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Analysis of Thermal Expansion Effects and Thermodynamic Control Strategies for Super High-Rise Building Structures

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ABSTRACT

With the advancement of urbanization, super high-rise buildings have become an integral part of modern cities. However, these structures face significant challenges due to thermal expansion effects in complex environments, especially considering the substantial impact of temperature-induced thermal expansion of concrete on the stability and safety of buildings. Although existing research has made some progress in exploring thermal expansion effects and their control strategies, traditional methods have limitations in addressing the complexities of super high-rise buildings. This study first solves the thermal expansion coefficient of concrete in super high-rise building structures based on an effective medium theory, providing a more precise calculation method from a microscopic perspective. Secondly, it proposes and validates a set of thermodynamic control strategies for super high-rise building structures to effectively manage the stress and deformation issues caused by temperature changes. The findings of this study will offer scientific support for the design and maintenance of super high-rise buildings, enhancing their overall safety and economic efficiency.

1. INTRODUCTION

With the accelerated process of modern urbanization, super high-rise buildings have gradually become the mainstream of urban architecture [1-4]. However, the structures of super high-rise buildings face many challenges in complex environments, among which the thermal expansion effect has a significant impact on the stability and safety of building structures [5, 6]. As the height and volume increase, the thermal expansion effect of building materials, especially concrete, under temperature changes becomes particularly prominent [7-9]. This thermal expansion effect not only affects the appearance and structural integrity of buildings but also may lead to potential safety hazards.

Researching the thermal expansion effects of super high-rise building structures and their control strategies has important theoretical and practical significance. First, understanding and mastering the impact of thermal expansion on structures helps to improve the scientific and rational design of buildings, thereby ensuring the long-term stability and service life of the buildings [10, 11]. Second, formulating effective thermodynamic control strategies can significantly reduce the maintenance costs caused by temperature changes, enhancing the economic benefits of buildings [12-14]. At the same time, this research also provides valuable references for the design and construction of similar buildings in the future.

However, existing research methods have certain limitations in dealing with the thermal expansion effects of super high-rise building structures. Many studies are mainly based on traditional empirical formulas and finite element analysis, neglecting the microscopic structural changes of building materials under complex temperature environments [15-18]. Moreover, the existing thermodynamic control strategies often lack systematicness and specificity, unable to fully address the unique challenges faced by super high-rise building structures [19-22]. Therefore, there is an urgent need for a more systematic and precise method to analyze and control the thermal expansion effects of super high-rise buildings.

The main content of this paper is divided into two parts. First, based on the effective medium theory, the thermal expansion coefficient of concrete in super high-rise building structures is solved, aiming to provide a more precise calculation method of the thermal expansion coefficient from the perspective of microscopic structure. Second, a set of thermodynamic control strategies for super high-rise building structures is proposed and verified, striving to effectively reduce the structural stress and deformation caused by temperature changes in practical applications. Through the above research, this paper hopes to provide more scientific and effective theoretical basis and technical means for the design and maintenance of super high-rise building structures, thereby enhancing the overall safety and economic benefits of buildings.

2. SOLVING THE THERMAL EXPANSION COEFFICIENT OF CONCRETE

In super high-rise building structures, concrete, as the main building material, has its thermal expansion characteristics directly affecting the overall performance and safety of the building. Concrete is a complex material composed of aggregates, cement paste, pores, and interfacial transition zones. The different thermal expansion characteristics of these components under temperature changes lead to the overall thermal expansion behavior of concrete. Based on micromechanics models and micromechanics fundamental theories, the thermal expansion coefficient of concrete can be theoretically calculated by analyzing the thermal expansion behavior of its internal microscopic components. The micromechanics model establishes the relationship between the macroscopic strain and the microscopic component strain by treating concrete as a composite material composed of multiple microscopic components. Specifically, when the temperature changes, various microscopic components such as aggregates and cement paste will produce different thermal strains, and these thermal strains interact through the interfacial transition zones to form the overall thermal expansion effect of concrete. To ensure the stability and safety of building structures, it is necessary to accurately calculate and control the thermal expansion coefficient of concrete. This study uses the micromechanics theory and effective medium theory to theoretically solve the thermal expansion coefficient of concrete in super high-rise building structures, thereby providing a more precise and scientific calculation method.

2.1 Effective medium estimation

The micromechanics model based on the generalized self-consistent model theoretically considers the interaction between inclusions and the matrix. However, in practical applications, this model has significant limitations. For super high-rise building structures, the size and distribution of inclusions within the concrete have great randomness and diversity, and the generalized self-consistent model appears to be insufficient when dealing with this complexity. Specifically, when the size ratio between inclusions and the matrix changes, the calculation results of the model may show significant deviations, affecting its accuracy and reliability. Moreover, the generalized self-consistent model is also influenced by the relative position of inclusions in the matrix. In the concrete of super high-rise building structures, the distribution of inclusions is not uniform, and various temperature gradients and stress states complicate the interactions of inclusions in different positions. However, the generalized self-consistent model finds it difficult to fully consider these complex relative position relationships during calculations, thus affecting the applicability of the model. Figure 1 shows the single inclusion models of different aggregate shapes in the concrete of super high-rise building structures.

To overcome these shortcomings, this paper adopts the micromechanics method based on the effective medium theory to analyze the thermal expansion behavior of concrete. Figure 2 shows a schematic diagram of the effective medium theory. The effective medium theory treats the cell unit composed of the matrix and inclusions as an equivalent medium composed of matrix material, and uses uniform stress and strain relationships to solve the thermal expansion coefficient of concrete.

