

Article

Effect of Steel Fiber Content on the Electrical, Electrothermal, and Thermal Conductivity Properties of Iron Tailings-Based UHPC

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Abstract: Iron tailings-based ultra-high-performance concrete (UHPC) was developed using iron tailings as aggregates, with steel fiber incorporation ranging from 0% to 2.5%. This study investigates the effects of steel fiber dosage and curing age on the electrical, electrothermal, and thermal conductivity properties of iron tailings-based UHPC. A comprehensive evaluation protocol was implemented to quantify resistivity, electrothermal conversion efficiency, and heat transfer characteristics, providing a systematic understanding of the material's multifunctional properties. Results demonstrate that steel fiber incorporation significantly reduces electrical resistivity, achieving optimal conductivity at 1.5% fiber content. Electrothermal analysis under a 60 V applied voltage revealed maximum heating efficiency ($\Delta T = 32.5\text{ }^{\circ}\text{C}/30\text{ min}$ for UHPC cured for 7 days and $\Delta T = 8.0\text{ }^{\circ}\text{C}/30\text{ min}$ for UHPC cured for 28 days) at 1.5% fiber content. Thermal conductivity measurements identified a non-monotonic relationship with steel fiber content, initially increasing and then decreasing, with maximum thermal conductivity observed at 1.5% fiber content. This trend aligns with the observed resistivity behavior, suggesting a strong correlation between electrical and thermal properties. Fiber distribution within the iron tailings-based UHPC matrix revealed that steel fiber dispersion significantly affects material properties, with 1.5% fiber content achieving optimal percolation network formation for electrical current flow and heat transfer.



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Keywords: iron tailings; ultra-high-performance concrete (UHPC); steel fibers; electrothermal properties; thermal conductivity; electrical resistivity

1. Introduction

Ultra-high-performance concrete (UHPC) has gained significant attention in recent years due to its superior mechanical properties, durability, and versatility, making it a preferred material for bridge construction, high-rise buildings, and other specialized structural applications [1–3]. The incorporation of steel fibers enhances tensile strength, toughness, and crack resistance in UHPC, further expanding its potential applications [4]. However, with the growing interest in multifunctional building materials, the electrical, electrothermal, and thermal conductivity properties of UHPC have become critical research focuses.

Investigating these properties not only supports the development of self-sensing and self-repairing smart concrete but also establishes a theoretical foundation for designing conductive materials [5]. Research on electrothermal properties offers innovative solutions for road de-icing and building heating in cold climates [6], while thermal conductivity studies contribute to advancements in building energy efficiency and thermal management [7].

Recent studies have significantly advanced the understanding of the electrical, electrothermal, and thermal conductivity properties of UHPC incorporating iron tailings. Regarding electrical properties, the addition of steel fibers significantly improves UHPC's electrical conductivity. Specifically, an optimal steel fiber content of 1.0–1.5% (by volume) reduces resistivity by forming a continuous conductive network. However, exceeding 2.0% steel fiber content causes fiber agglomeration and increased resistivity [8]. Uniform fiber dispersion is critical for maintaining stable conductivity [9]. Furthermore, iron tailings enhance UHPC's electrical properties due to their metal oxide content, though the synergistic mechanisms operating between iron tailings and steel fibers remain unclear [10]. While moderate amounts of iron tailings improve conductivity, excessive amounts increase porosity and reduce performance [11].

In an electrothermal property study, the incorporation of conductive phase materials significantly enhanced the electrothermal conversion efficiency of concrete and improved its resistive heating capability [12]. Applying voltage to conductive concrete induces heat generation, and higher voltage accelerates heating rate and temperature rise but may cause localized overheating, increasing the risk of cracking due to thermal shock [13]. Current strategies to mitigate risks and enhance electrothermal conversion efficiency include low-voltage operation, ensuring uniform heat distribution, and improving the thermal conversion efficiency of conductive phase materials [14]. Conductive concrete is primarily applied in road de-icing, snow melting [15], and building heating [16]. Factors influencing its electrothermal performance include the content of conductive materials, dispersion uniformity, and void ratio [17]. The type of conductive material also plays a crucial role in the thermal conductivity of concrete, with common conductive materials categorized into carbon-based and metallic materials [18].

