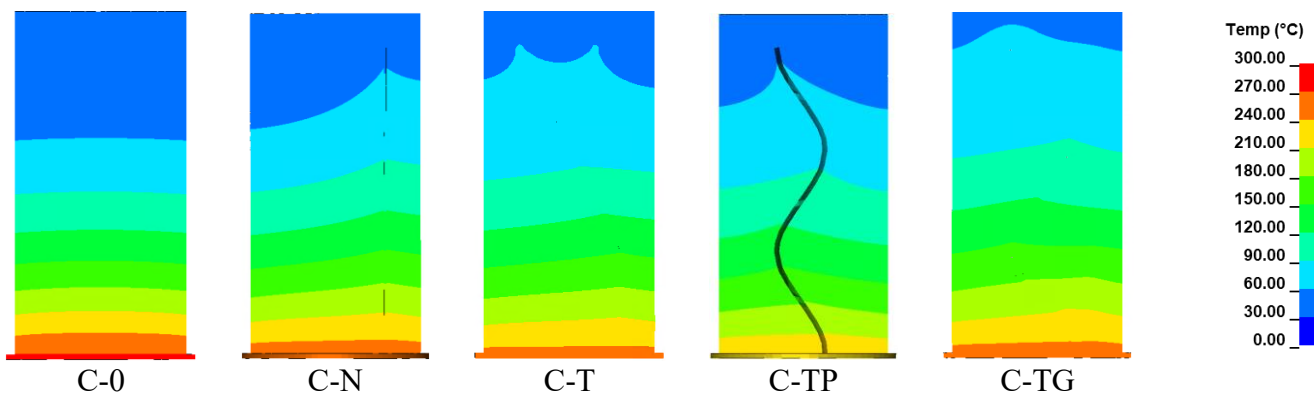


Figure 12 The temperature and strain evolution of C-TG sample under four heating and cooling cycles

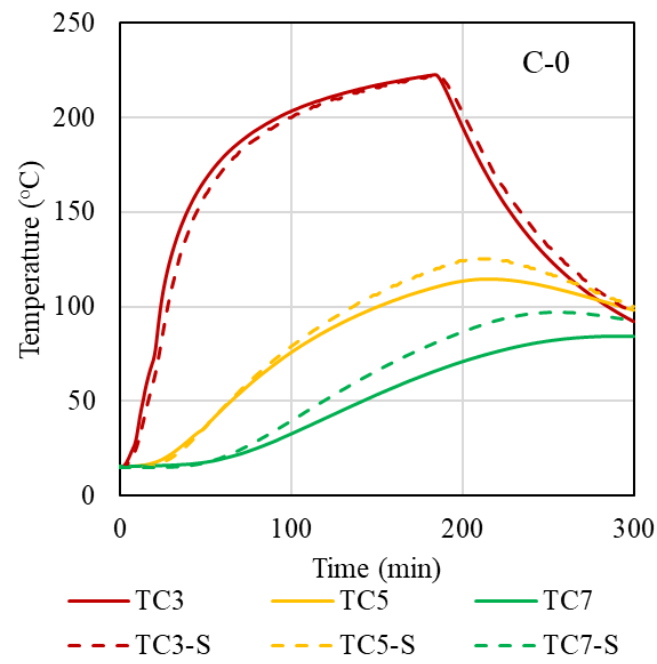
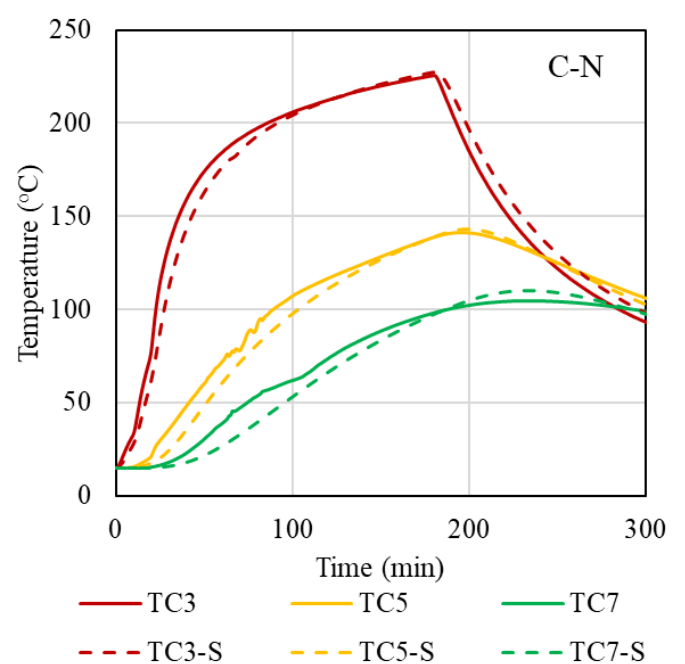
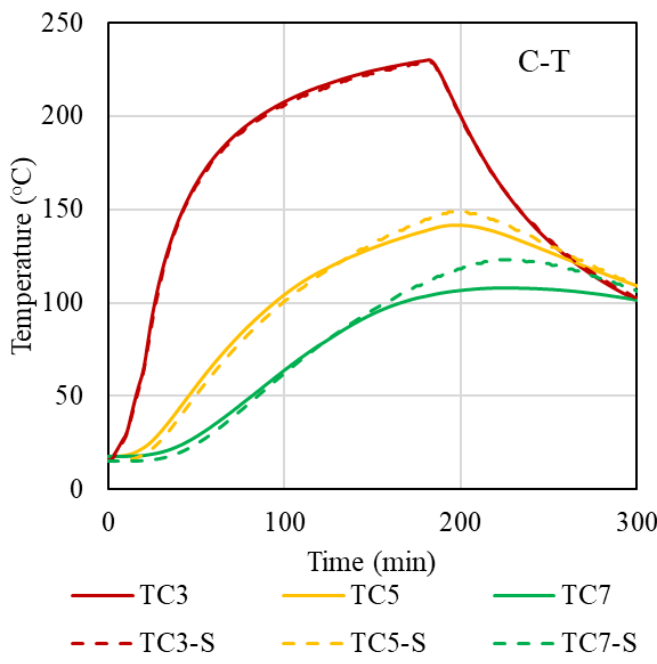
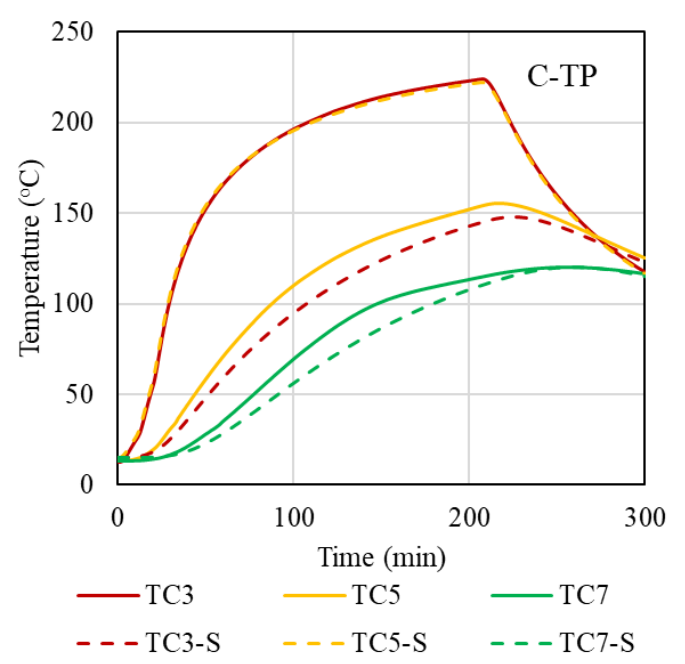
5. Numerical Results