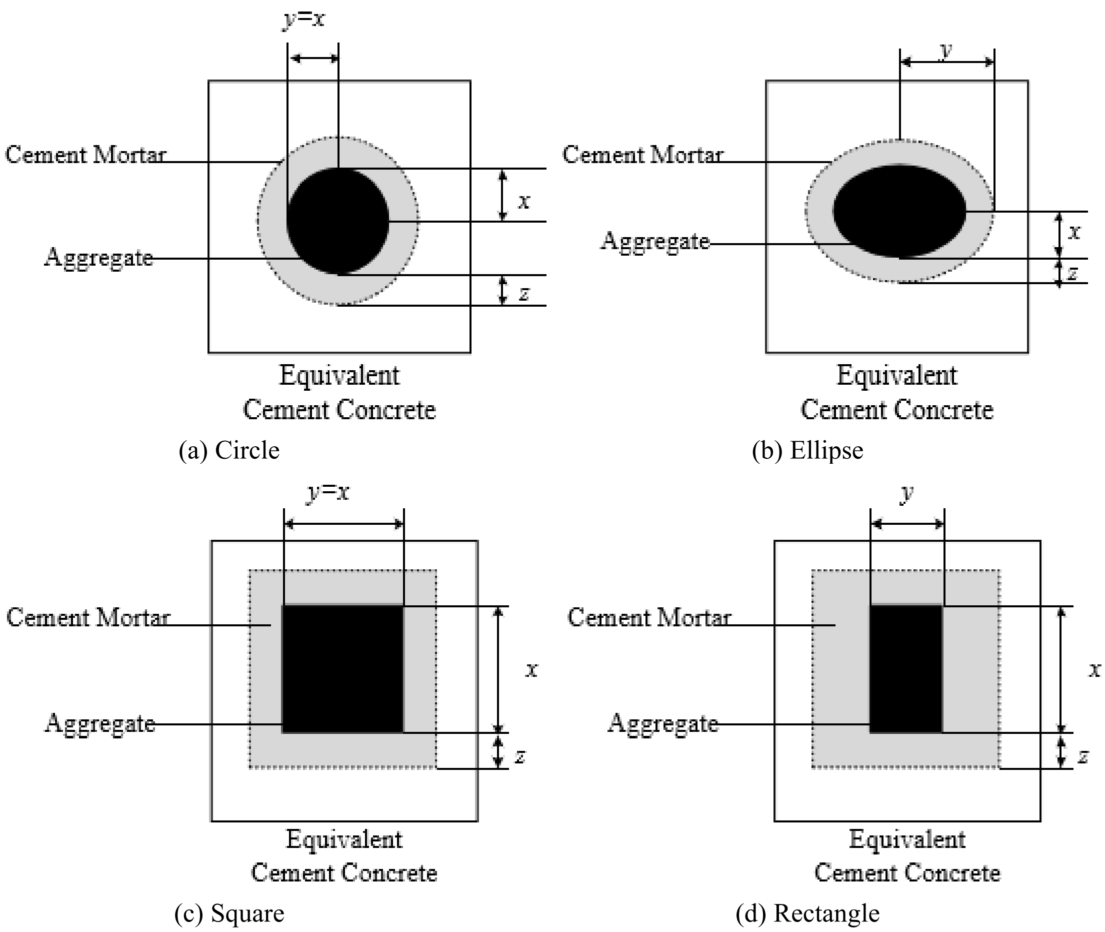

Figure 1. Single inclusion models of different aggregate shapes in the concrete of super high-rise building structures

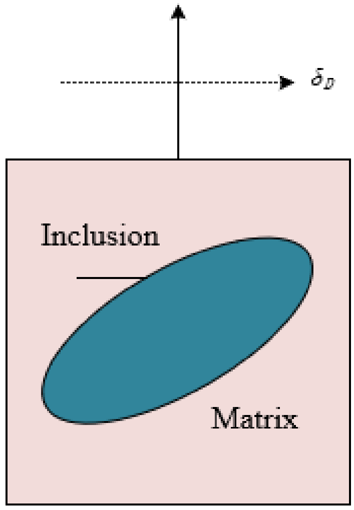

Figure 2. Effective medium theory

An important advantage of this model is that it overcomes the limitation of the generalized self-consistent model that can only handle circular or cylindrical inclusions. Regardless of how complex the shape of the inclusions is, the effective medium theory can perform accurate calculations, significantly enhancing the applicability and accuracy of the model. In addition, the effective medium theory is not affected by the relative size and relative position of the inclusions to the matrix. This is particularly important for super high-rise building structures because the shape and distribution of inclusions within the concrete are very complex and variable. By replacing the sparse solution of the far-field load with the uniform stress within a single inclusion, the effective medium theory can provide reliable thermal expansion coefficient calculation results under different temperature gradients and stress conditions. The specific solution steps are elaborated as follows.

In the generalized self-consistent model, it is assumed that the cell unit composed of inclusions and the matrix is completely composed of matrix material and placed in an infinitely large effective medium. This assumption helps to better understand the relationship between the microscopic structure and macroscopic behavior of concrete in super high-rise building structures, improving the reliability of the calculation results. Furthermore, according to the far-field effect, the average stress within the inclusion-matrix cell unit is calculated based on the following formula. This step is to determine the stress distribution between inclusions and the matrix under macroscopic boundary conditions. For super high-rise buildings, this helps engineers accurately predict the structural stress state under different temperature conditions. Assuming that the average strain within the inclusion-matrix cell unit is represented by $\gamma^{-}{}_{F}$; the average stress within the inclusion-matrix cell unit is represented by $\delta^{-}{}_{F}$; the compliance tensor of the effective medium is represented by Z^{-1}; the compliance tensor of the matrix is represented by $Z^{-1}{}_{0}$; the stiffness tensor of the effective medium is represented by Z; the Eshelby tensor corresponding to the geometry of the s-phase inclusion is represented by T_s; the Eshelby tensor corresponding to the geometry of the inclusion-matrix cell unit is represented by T_F, the calculation formulas are as follows:

$$\overline{\gamma_F} = Z_0^{-1}\overline{\delta_F} \tag{1}$$

$$\overline{\delta_F} = \left[U + Z\left(U - T_F\right)\left(Z_s^{-1} - Z^{-1}\right)\right]\delta^0 \tag{2}$$

$$\overline{\delta_s} = \left[U + Z_0\left(U - T_s\right)\left(Z_s^{-1} - Z_0^{-1}\right)\right]\overline{\delta_F} \tag{3}$$

The uniform stress effective medium estimation within the inclusion can be obtained by the following formula:

$$\begin{gathered}\overline{\delta_s} = \left[U + Z_0\left(U - T_s\right)\left(Z_s^{-1} - Z_0^{-1}\right)\right] \\ \left[U + Z\left(U - T_F\right)\left(Z_0^{-1} - Z^{-1}\right)\right]\delta^0\end{gathered} \tag{4}$$

Based on the obtained uniform stress within the inclusion, the effective medium estimation is performed. The effective medium estimation establishes the relationship between the average stress within the inclusion and the uniform stress boundary conditions, further simplifying and optimizing the calculation of the stress field, and replacing the sparse solution of the far-field load with the uniform stress within a single inclusion, thereby achieving more accurate stress estimation. Based on the known macroscopic boundary conditions, the stress field and strain field within the microscopic components can be further calculated using the results of the effective medium estimation. For super high-rise buildings, this calculation helps to identify weaknesses in the structure and prevent local damage caused by thermal expansion.

2.2 Calculation of thermal expansion coefficient

In practical super high-rise buildings, the thermal expansion effect of concrete arises from its nature as a multiphase composite material with different phases having different thermal expansion coefficients. Concrete is composed of various components, including the cement matrix, aggregates, and other additives. These components have different thermal expansion coefficients and will produce different strains under temperature changes. Due to these different thermal expansion coefficients, their relative deformation under temperature changes will induce internal stress, known as thermal stress. According to thermodynamic principles, the thermal stress of each phase is proportional to its thermal expansion coefficient. In the absence of external forces, even with uniform temperature changes, the stress distribution among different components of the composite material will vary due to the differences in their thermal expansion coefficients. The accumulation of these microscopic stresses and strains affects the macroscopic behavior of the entire material. The detailed steps for solving the thermal expansion coefficient of multiphase composite concrete are as follows.