In thermal conductivity, the study of thermally conductive concrete contrasts with that of thermal insulating concrete [19], aiming to enhance thermal conductivity coefficients to improve heat transfer efficiency [20]. Extensive research has been conducted on thermal insulating concrete, including foam concrete [21,22], recycled aggregate concrete [23,24], and plant fiber concrete [25,26]. Research on thermally conductive concrete remains limited, primarily focusing on carbon/steel fiber concrete [27] and metallic slag concrete [28]. Studies indicate that incorporating steel fibers and iron tailings enhances UHPC's thermal conductivity [29]. Factors affecting the thermal conductivity of concrete include moisture content, porosity, and aggregate properties [30,31], while those influencing UHPC thermal conductivity primarily involve fiber type, fiber content, and fiber dispersion [32]. Studies on steel fibers and iron tailings indicate that an optimal steel fiber content of 1.0–1.5% improves thermal conductivity, whereas exceeding 2.0% causes agglomeration and reduced performance [33]. Uniform fiber dispersion is essential for maximizing thermal conductivity [34]. Iron tailings also enhance thermal conductivity via metal oxides [35], but synergistic effects with steel fibers require further investigation. Excessive iron tailings increase porosity and degrade thermal performance [36].

Despite these advancements, three key challenges persist: (1) The impact of steel fiber dispersion on electrical, electrothermal, and thermal properties remains insufficiently quantified. Most studies emphasize fiber content while neglecting dispersion effects [37]. (2) As an industrial byproduct, iron tailings offer environmental and economic benefits by reducing pollution and production costs [38], yet their electrothermal and thermal

conductivity mechanisms remain underexplored. (3) Existing research is predominantly qualitative, lacking quantitative correlations between steel fiber content, dispersion quality, and material properties.

To address these gaps, the effects of steel fiber content (0–2.5%) and dispersion quality were investigated with respect to the electrical, electrothermal, and thermal conductivity properties of iron tailings-based UHPC. Specimens with varying fiber contents were prepared, and their resistivity, electrothermal efficiency, and thermal conductivity were measured, providing a comprehensive analysis of the material's multifunctional behavior. The effects of fiber dispersion were quantified using statistical methods, and optimization strategies were proposed to improve fiber distribution and enhance overall UHPC performance. The findings contribute to the development of theoretical frameworks for the application of iron tailings-based UHPC in electrical heating and thermal management and provide practical guidance for engineering applications.

2. Experiments and Testing

2.1. Experimental Materials

This study utilized P.W52.5 white cement, Class II silica fume, and Class I fly ash, all produced by Platinum Foundry Materials Co., Ltd. in Gongyi, Henan, China. The fine aggregate consisted of quartz sand with a maximum particle size of <1 mm and a bulk density of 1.6–1.8 t/m³, supplied by Minghai Environmental Technology Co., Ltd. in Henan, China. A polycarboxylate-based superplasticizer, with a water reduction rate of 18–25%, and <10% of particles finer than 0.315 mm, was obtained from Hongxiang Building Additive Factory in Laiyang, China. Steel fibers, produced by Zhongde Xinya Building Materials Co., Ltd. in Zhengzhou, China, were copper-coated, hooked-end microfilament fibers, with a length of 13 mm, diameter of 0.2 mm, aspect ratio of 65, tensile strength of 2000 MPa, cross-sectional area of 0.03 mm², individual fiber weight of 3.2 mg, and a fiber count of 312 per gram (as shown in Figure 1a). Iron tailings sand (as shown in Figure 1b) was sourced from the iron ore plant of Sanhe Mining Co., Ltd. in Songxi County, Nanping City, Fujian, China. It had a median particle size (d_{50}) of 225 μ m and primary chemical compositions of SiO₂ (21.4%), Fe₂O₃ (20.1%), and CaO (33.7%). The particle size distribution of iron tailings sand is presented in Figure 2, demonstrating well-graded and uniform distribution suitable for ultra-high-performance concrete (UHPC) preparation.



Figure 1. Conductive phase materials: hooked-end steel fibers (a) and iron tailings sand (b).

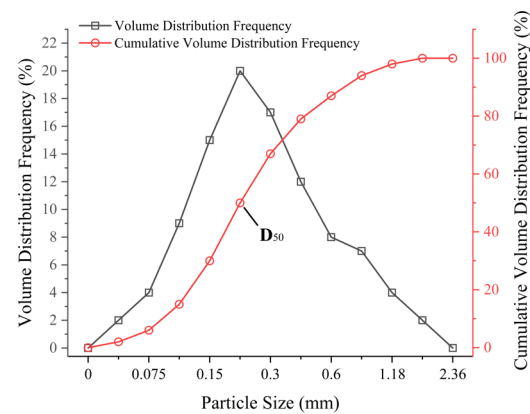


Figure 2. Particle size distribution plot of iron tailings sand.