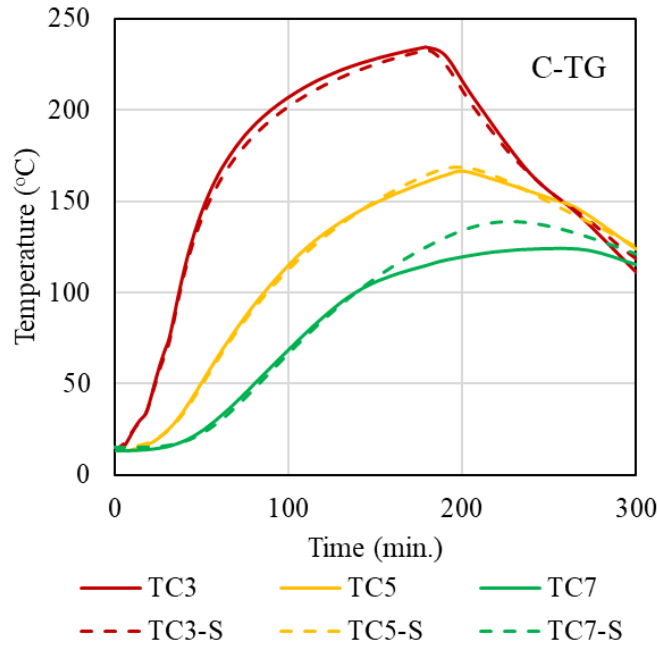
This section provides a detailed comparison between numerical predictions and experimental observations regarding temperature changes, strain responses, and crack behaviour. Figure 13 illustrates the temperature distribution contours at 90 minutes, alongside a comparison between experimental and simulated temperature profiles. As shown in Figure 13(a) that the incorporation of straight (C-N) and branched (C-T) fin designs effectively enhances vertical heat transfer along the fin pathways, extending the hot zone and reducing the temperature gradient between the bottom and mid-height regions of the sample. However, some thermal stratification persists in the upper section due to the predominantly one-dimensional heat flow in these configurations. In contrast, the TPMS-based fin design (C-TG) demonstrates superior three-dimensional heat propagation, resulting in a more uniform temperature field with a markedly lower vertical gradient. This observation is corroborated by experimental data at TC 5 and TC 7 (Figure 9c and d), which shows that the C-TG sample achieves the highest temperatures among all tested configurations. Figure 13(b) presents the comparison between simulated and measured temperature development at TC 3, TC 5, and TC 7. The numerical results show good agreement with experimental data for all specimens, accurately capturing both the heating and cooling phases. The predicted temperature curves for TC 3 and TC 5 closely follow the experimental trends. The largest discrepancy is observed at TC 7, located near the top of the specimen, where longer heat transfer pathways may introduce greater uncertainty and variability. Nonetheless, the maximum deviation between simulated and measured temperatures remains within 5%, indicating the validity and accuracy of the numerical model. These results confirm that the developed numerical framework can reliably predict transient heat transfer behaviour in concrete specimens incorporating various fin geometries, and can serve as a valuable tool for optimising CTES designs.