Assuming that the cement concrete material consists of N-phase aggregate inclusions, under temperature changes, each component will produce characteristic strains. Without external force, the macroscopic strain of the concrete material is mainly composed of these characteristic strains. Assuming the macroscopic effective strain of the multiphase composite material is represented by γ^{-}, and the characteristic strain within the s-phase inclusion is represented by $\gamma^{*}{}_{s}$, based on the stress relationship, these characteristic strains can be described as:

$$\overline{\gamma} = \sum_{s=1}^{V}\gamma_s^{*} \tag{5}$$

To separate the stress-strain field under external force, so as to consider the characteristic strains caused by temperature in subsequent steps, it is assumed that the material, under uniform external force δ^0, without characteristic strain, has the stress and strain fields of the super high-rise building structure concrete as δ' and γ' respectively. The equations are as follows:

$$\overline{\delta'\gamma} = \delta^0 \overline{\gamma} = \delta^0 \gamma^* \tag{6}$$

The overall characteristic strain is expressed as the weighted average of the characteristic strains of each phase based on the volume fraction of the matrix and each inclusion phase in the concrete. This comprehensively considers the deformation characteristics of different materials under temperature changes, accurately predicting the thermal expansion behavior of concrete in practical use. This step is particularly important for optimizing concrete mix proportions and improving material performance, thereby enhancing the durability and stability of buildings. The overall characteristic strain can be expressed as:

$$\begin{aligned} \overline{\delta'\gamma} = \overline{\delta'\gamma^*} &= z_0 \overline{\delta_0^*} \gamma_0^* + \sum_{s=1}^{V} z_s \overline{\delta_t'} \gamma_s^* \\ &= \delta^0 \gamma_0^* + \sum_{s=1}^{V} z_s \overline{\delta_s'} \left(\gamma_s^* - \gamma_0^* \right) \end{aligned} \tag{7}$$

Combining Eqs. (5) and (7), we get:

$$\delta^0 \gamma^* = \delta^0 \gamma_0^* + \sum_{s=1}^{V} z_s \overline{\delta_s^*} \left(\gamma_s^* - \gamma_0^* \right) \tag{8}$$

By combining Eq. (4) and Eq. (7), the macroscopic equivalent characteristic strain calculation formula for cement concrete can be obtained as follows:

$$\gamma^* = \gamma_0^* + \sum_{s=1}^{V} z_s \left[U + Z\left(U - T_F\right)\left(Z_0^{-1} - Z^{-1}\right) \right] \left[U + Z_0\left(U - T_s\right)\left(Z_t^{-1} - Z_0^{-1}\right) \right]^{-1} \left(\gamma_s^* - \gamma_0^* \right) \tag{9}$$

The overall effective strain of the concrete, the characteristic strain of the matrix, and the inclusion phases are expressed using the corresponding thermal expansion coefficients. That is, the overall effective strain of the material, the characteristic strain in the matrix phase, and the characteristic strain in the inclusion phase are represented by the effective thermal expansion coefficient β, the thermal expansion coefficient of the matrix material β_0, and the thermal expansion coefficient of the s-phase inclusion β_s, respectively. This step integrates the thermal expansion characteristics of different materials into a unified framework, providing an effective method for predicting the behavior of concrete under temperature changes. The expressions are as follows:

$$\gamma^* = \beta S \tag{10}$$

$$\gamma_0^* = \beta_0 S \tag{11}$$

$$\gamma_s^* = \beta_s S \tag{12}$$

Assuming the compliance matrix of the aggregate is represented by $Z^{-1}{}_u$, and the thermal expansion coefficient of the aggregate is represented by β_u. Combining Eqs. (10)-(12) with Eq. (9), the equivalent thermal expansion coefficient of the multiphase composite material can be derived:

$$\beta = \beta_0 + \sum_{s=1}^{V} z_s \left[U + Z\left(U - T_F\right)\left(Z_0^{-1} - Z^{-1}\right) \right] \left[U + Z_0\left(U - T_s\right)\left(Z_s^{-1} - Z_0^{-1}\right) \right]^{-1} \left(\beta_s - \beta_0 \right) \tag{13}$$

Typically, the concrete used in super high-rise building structures uses the same type of coarse aggregate. Therefore, it can be assumed that the thermal expansion coefficient and elastic modulus of the concrete are fixed and unchanged. Thus, the above equation can be expressed in another form:

$$\beta = \beta_0 + \sum_{s=1}^{V} z_s \left[U + Z\left(U - T_F\right)\left(Z_0^{-1} - Z^{-1}\right) \right] \left[U + Z_0\left(U - T_s\right)\left(Z_u^{-1} - Z_0^{-1}\right) \right]^{-1} \left(\beta_u - \beta_0 \right) \tag{14}$$

This equation derives the thermal expansion coefficient of cement concrete by solving the macroscopic strain. Since the material expands uniformly in two mutually perpendicular directions and the shear direction under the assumption of isotropy, there is no strain in the shear direction. Thus, the matrix calculation result is a 3×1 matrix with the third component being zero. In practical applications, super high-rise building structures typically require materials to exhibit macroscopic isotropy to ensure uniformity and stability in all directions. Therefore, this paper considers taking the larger value as the overall thermal expansion coefficient of cement concrete under the most unfavorable conditions. This conservative choice can increase the safety margin of the building and reduce potential risks caused by material anisotropy. Meanwhile, in super high-rise building structures, concrete needs to withstand complex loads and environmental temperature changes. Accurately solving the thermal expansion coefficient of multiphase composite cement concrete helps to predict the deformation and stress distribution of the structure under temperature changes, thereby formulating effective thermodynamic control strategies. For example, during extreme temperature changes in hot summers and cold winters, the thermal expansion and contraction of concrete can cause deformation and stress concentration in the structure. By using the larger calculated thermal expansion coefficient for design, the safety of the structure under extreme conditions can be ensured.

3. THERMODYNAMIC CONTROL STRATEGIES FOR SUPER HIGH-RISE BUILDING STRUCTURES

In super high-rise buildings, due to the height and complexity of the structures, the problems caused by the thermal expansion of concrete structures are particularly prominent. The thermal expansion coefficient of multiphase composite cement concrete varies in different directions and is greatly affected by temperature changes. Therefore, formulating effective thermodynamic control strategies is of great significance for ensuring the safety and stability of super high-rise building structures. Figure 3 provides a schematic diagram of the thermodynamic control test frame for super high-rise building structures. Figure 4 shows the thermodynamic control flowchart for super high-rise building structures.