2.2. Testing Instruments

This study utilizes the UC2876 high-frequency LCR digital bridge, manufactured by Youce Electronics Technology Co., Ltd. in Changzhou, Jiangsu, for resistance measurements. An MP12010D DC stabilized power supply from Maisheng Electronics Co., Ltd. in Dongguan, Guangdong, China, is employed for electrical testing. Surface-mount thermistors (model WZPT-TP-04-FY3PF), supplied by Songdao Heating Sensor Co., Ltd. in Shanghai, along with an 8-channel standard temperature recorder from Kesun Instruments Co., Ltd. in Ningbo, China, were used for thermal performance testing. Additionally, a concrete thermophysical parameter tester, manufactured by Gangyuan Testing Instrument Factory in Tianjin, China, was utilized for thermal conductivity measurements.

2.3. Sample Preparation

The mechanical properties and static elastic modulus of the UHPC used in this study were designed and evaluated in accordance with the Chinese national standard “Reactive Powder Concrete” [39]. Test specimens, including 100 mm cubic samples and prismatic specimens measuring 100 mm × 100 mm × 400 mm and 100 mm × 100 mm × 300 mm, were prepared in compliance with the performance testing requirements specified in the standard. All specimens were cured under standard conditions for 28 days (20 ± 2 °C, relative humidity > 95%). The average compressive strength recorded after testing was 125.6 MPa, the flexural strength was 21.9 MPa, and the static elastic modulus was 49.2 GPa. These measured performance parameters are consistent with the typical values associated with UHPC materials.

To simultaneously evaluate the electrical and electrothermal properties of the material, specimens measuring 40 mm × 40 mm × 160 mm were fabricated in accordance with the Chinese standard “Test Method of Cement Mortar Strength” [40]. To evaluate the electrical and electrothermal performance of iron tailings-based UHPC, U-shaped copper mesh electrodes tied with polyester threads were pre-embedded at both ends of the specimen; each electrode consisted of a polyester thread and a U-shaped copper mesh securely fastened together. To avoid displacing steel fibers during post-casting electrode insertion, the copper mesh electrodes were positioned with the opening facing downward into the mold before casting, after which the fresh mix was poured while simultaneously vibrating and adjusting the electrode position to ensure stability. Upon completion of vibration, a surface-mounted thermistor was diagonally inserted at the midpoint between the electrodes, and once the specimen was fully cured, the copper mesh was trimmed to form electrodes suitable for the two-electrode measurement method. The configuration of the electrodes and the specimen is illustrated in Figure 3. To determine the thermal conductivity of iron tailings-based UHPC, cylindrical specimens with an outer diameter of

200 mm, inner diameter of 40 mm, and height of 400 mm (wall thickness of 80 mm) were prepared in accordance with the specimen specifications required by the DR-2A Concrete Thermophysical Properties Analyzer. The mix design for iron tailings UHPC included a water-to-binder ratio of 0.2, with cement, silica fume, and fly ash mixed in a 7:2:1 ratio. A superplasticizer dosage of 2.5% (by binder weight) was used, with sand content at 1.2 times the binder weight and an iron tailings sand-to-quartz sand ratio of 1:1. Previous studies have shown that the most notable improvements in the workability, mechanical properties, and electrical conductivity of UHPC occur within the 1.0–1.5% fiber content range [41]. To capture this critical transition range, dosages of 0%, 0.5%, 1.0%, and 1.5% were included in incremental steps. The 0.5% intervals below 1.5% allowed for the precise identification of the optimal fiber content. Additionally, a high-dosage group of 2.5% was incorporated to evaluate potential adverse effects associated with excessive fiber content. Composition proportions of iron tailings-based UHPC mixtures are shown in Table 1.