(a) Temperature distribution at 90 min. obtained from the numerical simulation (90 min)

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65





(b) Comparison of temperature development between the experiments (solid line) and simulation (S suffix, dashed line)

Figure 13 (a) Contour plot of temperature distribution; (b) and validation of numerical results

The average concrete temperatures obtained from the numerical simulations reveal a clear enhancement in heat transfer performance of the CTES system with the incorporation of fins (Figure 14). Compared to the control specimen (C-0), which reached a peak average temperature of 143 °C, the C-N and C-T samples showed moderate improvements, reaching 155 °C, an approximate increase of 8.4%. The C-TP specimen achieved a peak temperature of 162 °C (+13.3%), while the C-TG specimen exhibited the highest temperature of 180 °C, corresponding to a 25.9% improvement.

These results indicate that while straight and branched fin designs (C-N and C-T) offer modest thermal performance gains, the TPMS-based fins (C-TP and especially C-TG) provide significantly greater enhancement in heat transfer. This trend aligns with the experimental observations presented in Figure 9, reinforcing that the optimised gradient TPMS fin (C-TG) delivers the most effective improvement in thermal performance within the concrete matrix.

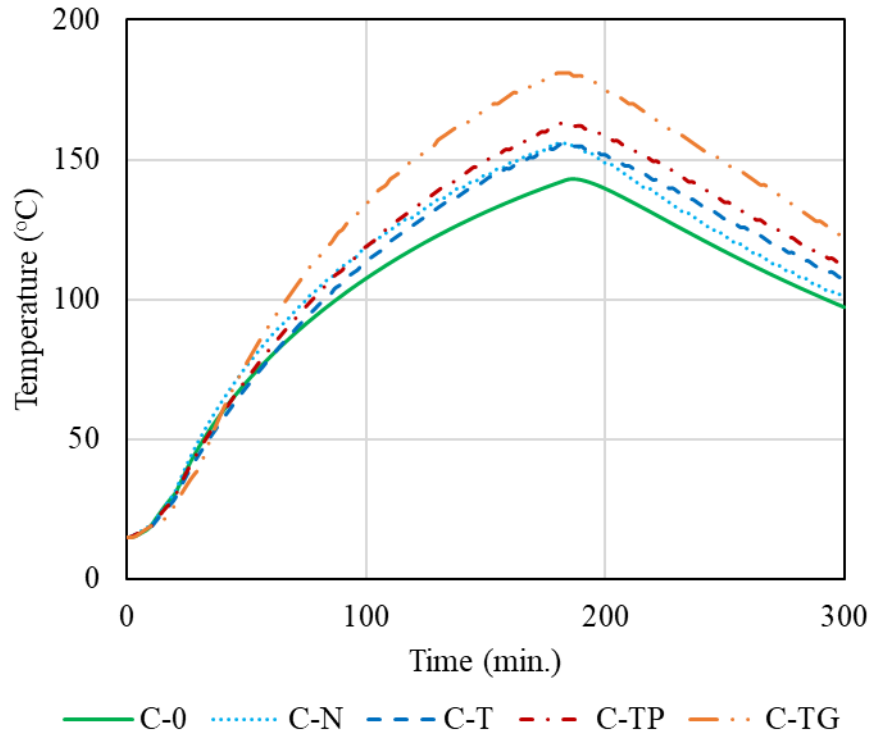
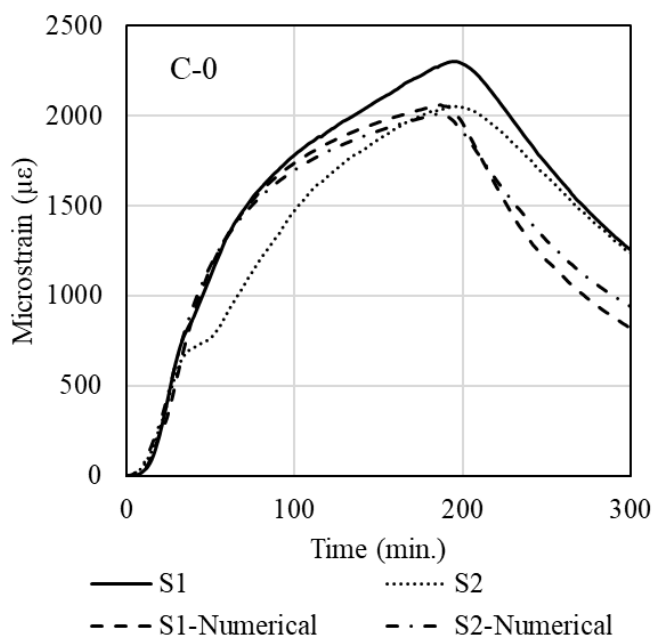
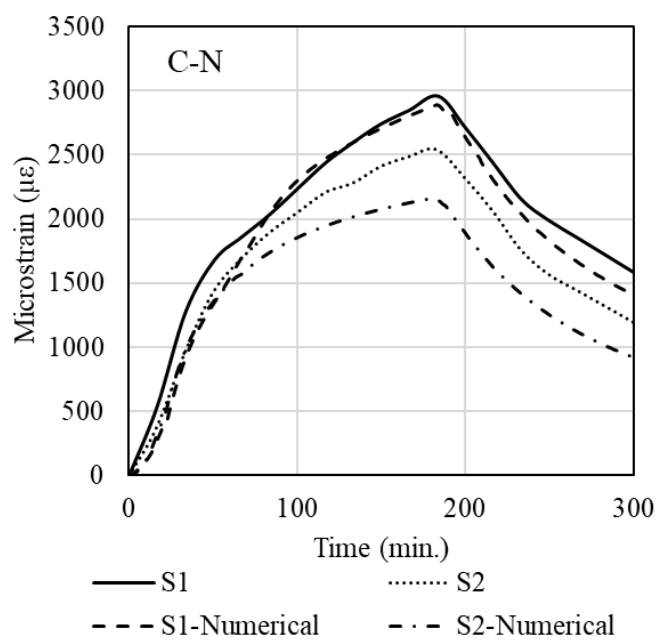
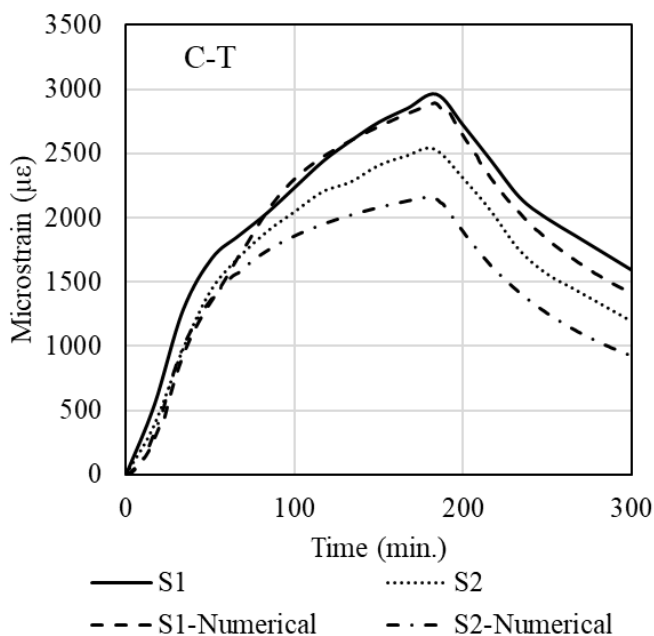