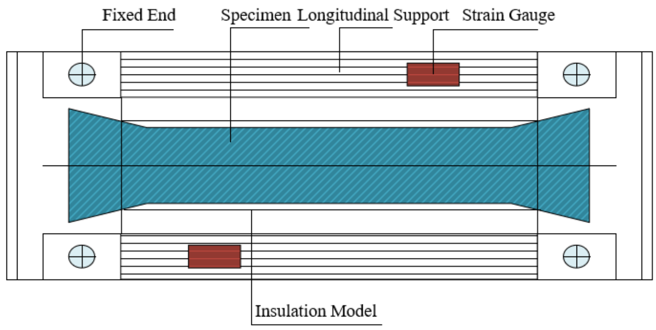

Figure 3. Schematic diagram of the thermodynamic control test frame for super high-rise building structures

(1) Applying Insulation Layers on the Structure Surface

In the thermodynamic control strategy for super high-rise buildings, applying insulation layers is one of the key measures to reduce the impact of thermal expansion. By installing insulation materials such as polyurethane foam, rock wool board, or vacuum insulation panels on the surface of the structure, the impact of external environmental temperature changes on the internal temperature of the structure can be effectively reduced. These insulation materials have excellent thermal insulation properties and can effectively block the rapid temperature changes from being transmitted to the inside of the concrete, thereby reducing the drastic internal temperature changes of the concrete. This not only reduces the possibility of stress concentration and crack formation caused by temperature but also improves the energy efficiency of the building, reducing the energy consumption for air conditioning and heating.

Selecting suitable insulation materials and ensuring their construction quality are crucial for the implementation of insulation layers. Polyurethane foam has the advantages of light weight, high strength, and excellent thermal insulation properties, making it suitable for complex shapes and high-demand insulation projects. Rock wool board has good fire resistance and sound insulation effects, making it suitable for buildings with high fire protection requirements. Vacuum insulation panels have extremely low thermal conductivity and can provide the best insulation effect, making them suitable for building parts with extremely high insulation requirements. During construction, it is necessary to ensure the continuity and integrity of the insulation layer and avoid gaps between the insulation layer and the structure surface to achieve the best insulation effect.

(2) Installing Cooling Systems Inside the Structure

By embedding cooling water pipes and installing refrigeration equipment, the internal temperature of the structure can be effectively controlled. The cooling system reduces the internal temperature of the concrete through circulating cooling water, thereby alleviating thermal expansion caused by external high temperatures. This system can not only adjust in real time according to actual temperature changes but also provide stable cooling effects under extreme high-temperature conditions, ensuring the stability of the structure in complex environments. Specifically, the layout design of the cooling water pipes needs to be reasonably planned to ensure uniform cooling effects and avoid adverse impacts of cooling water on the structure. The cooling water pipes should be distributed in key parts of the structure, such as areas of concentrated stress and parts with significant temperature changes. Installing temperature sensors and automatic control systems can achieve precise monitoring and adjustment of the temperature. Temperature sensors monitor the internal temperature changes of the concrete in real-time and transmit the data to the automatic control system. The control system adjusts the flow of cooling water according to the temperature change trend to ensure that the internal temperature of the structure is within a safe range. Additionally, the design of the cooling system needs to consider the source and circulation method of the cooling water. Cooling water temperature can be managed by setting up cooling towers or utilizing natural water sources to ensure the efficient operation of the cooling system. In high-rise buildings, due to the significant height difference, pressure control of the cooling water is also a key issue. By setting up booster pumps and pressure regulation devices, uniform distribution and stable flow of cooling water at different heights can be ensured.

(3) Setting Expansion Joints and Contraction Joints

By reserving appropriate expansion joints and contraction joints in the structure, concrete can expand and contract freely due to temperature changes, effectively reducing stress concentration caused by temperature changes and preventing the structure from cracking. Filling the joints with elastic materials can ensure that the joints function properly when the temperature changes. Specifically, expansion joints and contraction joints should be set in areas where stress is concentrated and temperature changes significantly, such as between floors, at the intersections of walls and columns, and between concrete slabs. Based on the height of the building and design requirements, the spacing and number of joints should be scientifically calculated to ensure their effectiveness. Generally, setting an expansion joint or contraction joint at regular intervals can effectively disperse the stress caused by thermal expansion. It is also necessary to choose suitable elastic materials to fill the joints. These materials should have good expansion performance and durability, able to function under temperature changes. Commonly used elastic materials include polyurethane sealant, silicone sealant, and rubber gaskets. These materials can not only expand and contract freely with temperature changes but also prevent water and impurities from entering the joints, protecting the long-term stability of the structure. During construction, it is also important to ensure the cleanliness and filling quality of the joints. The joints should be kept clean, free of dust and debris, to ensure the bonding effect of the elastic materials. When filling the elastic materials, construction should be carried out according to design requirements to ensure the continuity and integrity of the joints, thus achieving the best thermal expansion control effect.

(4) Coating the Surface with Protective Coatings with Thermal Reflective Properties or Laying Protective Films

Coating the surface with protective coatings that have thermal reflective properties or laying protective films can effectively reduce the heating of concrete by solar radiation, lower surface temperature changes, and prevent surface damage caused by temperature changes. Selecting suitable coating materials and ensuring construction quality can achieve the best protective effect. Specifically, first, choose appropriate coating materials and protective films. Commonly used thermal reflective coating materials include white or silver reflective paint, ceramic coatings, and metal coatings. These materials have high reflectivity and can effectively reflect solar radiation, reducing surface temperature. Protective films often use high reflectivity metal films or multilayer composite films. These film materials not only have good reflective properties but also provide additional mechanical protection, preventing the concrete surface from external physical damage. During construction, ensure that the coatings or protective films are applied or laid uniformly, avoiding problems such as uneven thickness or bubbles. Before application, the concrete surface should be cleaned and treated to improve the adhesion of the coatings or protective films. After construction is completed, quality inspection and testing should be carried out to ensure that the reflective effect of the coatings or protective films meets expectations. Due to long-term exposure to the external environment, the coatings or protective films may suffer wear and aging. Regular inspection and maintenance are necessary to ensure the continuous effectiveness of their thermal reflective properties. When necessary, repair or replace damaged or aged parts to maintain the thermal protection effect of the building surface.

Comprehensive application of the above thermodynamic control strategies can effectively manage the thermal expansion issues of multiphase composite cement concrete. These measures not only help to improve the thermal stability of the building but also extend the service life of the building and reduce safety risks caused by temperature changes. Through scientific thermodynamic control, the stability and safety of super high-rise building structures under extreme conditions can be ensured.