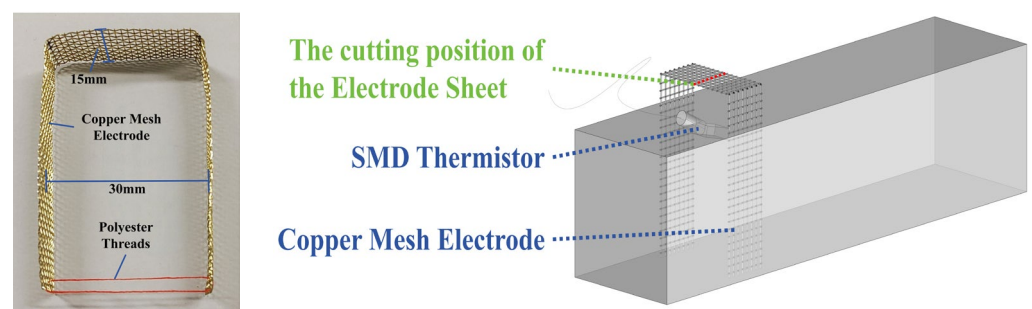


Figure 3. The configuration of the electrodes (left) and the specimen (right).

Table 1. Composition proportions of iron tailings-based UHPC mixtures (wt%).

Constituents	Cement	Silica Fume	Fly Ash	Iron Tailings Sand	Quartz Sand	Water	Superplasticizer
Proportion (wt%)	28.87	8.25	4.12	24.74	24.74	8.25	1.03

Note: Steel fibers were incorporated at 0%, 0.5%, 1%, 1.5%, and 2.5% by volume of the total mixture.

2.4. Testing Methods

Resistivity Testing Method: In accordance with the Chinese standard “Solid Insulating Materials—Dielectric and Resistive properties” [42]—the electrical resistivity of the specimens was measured using the two-electrode method. The resistance values of iron tailings-based UHPC with five different steel fiber contents were measured at curing ages of 7 and 28 days using an LCR digital bridge (as shown in Figure 4). During testing, the instrument’s voltage was set to 1 V, and the frequency range was 30 Hz to 5 MHz. The resistivity was then calculated from the measured resistance values using Equation (1) [43]:

$$\rho = \frac{RA}{L} \quad (1)$$

In the equation, ρ represents the resistivity of the material ($\Omega \cdot \text{m}$), R denotes the resistance of the material (Ω), A is the overlapping area between the two electrodes (m^2), and L is the distance between the electrodes (m).

Testing Method for Thermoelectric Properties: In this study, a testing model for evaluating the electrical and thermal properties of the material was developed based on direct calorimetry. According to the Joule–Lenz law, the electrothermal behavior of the material was characterized by monitoring the temperature variation within a fixed test volume over a constant energization period. During specimen preparation, a pair of parallel

electrode sheets was pre-embedded within the material, and a surface-mount thermistor was positioned between them [44]. Before testing the thermoelectric properties, the positive and negative terminals of a DC stabilized power supply were connected to the electrode sheets, while the temperature sensor was linked to a temperature recorder (as shown in Figure 5). In this study, the internal temperature variations of iron tailings UHPC were examined under applied voltages of 30 V and 60 V, with a 30 min power-on phase followed by a 30 min power-off interval.



Figure 4. Resistivity test.

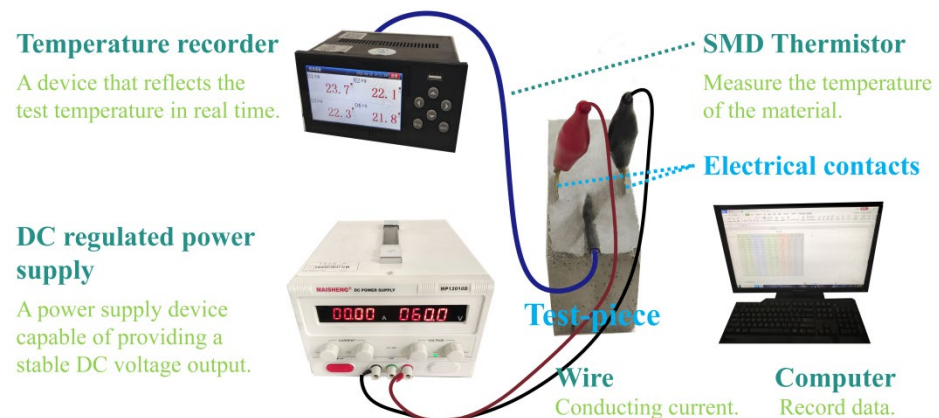


Figure 5. Electrothermal testing system.

Testing Method for Thermophysical Parameters: In this study, the DR-2A concrete thermal property analyzer was employed to measure the thermal conductivity, following the guarded hot plate method as specified in “Thermal insulation—Determination of steady-state thermal resistance and related properties—Guarded hot plate method.” [45]. The test specimens were placed inside the testing chamber (as shown in Figure 6), where the heating rods and thermometer were connected. The testing chamber was then linked to the testing instrument, and the controller was operated to initiate the test. In this experiment, the thermal conductivity of iron tailings UHPC specimens with varying steel fiber contents was measured at 7-day and 28-day curing ages.