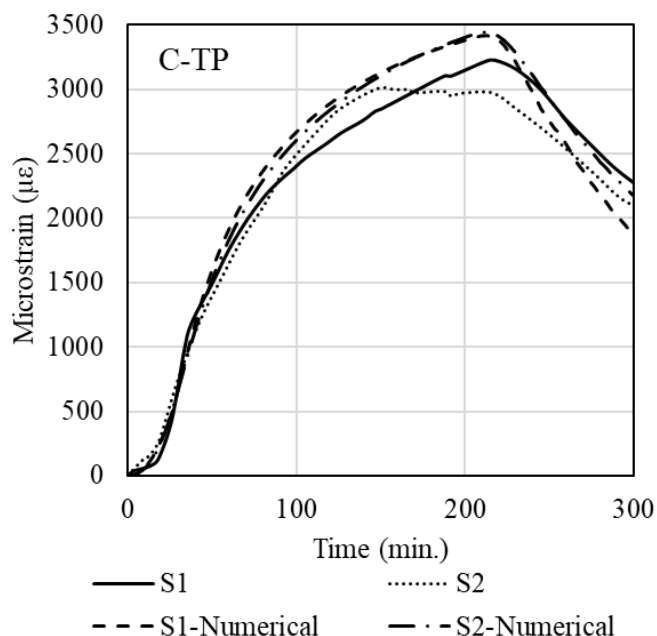


Figure 14 Average temperature of five CTES samples obtained from the numerical simulation

Figure 15 compares the strain evolution obtained from experimental measurements and numerical simulations across all test specimens. Overall, the numerical results exhibit trends consistent with the experimental data: strain increases with rising temperature, peaking around 180–200 minutes, and subsequently decreases during the cooling phase. The predicted strain magnitudes show good agreement with the measured values for all configurations (C-0 to C-TG), thereby validating the accuracy of the developed thermo-mechanical coupling model. Minor discrepancies are observed in specific cases, such as the S1 strain in the C-0 specimen and the S2 strain in the C-T specimen. These deviations can largely be attributed to the inherent complexity of thermally induced stress and strain behaviour, including localised temperature gradients, simplified boundary conditions in the model, and potential inconsistencies in the bonding quality between strain gauges and the concrete surface in the experimental setup. It is also worth noting that high-fidelity thermo-mechanical modelling typically requires detailed calibration of temperature-dependent material properties and constitutive law [49]. While such calibration was beyond the scope of the present study, the results demonstrate that the current numerical model provides a sufficiently accurate representation of the strain behaviour in CTES specimens under thermal loading.