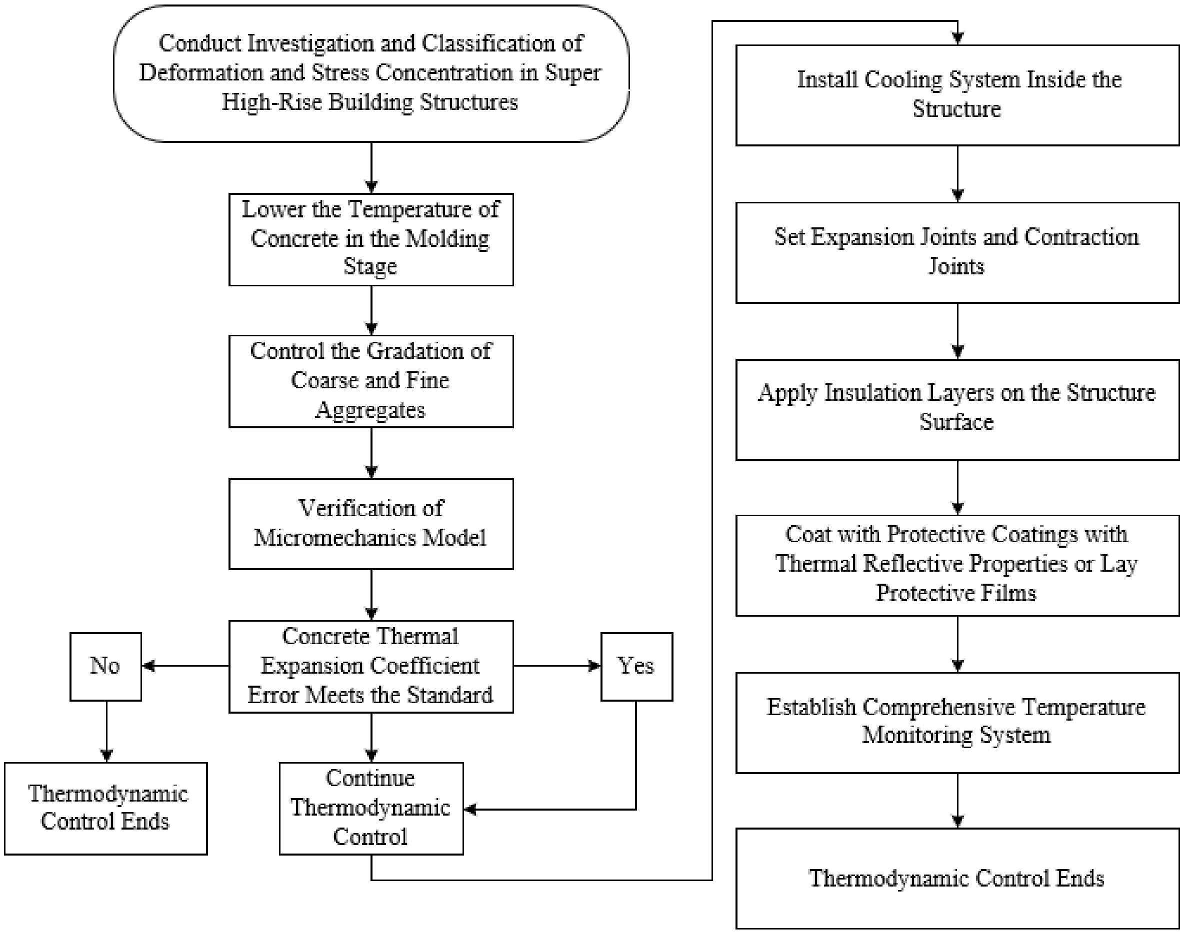

Figure 4. Thermodynamic control flowchart for super high-rise building structures

4. EXPERIMENTAL RESULTS AND ANALYSIS

Table 1 shows the relationship data between different aggregate content and the thermal expansion coefficient of concrete in super high-rise buildings. In the experiment, the aggregate content was 50%, 60%, and 70%, respectively. While keeping the aggregate thermal expansion coefficient (4.7×10^{-6}/°C), aggregate porosity (1.956%), and water-cement ratio (0.52) constant, the thermal expansion coefficients of the concrete were 11.23×10^{-6}/°C, 10.21×10^{-6}/°C, and 9.98×10^{-6}/°C, respectively. It can be observed that as the aggregate content increases, the thermal expansion coefficient of the concrete gradually decreases, indicating that the aggregate content has a significant impact on the thermal expansion performance of the concrete. The experimental results show that increasing the aggregate content can effectively reduce the thermal expansion coefficient of the concrete, thereby reducing the structural stress and deformation caused by temperature changes. Based on these experimental results, this paper uses the effective medium theory from a microscopic structure perspective to calculate the thermal expansion coefficient of the concrete, providing a more accurate calculation method.

Table 2 shows the difference changes in the aggregate thermal expansion coefficient, porosity, and concrete thermal expansion coefficient in different experimental groups. Under the same water-cement ratio (0.52), experimental groups 2 and 3 show that the difference changes in aggregate thermal expansion coefficient are 34.5% and 51.2%, respectively, and the difference changes in porosity are -61.2% and 48.9%, corresponding to the difference changes in concrete thermal expansion coefficient of 12.1% and 13.1%. In the experimental groups with a water-cement ratio of 0.35, experimental groups 5 and 6 show that the difference changes in aggregate thermal expansion coefficient are 47.6% and 45.2%, respectively, and the difference changes in porosity are -15.2% and -44.3%, corresponding to the difference changes in concrete thermal expansion coefficient of 3.1% and 15.2%. These data indicate that different parameter combinations have significant effects on the thermal expansion coefficient of the concrete, especially the changes in aggregate thermal expansion coefficient and porosity significantly affect the thermal expansion behavior of the concrete. The experimental results show that the changes in aggregate thermal expansion coefficient and porosity have a very significant impact on the thermal expansion coefficient of the concrete. Especially under the same water-cement ratio, as the aggregate thermal expansion coefficient increases and the porosity changes significantly, the difference changes in the thermal expansion coefficient of the super high-rise building concrete also increase significantly.

Figure 5 shows the changes in the thermal expansion coefficient of concrete in super high-rise buildings under different water-cement ratios (0.35, 0.45, 0.55) and aggregate content (70%, 60%). When the aggregate content is 70%, as the water-cement ratio increases from 0.35 to 0.55, the thermal expansion coefficient of the concrete is 10.9×10^{-6}/°C, 10.3×10^{-6}/°C, and 10×10^{-6}/°C, respectively. When the aggregate content is 60%, as the water-cement ratio increases from 0.35 to 0.55, the thermal expansion coefficient of the concrete is 11.2×10^{-6}/°C, 10.85×10^{-6}/°C, and 10.25×10^{-6}/°C, respectively. These data indicate that as the water-cement ratio increases, the thermal expansion coefficient of the concrete in super high-rise buildings gradually decreases, and the aggregate content has a significant impact on this trend. The experimental results show that reducing the water-cement ratio can effectively reduce the thermal expansion coefficient of concrete in super high-rise buildings, thereby reducing stress and deformation caused by temperature changes. Under the same aggregate content, the lower the water-cement ratio, the smaller the thermal expansion coefficient of the concrete, indicating that the water-cement ratio has an important impact on the thermal expansion performance of the concrete. This paper uses the effective medium theory from a microscopic structure perspective to accurately solve the thermal expansion coefficient of concrete, providing a more accurate calculation method.

Table 1. Relationship data between aggregate content and concrete thermal expansion coefficient

Experimental Group Number	Aggregate Content (%)	Aggregate Thermal Expansion Coefficient	Aggregate Porosity (%)	Water-Cement Ratio	Concrete Thermal Expansion Coefficient (10^{-6}/°C)
1	50	4.7	1.956	0.52	11.23
2	60	4.7	1.956	0.52	10.21
3	70	4.7	1.956	0.52	9.98

Table 2. Difference changes in aggregate thermal expansion coefficient, porosity, and concrete thermal expansion coefficient

Experimental Group Number	Aggregate Thermal Expansion Coefficient Difference Change (%)	Aggregate Porosity Difference Change (%)	Water-Cement Ratio	Concrete Thermal Expansion Coefficient Difference Change (%)
1	0.0	0.0	0.52	0.0
2	34.5	-61.2	0.52	12.1
3	51.2	48.9	0.52	13.1
4	0.0	0.0	0.35	0.0
5	47.6	-15.2	0.35	3.1
6	45.2	-44.3	0.35	15.2

Table 3. Comparison of effects of concrete thermodynamic control measures

Concrete Thermodynamic Control Measures	Stage of Thermodynamic Control Measures	Reduction Effect on Damage and Destruction	Defects of Thermodynamic Control Measures
Use of High-Performance Concrete	Design and Construction Stage	4.00%→ 0.54%	High cost, high construction difficulty
Lowering the Temperature of Concrete in the Molding Stage	Design and Construction Stage	4.00%→2.24%	Limited by environmental conditions, increases construction complexity
Controlling the Gradation of Coarse and Fine Aggregates	Design and Construction Stage	4.00%→0.57%	Complex design and verification, limited material selection
Coating the Surface with Protective Coatings with Thermal Reflective Properties or Laying Protective Films	Design and Construction Stage	4.00%→1.71%	Durability issues, high construction quality requirements
Setting Expansion Joints and Contraction Joints	Design and Construction Stage	9.94%→2.54%	Complex design, impacts structural integrity
Applying Insulation Layers on the Structure Surface	Structural Maintenance Stage	4.00%→1.99%	Increases structural weight, complex construction process
Installing Cooling Systems Inside the Structure	Structural Maintenance Stage	4.00%→0.00%	High cost, complex system
Grouting to Repair Cracks	Structure Formation Stage	None	Temporary measure, limited application scope

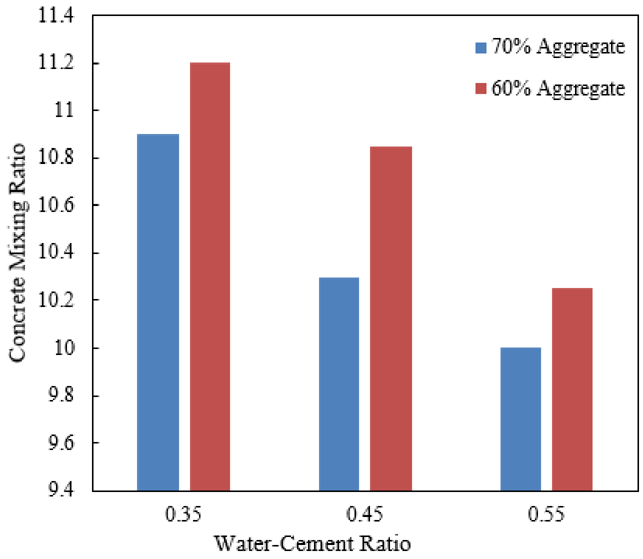

Figure 5. Relationship between water-cement ratio and concrete thermal expansion coefficient under the same aggregate content

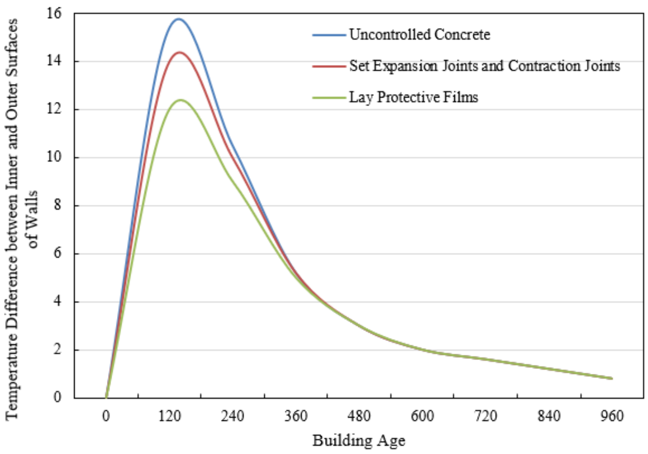

Figure 6. Temperature difference curve between inner and outer surfaces of concrete walls under different thermodynamic control strategies

Table 3 shows the reduction effects and defects of various thermodynamic control measures for super high-rise concrete buildings at different stages. The use of high-performance concrete, controlling the gradation of coarse and fine aggregates, and installing cooling systems inside the structure show significant reduction effects on damage and destruction during the design and construction stages and structural maintenance stage, reducing from 4.00% to 0.54%, 0.57%, and 0.00% respectively. However, the defects of these measures include high cost, high construction difficulty, and system complexity. Other measures, such as lowering the temperature of concrete in the molding stage, coating the surface with protective coatings with thermal reflective properties or laying protective films, and setting expansion joints and contraction joints, although effective in reducing damage and destruction (reducing to 2.24%, 1.71%, and 2.54% respectively), also have defects such as being limited by environmental conditions, durability issues, and complex design. The experimental results show that various thermodynamic control measures for super high-rise concrete buildings have different effects and defects in reducing structural damage and destruction caused by temperature changes. The most effective measures are the use of high-performance concrete and the installation of cooling systems inside the structure, but their high cost and complexity limit their widespread practical application.

Figure 6 shows the temperature difference between the inner and outer surfaces of concrete walls at different building ages for uncontrolled concrete, concrete with expansion and contraction joints, and concrete with protective films. The temperature difference of uncontrolled concrete is 0 on the 0th day, reaching a maximum temperature difference of 15.4℃ on the 120th day, then gradually decreasing to 0.8℃ on the 960th day. The temperature difference of concrete with expansion and contraction joints gradually increases from 0℃ on the 0th day to 14℃ on the 120th day, then slowly decreases to 0.8℃ on the 960th day. The temperature difference of concrete with protective films shows a similar trend, increasing from 0℃ on the 0th day to 12℃ on the 120th day, then gradually decreasing to 0.8℃ on the 960th day. These data indicate that both setting expansion joints and laying protective films can effectively reduce the peak temperature difference and maintain a low temperature difference over the long term. The experimental results show that by setting expansion joints and contraction joints and laying protective films, the peak temperature difference between the inner and outer surfaces of concrete walls can be significantly reduced and maintain a low temperature difference during the extended building age, indicating that these thermodynamic control strategies have a significant effect in practical applications. Especially laying protective films can reduce the peak temperature difference from 15.4℃ for uncontrolled concrete to 12℃, effectively controlling the impact of temperature changes on the concrete structure.