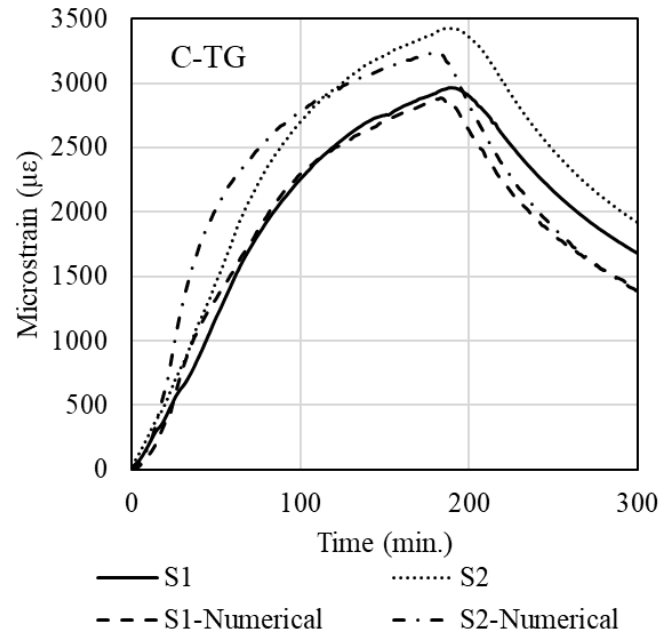


Figure 15 Comparison of experimental (solid line) and simulated (dashed line) strain evolution of five CTES samples subjected to one thermal cycle

Figure 16 presents the distribution of effective plastic strain (EPS) in the specimens, as obtained from numerical simulations. In this study, EPS is used as a damage indicator to predict crack initiation and propagation, in line with established practices in the literature [50]. Regions exhibiting elevated EPS values correspond to zones of stress concentration and are indicative of potential crack formation. The EPS contours clearly reveal the influence of fin geometry on crack development. In specimens incorporating fins, distinct cracking patterns emerge that correspond with the fin configurations, consistent with the experimental observations. For instance, the straight fin (C-N) induces a vertical tensile zone along the fin–concrete interface (Figure 16a), while the branched fin (C-T) promotes diagonal crack propagation following the fin arms (Figure 16b). The predicted crack paths based on the EPS distribution demonstrate a strong correlation with the crack propagation patterns observed through experimental procedures, thereby affirming the accuracy of the numerical model in predicting the thermally induced cracking behaviour of the specimens. The validated numerical model will be used to conduct parametric study on the influence of fin parameters on the performance of CTES in the authors’ future study.

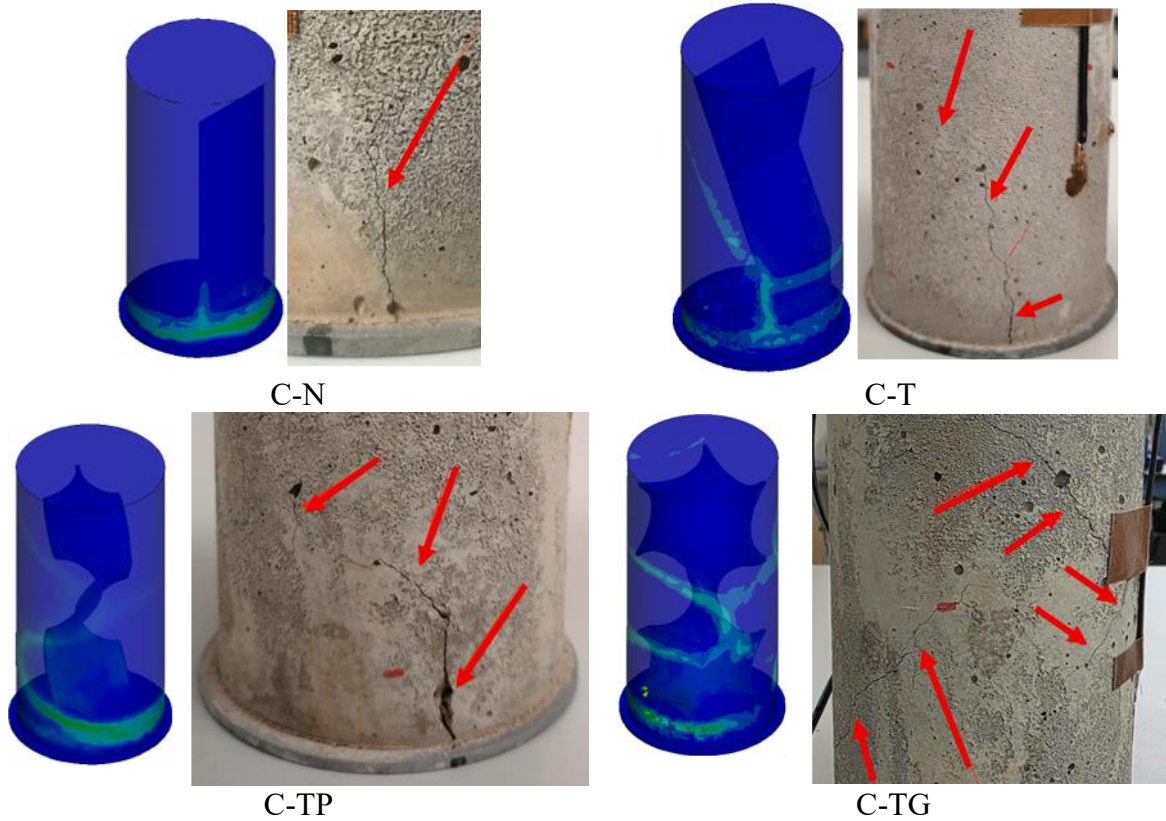


Figure 16 Comparison of predicted crack pattern from the simulation (effective plastic strain distribution) and experiments

6. Conclusion

This study experimentally and numerically investigated the thermo-mechanical behaviour of fin-enhanced concrete thermal energy storage (CTES) modules incorporating different fin morphologies, including straight, branched, and triply periodic minimal surface (TPMS) designs. Based on the combined experimental observations and numerical analyses, it is concluded that the incorporation of metallic fins substantially enhances heat transfer and temperature uniformity within the concrete domain. Compared with the control specimen without fins (C-0), TPMS fin configurations significantly reduce temperature gradients and increase mid-depth temperatures by up to 46%, demonstrating their superior capability for heat transfer enhancement relative to straight and branched fin designs. Additionally, thermal cycling tests confirm the robustness of heat transfer performance in TPMS-based CTES modules. Despite the occurrence of visible surface cracking, the temperature evolution remains highly consistent across repeated cycles. This behaviour is attributed to the heat transfer pathway and radiative heat transfer across crack interfaces. The results indicate that thermally induced cracking has a negligible effect on the overall heat transfer performance of CTES under the tested conditions. Finally, the developed thermo-mechanical numerical model accurately

predicts both temperature and strain evolution in CTES specimens, demonstrating good agreement with experimental results. Simulation results show that straight (C-N) and tree-branched (C-T) fins provide only marginal thermal improvements (~8.4%) over the control sample (without fin), whereas TPMS fins achieve a significantly higher enhancement (~25.9%). These findings highlight that heat transfer efficiency in CTES systems is strongly governed by fin geometry, rather than fin presence alone.

Overall, this study demonstrates the strong potential of TPMS fin designs for improving the thermal performance of CTES systems while maintaining stable performance under thermal cycling. The experimental programme was conducted using a simplified laboratory-scale configuration; therefore, future work will focus on full-scale CTES modules operating with heat transfer fluids under realistic conditions. In addition, further investigation is required to comprehensively assess the long-term effects of thermally induced cracking on both the structural integrity and performance consistency of CTES systems under extended charge–discharge cycling.

Acknowledgement

Reference

- [1] A. G. Olabi *et al.*, "Application of artificial intelligence for prediction, optimization, and control of thermal energy storage systems," *Thermal Science and Engineering Progress*, vol. 39, p. 101730, 2023/03/01/ 2023.
- [2] L. Qiu *et al.*, "Pathways to decarbonizing buildings: Harnessing energy efficiency and sustainable technologies," *Thermal Science and Engineering Progress*, vol. 66, p. 103991, 2025/10/01/ 2025.
- [3] L. Baindu Gobio-Thomas, M. Darwish, and V. Stojceska, "Review on the economic impacts of solar thermal power plants," *Thermal Science and Engineering Progress*, vol. 46, p. 102224, 2023/12/01/ 2023.
- [4] M. Thonon, G. Fraisse, L. Zalewski, and M. Pailha, "Simultaneous charging and discharging processes in latent heat thermal energy storage: A review," *Thermal Science and Engineering Progress*, vol. 47, p. 102299, 2024/01/01/ 2024.
- [5] M. Teggat, A. Atia, T. T. M. Rocha, and A. Laouer, "Long and short-term storage of food and agriculture products: Prospects of latent heat thermal energy storage," *Thermal Science and Engineering Progress*, vol. 59, p. 103324, 2025/03/01/ 2025.
- [6] J. Ren, C. Wang, Q. Zhang, L. Zhang, X. Guo, and K. Chang, "Optimizing T-shaped fin designs for enhanced thermal management in photovoltaic-phase change material systems," *Thermal Science and Engineering Progress*, vol. 71, p. 104594, 2026/03/01/ 2026.
- [7] F. Ma *et al.*, "Porous-scale and nanoscale dual-enhanced thermal conductive composite phase change materials," *Thermal Science and Engineering Progress*, vol. 68, p. 104282, 2025/12/01/ 2025.
- [8] Z. Liu, H. Xing-Huai, and W. Xiu-Xin, "The role of multi-walled carbon nanotubes in enhancing the thermal performance of phase change materials for sustainable energy storage," *Thermal Science and Engineering Progress*, p. 104817, 2026/06/24/ 2026.
- [9] R. Hazarika, R. Majumdar, S. Mahapatra, and S. K. Saha, "Sensible heat storage performances of Hytherm 600 oil and energy-harnessing features of glycol-water mixture under simultaneous charging and discharging conditions," *Thermal Science and Engineering Progress*, vol. 68, p. 104311, 2025/12/01/ 2025.
- [10] R. K. Sambare, S. Joshi, and N. C. Kanojiya, "Improving the freshwater production from tubular solar still using sensible heat storage materials," *Thermal Science and Engineering Progress*, vol. 38, p. 101676, 2023/02/01/ 2023.
- [11] A. Famiglietti, I. Calderón-Vásquez, J. M. Cardemil, I. Wolde, and R. Abbas, "Techno-economic assessment of a concentrating solar air heater and packed-bed thermal energy storage for medium-temperature industrial process heat," *Thermal Science and Engineering Progress*, vol. 70, p. 104529, 2026/02/01/ 2026.
- [12] R. Tamme, D. Laing, and W.-D. Steinmann, "Advanced thermal energy storage technology for parabolic trough," *J. Sol. Energy Eng.*, vol. 126, no. 2, pp. 794-800, 2004.
- [13] S. Kuravi, J. Trahan, D. Y. Goswami, M. M. Rahman, and E. K. Stefanakos, "Thermal energy storage technologies and systems for concentrating solar power plants," *Progress in energy and combustion science*, vol. 39, no. 4, pp. 285-319, 2013.
- [14] S. Wang *et al.*, "Thermal energy storage in concrete: Review, testing, and simulation of thermal properties at relevant ranges of elevated temperature," *Cement and Concrete Research*, vol. 166, p. 107096, 2023/04/01/ 2023.
- [15] S. Barbhuiya, B. B. Das, and M. Idrees, "Thermal energy storage in concrete: A comprehensive review on fundamentals, technology and sustainability," *Journal of Building Engineering*, vol. 82, p. 108302, 2024/04/01/ 2024.