Figure 7 shows the temperature difference between the inner and outer surfaces of concrete walls at different building ages for concrete without insulation layers and with insulation layers. The temperature difference of concrete without insulation layers is 0 on the 0th day, reaching a maximum temperature difference of 15.4℃ on the 120th day, then gradually decreasing to 0.8℃ on the 960th day. In contrast, the temperature difference of concrete with insulation layers is 0 on the 0th day, 8℃ on the 120th day, then gradually increasing to 10℃ on the 240th day, and slowly decreasing to 4℃ on the 960th day. These data indicate that setting insulation layers can significantly reduce the peak temperature difference and maintain a relatively stable temperature difference over the long term. The experimental results show that by setting insulation layers on the surface of concrete structures, the peak temperature difference caused by temperature changes can be effectively reduced, and the temperature difference can be maintained within a lower and stable range. The temperature difference of concrete without insulation layers reaches a maximum peak of 15.4℃ in the early building age, while the peak temperature difference of concrete with insulation layers is only 10℃, and the temperature difference remains stable at 4℃ at 960 days.

Figure 8 shows the temperature difference between the inner and outer surfaces of concrete walls at different building ages for concrete with and without cooling pipes. The temperature difference of concrete with cooling pipes is 0 on the 0th day, reaching a maximum temperature difference of 15.4℃ on the 120th day, then gradually decreasing to 0.8℃ on the 960th day. In contrast, the temperature difference of concrete without cooling pipes is 0 on the 0th day, 8℃ on the

120th day, then gradually decreasing to 0.5℃ on the 960th day. These data indicate that the temperature difference change in concrete with cooling pipes is larger, while the temperature difference in concrete without cooling pipes is smaller and more stable. The experimental results show that concrete without cooling pipes performs better in temperature difference control, with a lower peak temperature difference and more stable changes throughout the building age, finally maintaining at 0.5℃ at 960 days. In contrast, the concrete with cooling pipes reaches a peak temperature difference of 15.4℃ initially, then gradually decreases but remains larger than the concrete without cooling pipes.

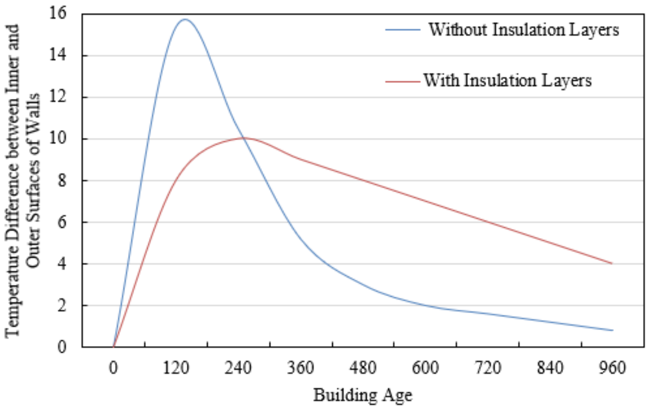

Figure 7. Temperature difference curve between inner and outer surfaces of concrete walls with insulation layers

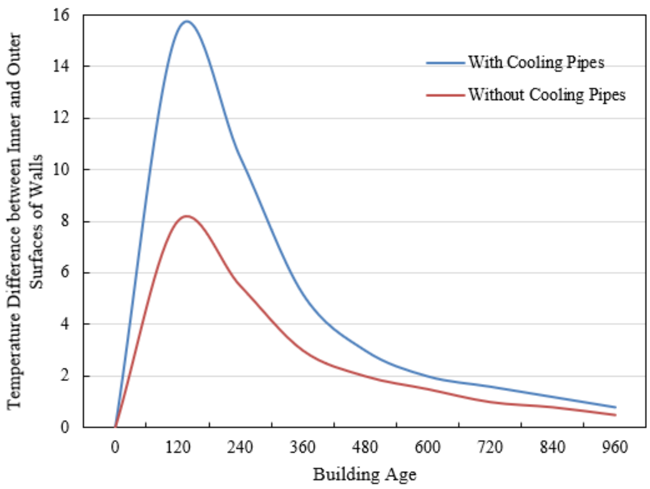

Figure 8. Temperature difference curve between inner and outer surfaces of concrete walls with cooling pipes

This paper accurately calculates the thermal expansion coefficient of concrete using the effective medium theory and proposes a systematic set of thermodynamic control strategies. These strategies show significant effects in reducing structural stress and deformation caused by temperature changes, particularly strategies without setting expansion and contraction joints, without laying protective films, without setting insulation layers, and without installing cooling pipes, which maintain a low temperature difference over a long period. This provides scientific evidence and engineering guidance for the thermodynamic management of super high-rise buildings, further verifying the effectiveness and practical application value of this study.

5. CONCLUSION

The research content of this paper mainly includes two parts. First, based on the effective medium theory, this paper accurately solved the thermal expansion coefficient of concrete in super high-rise building structures, providing a more accurate calculation method from the microscopic structure perspective. By analyzing the relationship data between aggregate content and concrete thermal expansion coefficient, the difference changes in aggregate thermal expansion coefficient, porosity, and concrete thermal expansion coefficient were studied, and a relationship curve between water-cement ratio and concrete thermal expansion coefficient under the same aggregate content was plotted, providing theoretical basis for further optimizing concrete mix design. Second, this paper proposed and verified a set of thermodynamic control strategies for super high-rise building structures. The experimental results show that measures such as using high-performance concrete, setting expansion and contraction joints, laying protective films, setting insulation layers, and installing cooling pipes exhibit different effects and advantages in reducing the temperature difference between inner and outer surfaces of concrete walls caused by temperature changes.

The thermal expansion coefficient of concrete calculated based on the effective medium theory provides higher precision theoretical data, helping to optimize the selection and mix design of concrete materials. The verification results of thermodynamic control strategies show that various control measures can reduce structural stress and deformation caused by temperature changes to varying degrees, with the strategies of not installing cooling pipes and setting insulation layers maintaining a low temperature difference over a long period, performing particularly well. This provides scientific evidence and engineering guidance for the thermodynamic management of super high-rise buildings.

The experimental study in this paper is mainly based on model verification under laboratory conditions and cannot fully simulate the complex environment of actual engineering. Moreover, the control measures considered in the study, though diverse, may be limited by factors such as construction difficulty, cost, and maintenance management in practical applications. Therefore, the practical application of the research results needs to be comprehensively evaluated in combination with specific engineering conditions. Future research should further combine long-term monitoring data in actual engineering to verify and optimize the thermal expansion coefficient of concrete and thermodynamic control measures. Additionally, considering the impact of different environmental conditions on concrete structures, more research can be conducted on the thermodynamic behavior of concrete under different climatic conditions to propose more widely applicable control strategies and design methods. Developing new materials and technologies to improve the feasibility and economy of control measures is also an important direction for future research.

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REFERENCES

[1] Selim, A.M., Salama, E.A., Gaber, H.M. (2024). Optimizing safe evacuation using pathfinder: Emergency strategies in high-rise and super high-rise complex buildings in the new administrative capital. HBRC Journal, 20(1): 385-413. https://doi.org/10.1080/16874048.2024.2320621

[2] Pan, X., Zhao, T. (2024). Pressure deviation monitoring and early warning in large integrated tower crane support system for super high-rise buildings. Measurement: Sensors, 31: 101019. https://doi.org/10.1016/j.measen.2023.101019

[3] Jiang, L., Liu, Z., Ma, X. (2024). Seismic vulnerability analyses of multi-tower super high-rise buildings under near fault ground motions. Journal of Vibration and Shock, 43(5): 273-282. https://doi.org/10.13465/j.cnki.jvs.2024.05.030

[4] Liu, C., Xie, Z., Yu, X., Zhang, L. (2024). Wind effects of super high-rise buildings in the pearl river delta of China based on 10-year full-scale measurements. Journal of Structural Engineering, 150(2): 04023222. https://doi.org/10.1061/JSENDH.STENG-12667

[5] Nie, W., Tang, Y., Cheng, H., Tian, F., Sun, Q., Lu, X., Zhao, Y. (2023). Building Negative-Thermal-Expansion protective layers on the grain boundary of Ni-rich cathodes enables safe and durable high voltage Lithium-Ion batteries. Small, 19(52): 2306351. https://doi.org/10.1002/smll.202306351

[6] Alazmi, A., Seo, H. (2023). Thermal displacement mapping for detecting thermal expansion of heritage building during heatwave using 3D laser scanning. Developments in the Built Environment, 16: 100226. https://doi.org/10.1016/j.dibe.2023.100226

[7] Yu, H., Wang, H., Guo, X., Liang, B., Wang, X., Zhou, H., Zhang, X., Chen, M., Lei, H. (2022). Building block design for composite metamaterial with an ultra-low thermal expansion and high-level specific modulus. Composite Structures, 300: 116131. https://doi.org/10.1016/j.compstruct.2022.116131

[8] López-Doncel, R., Wedekind, W., Aguillón-Robles, A., Dohrmann, R., Molina-Maldonado, S., Leiser, T., Anna W., Siegesmund, S. (2018). Thermal expansion on volcanic tuff rocks used as building stones: examples from Mexico. Environmental Earth Sciences, 77(9): 1-23. https://doi.org/10.1007/s12665-018-7533-0

[9] Krzhizhanovskaya, M.G., Bubnova, R.S., Filatov, S.K. (2019). Crystalline borosilicates of alkali and alkaline earth metals: hierarchy, fundamental building blocks and thermal expansion. Physics and Chemistry of Glasses-European Journal of Glass Science and Technology Part B, 60(4): 129-139. https://doi.org/10.13036/17533562.60.4.049

[10] Xu, H., Farag, A., Pasini, D. (2018). Routes to program thermal expansion in three-dimensional lattice metamaterials built from tetrahedral building blocks. Journal of the Mechanics and Physics of Solids, 117: 54-87. https://doi.org/10.1016/j.jmps.2018.04.012

[11] Mukai, K., Kim, J.H., Nakamichi, M. (2023). Measurement of thermal expansion anisotropy in Be12Ti and Be12V. Nuclear Materials and Energy, 36: 101473. https://doi.org/10.1016/j.nme.2023.101473

[12] Hund, S., Rudolph, M., Brandt, U., Scheiba, S. (2023). Systemdiagnose an haustechnischen Kompensator-Installationen: Zur Ableitung einer zustandsabhängigen Instandhaltungsstrategie mit automatisierter Entscheidungsfindung. Zeitschrift für wirtschaftlichen Fabrikbetrieb, 118(4): 237-243. https://doi.org/10.1515/zwf-2023-1035

[13] Rishmawi, I., Rogalsky, A., Vlasea, M., Salarian, M., Bakhshivash, S. (2022). The effects of heat treatment on tensile and thermal expansion behavior of laser powder-bed fusion Invar36. Journal of Materials Engineering and Performance, 31(12): 9727-9739. https://doi.org/10.1007/s11665-022-07013-x

[14] Pan, J., Liu, J., Zhang, L., Liu, X., Li, B. (2023). Prediction of thermal expansion coefficient of fiber-reinforced cement concrete based on micromechanics method. Applied Physics A, 129(8): 531. https://doi.org/10.1007/s00339-023-06800-0

[15] Sood, A., Schimmel, J., Bosman, M., Goulas, C., Popovich, V., Hermans, M.J. (2024). Fabrication of low thermal expansion Fe–Ni alloys by in-situ alloying using twin-wire arc additive manufacturing. Materials & Design, 240: 112837. https://doi.org/10.1016/j.matdes.2024.112837

[16] Huang, G., He, G., Liu, Y., Huang, K. (2024). Anisotropy of microstructure, mechanical properties and thermal expansion in Invar 36 alloy fabricated via laser powder bed fusion. Additive Manufacturing, 82: 104025. https://doi.org/10.1016/j.addma.2024.104025

[17] Kim, M.H., Kim, D., Heo, J., Lee, D.W. (2023). Energy performance of direct-expansion solar heat pump integrated with thermal network. Case Studies in Thermal Engineering, 49: 103267. https://doi.org/10.1016/j.csite.2023.103267

[18] Esteban-Cantillo, O.J., Menendez, B., Quesada, B. (2024). Climate change and air pollution impacts on cultural heritage building materials in Europe and Mexico. Science of the Total Environment, 921: 170945. https://doi.org/10.1016/j.scitotenv.2024.170945

[19] Bai, Y., Zhao, C., Zhang, J., Wang, H. (2022). Abnormal thermal expansion behaviour and phase transition of laser powder bed fusion maraging steel with different thermal histories during continuous heating. Additive Manufacturing, 53: 102712. https://doi.org/10.1016/j.addma.2022.102712

[20] Lindley, B., Álvarez Velarde, F., Baker, U., Bodi, J., Cosgrove, P., Charles, A., Fiorina, C., Fridman, E., Krepel, J., Lavarenne, J., Mikityuk, K., Nikitin, E., Ponomarev, A., Radman, S., Shwageraus, E., Tollit, B. (2023). Impact of Thermal-Hydraulic feedback and differential thermal expansion on European Sodium-Cooled fast reactor core power distribution. Journal of Nuclear Engineering and Radiation Science, 9(3): 031301. https://doi.org/10.1115/1.4056930

[21] Liu, Y., Zhao, N., Xu, J. (2023). Mechanically strong and flame-retardant PBO/BN/MXene nanocomposite paper with low thermal expansion coefficient, for efficient EMI shielding and heat dissipation. Advanced Fiber Materials,

5(5): 1657-1670. https://doi.org/10.1007/s42765-023-00298-0
[22] Maracchini, G., Di Giuseppe, E., D'Orazio, M. (2021). Impact of occupants' behavior uncertainty on building energy consumption through the Karhunen-Loève expansion technique: A case study in Italy. In Sustainability in Energy and Buildings 2021. Springer, Singapore, 263: 197-207. https://doi.org/10.1007/978-981-16-6269-0_17