- [16] N. Hoivik *et al.*, "Long-term performance results of concrete-based modular thermal energy storage system," *Journal of Energy Storage*, vol. 24, p. 100735, 2019.
- [17] P. D. Tagle-Salazar, L. F. Cabeza, and C. Prieto, "Advancing sensible heat storage: A novel transient heat transfer model for concrete-based TES modules for CSP applications," *Renewable Energy*, vol. 256, p. 124558, 2026/01/01/ 2026.
- [18] J. Tinker, J. Cabrera, and E. Ganjian, "Thermal conductivity of concrete: Effect of moisture," *Building Services Engineering Research and Technology*, vol. 13, no. 1, pp. 31-36, 1992.
- [19] M. Ammari, B. Belhadj, M. Bederina, A. Ferhat, and M. Quéneudec, "Contribution of hybrid fibers on the improvement of sand concrete properties: Barley straws treated with hot water and steel fibers," *Construction and building materials*, vol. 233, p. 117374, 2020.
- [20] L. Boquera *et al.*, "Thermo-mechanical stability of supplementary cementitious materials in cement paste to be incorporated in concrete as thermal energy storage material at high temperatures," *Journal of Energy Storage*, vol. 54, p. 105370, 2022/10/01/ 2022.
- [21] C. Yu, D. Shen, J. Tu, and L. Fang, "Parametric thermal analysis of a phase change material wall combining with autoclaved aerated concrete," *Thermal Science and Engineering Progress*, vol. 71, p. 104563, 2026/03/01/ 2026.
- [22] O. Gencel *et al.*, "Properties of 3D printed concrete (3DPC) containing microencapsulated phase change material (PCM)," *Thermal Science and Engineering Progress*, vol. 67, p. 104082, 2025/11/01/ 2025.
- [23] K. A. D. Y. T. Kahandawa Arachchi, O. Mirza, F. Mashiri, S. Pathirana, and C. Camille, "Mechanical and thermal performance of concrete with embedded organic and inorganic PCMs for building applications," *Thermal Science and Engineering Progress*, vol. 69, p. 104478, 2026/01/01/ 2026.
- [24] S. Wang *et al.*, "Enhancement of conventional concrete mix designs for sensible thermal energy storage applications," *Journal of Energy Storage*, vol. 61, p. 106735, 2023/05/01/ 2023.
- [25] T. Liuhui and N. Tuan, "A comparative study of different fin designs for enhancing the performance of concrete thermal energy storage," *Energy*, vol. 349, p. 140677, 2026.
- [26] A. M. Ali, A. Bagdanavicius, A. Rona, and S. Shahzad, "Enhanced solidification in latent heat storage systems using fins and twisted tapes," *Thermal Science and Engineering Progress*, vol. 74, p. 104718, 2026/06/01/ 2026.
- [27] H. Li *et al.*, "Numerical investigation on melting and solidification in a novel bionic honeycomb-fin triple-tube latent heat storage unit with nanoparticle-enhanced PCM," *Thermal Science and Engineering Progress*, vol. 69, p. 104403, 2026/01/01/ 2026.
- [28] J. Zou, W. Ge, J. Li, H. Fukuda, and X. Meng, "Improvement of copper foam fin thickness on thermal performance of spherical encapsulated phase-change material," *Thermal Science and Engineering Progress*, vol. 68, p. 104394, 2025/12/01/ 2025.
- [29] L. Prasad and P. Muthukumar, "Design and optimization of lab-scale sensible heat storage prototype for solar thermal power plant application," *Solar Energy*, vol. 97, pp. 217-229, 2013/11/01/ 2013.
- [30] C. Aswin Karthik and P. Muthukumar, "Numerical study on heat transfer augmentation techniques in concrete based thermal storage module for solar-thermal applications," *Thermal Science and Engineering Progress*, vol. 33, p. 101350, 2022/08/01/ 2022.
- [31] C. Liu and H. Yang, "Multi-objective optimization of a concrete thermal energy storage system based on response surface methodology," *Applied Thermal Engineering*, vol. 202, p. 117847, 2022/02/05/ 2022.

- [32] J. E. Skinner, M. N. Strasser, B. M. Brown, and R. Panneer Selvam, "Testing of high-performance concrete as a thermal energy storage medium at high temperatures," *Journal of solar energy Engineering*, vol. 136, no. 2, p. 021004, 2014.
- [33] R. R. J. Sélo, S. Catchpole-Smith, I. Maskery, I. Ashcroft, and C. Tuck, "On the thermal conductivity of AlSi10Mg and lattice structures made by laser powder bed fusion," *Additive Manufacturing*, vol. 34, p. 101214, 2020/08/01/ 2020.
- [34] A. V. Gusarov, M. Pavlov, and I. Smurov, "Residual Stresses at Laser Surface Remelting and Additive Manufacturing," *Physics Procedia*, vol. 12, pp. 248-254, 2011/01/01/ 2011.
- [35] "Earthwool Wall Batt Datasheet," ed: Knauf Insulation Australia, 2024.
- [36] C. Yuan, X. Gao, H. K. Wong, B. Feng, and J. Xu, "A multiphysics computational framework for cylindrical battery behavior upon mechanical loading based on LS-DYNA," *Journal of the Electrochemical Society*, vol. 166, no. 6, p. A1160, 2019.
- [37] F. P. Incropera, D. P. DeWitt, T. L. Bergman, and A. S. Lavine, *Fundamentals of heat and mass transfer*. New York John Wiley & Sons, Inc., 1990.
- [38] J. Lubliner, "1990Plasticity theory," *New York: McMillan*.
- [39] S. Timoshenko, "Goodier. JN, Theory of Elasticity," *New. York McGraw—Hill*, vol. 970, no. 4, pp. 279-291, 1970.
- [40] Y. V. Novozhilov, A. N. Dmitriev, and D. S. Mikhaliuk, "Precise calibration of the continuous surface cap model for concrete simulation," *Buildings*, vol. 12, no. 5, p. 636, 2022.
- [41] B. En, "1-2: 2004 Eurocode 2: Design of concrete structures-Part 1-2: General rules-Structural fire design," *European Standards, London*, 2004.
- [42] N.-S. Cheng, "Wall effect on pressure drop in packed beds," *Powder Technology*, vol. 210, no. 3, pp. 261-266, 2011/07/10/ 2011.
- [43] S. Wang *et al.*, "Thermal energy storage in concrete utilizing a thermosiphon heat exchanger," *Journal of Energy Storage*, vol. 64, p. 107201, 2023/08/01/ 2023.
- [44] S. Al Hasani, H. Nasrellah, and A. A. Abdulraeg, "Numerical study of reinforced Concrete beam by using ABAQUS software," *International Journal of Innovative Technology and Interdisciplinary Sciences*, vol. 4, no. 3, pp. 733-741, 2021.
- [45] C. Geuzaine and J. F. Remacle, "Gmsh: A 3-D finite element mesh generator with built-in pre-and post-processing facilities," *International journal for numerical methods in engineering*, vol. 79, no. 11, pp. 1309-1331, 2009.
- [46] A. Hattiangadi and T. Siegmund, "A numerical study on interface crack growth under heat flux loading," *International Journal of Solids and Structures*, vol. 42, no. 24, pp. 6335-6355, 2005/12/01/ 2005.
- [47] X.-Y. Miao, O. Kolditz, and T. Nagel, "Modelling thermal performance degradation of high and low-temperature solid thermal energy storage due to cracking processes using a phase-field approach," *Energy Conversion and Management*, vol. 180, pp. 977-989, 2019/01/15/ 2019.
- [48] J. J. Gaitero *et al.*, "Reviewing experimental studies on sensible thermal energy storage in cementitious composites: report of the RILEM TC 299-TES," *Materials and Structures*, vol. 57, no. 4, p. 100, 2024/05/14 2024.
- [49] I. P. Sfikas, J. Ingham, and J. Baber, "Simulating thermal behaviour of concrete by FEA: state-of-the-art review," *Proceedings of the Institution of Civil Engineers - Construction Materials*, vol. 171, no. 2, pp. 59-71, 2016.
- [50] P. Grassl, D. Xenos, U. Nyström, R. Rempling, and K. Gylltoft, "CDPM2: A damage-plasticity approach to modelling the failure of concrete," *International Journal of Solids and Structures*, vol. 50, no. 24, pp. 3805-3816, 2013.