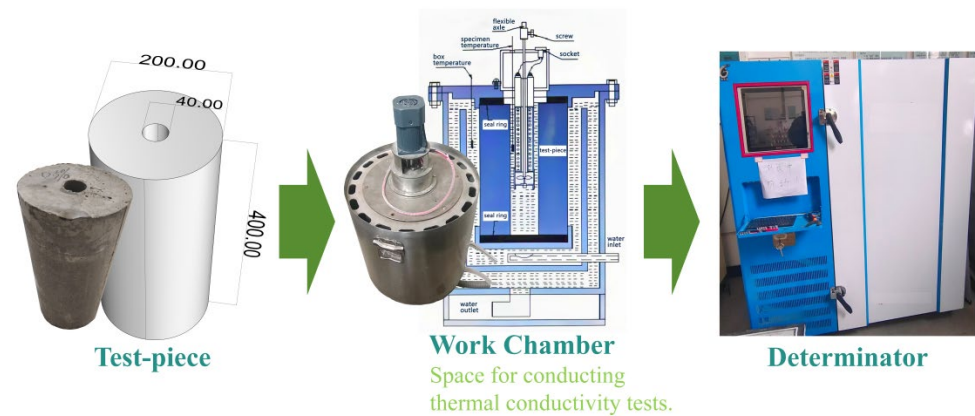


Figure 6. Thermal conductivity measurement system.

3. Experimental Results and Analysis

3.1. Electrical Performance Analysis

Figure 7 illustrates the variation in the resistivity of iron tailings UHPC at 7-day and 28-day curing ages with different steel fiber contents, measured at various testing frequencies. It is evident from the figure that, regardless of the testing frequency, the addition of steel fibers significantly reduces the resistivity of iron tailings UHPC. The resistivity reduction initially increases and then decreases as the steel fiber content rises. Specifically, when the steel fiber content reaches 1.5%, the resistivity reaches its lowest value. However, when the steel fiber content exceeds 1.5%, the resistivity begins to increase and the reduction becomes less pronounced. This occurs because an optimal amount of steel fibers forms a well-distributed conductive network within the UHPC matrix, thereby reducing electrical resistance. However, when excessive steel fibers are added, the mixture becomes too dry, reducing its flowability, which leads to fiber agglomeration and segregation. This hinders the uniform distribution of fibers, disrupting the formation of a continuous conductive network and subsequently increasing electrical resistance [46]. From the perspective of minimizing resistivity, the optimal steel fiber content threshold is 1.5%.

A comparative analysis of the resistivity trends of iron tailings UHPC at 7-day and 28-day curing ages across different steel fiber contents reveals the following:

(1) The resistivity of the 7-day cured material is significantly lower than that at 28 days, with the resistivity difference ($\Delta\rho$) initially decreasing and then increasing as steel fiber content increases. For instance, at a testing frequency of 1 kHz, the resistivity differences ($\Delta\rho$) at 7 and 28 days for steel fiber contents of 0%, 0.5%, 1.0%, 1.5%, and 2.5% were $-303.5 \Omega\cdot\text{m}$, $-81.5 \Omega\cdot\text{m}$, $-67.8 \Omega\cdot\text{m}$, $-38.4 \Omega\cdot\text{m}$, and $-55.1 \Omega\cdot\text{m}$, respectively.

(2) When the steel fiber content exceeds 1.5%, the resistivity of the 7-day cured material does not exhibit the significant reverse increase observed in the 28-day cured material.

The explanation for observations (1) and (2) is as follows: In the early curing stages, iron tailings UHPC retains a high water content, resulting in numerous conductive ions within its internal pores [47]. These ions significantly enhance electrical conductivity, even surpassing the contribution of steel fibers. Consequently, at equal steel fiber contents, the resistivity of the early-stage material is notably lower than that of the later-stage material. Specifically, at 0% steel fiber content, the resistivity difference between early and late stages is most pronounced, as the absence of steel fibers makes ionic conductivity the dominant factor influencing electrical conductivity. Additionally, the high ion concentration in the early stage mitigates the negative effects of fiber agglomeration, explaining why, beyond 1.5% steel fiber content, the resistivity of the 7-day cured material does not exhibit a significant reverse increase, unlike the 28-day cured material.

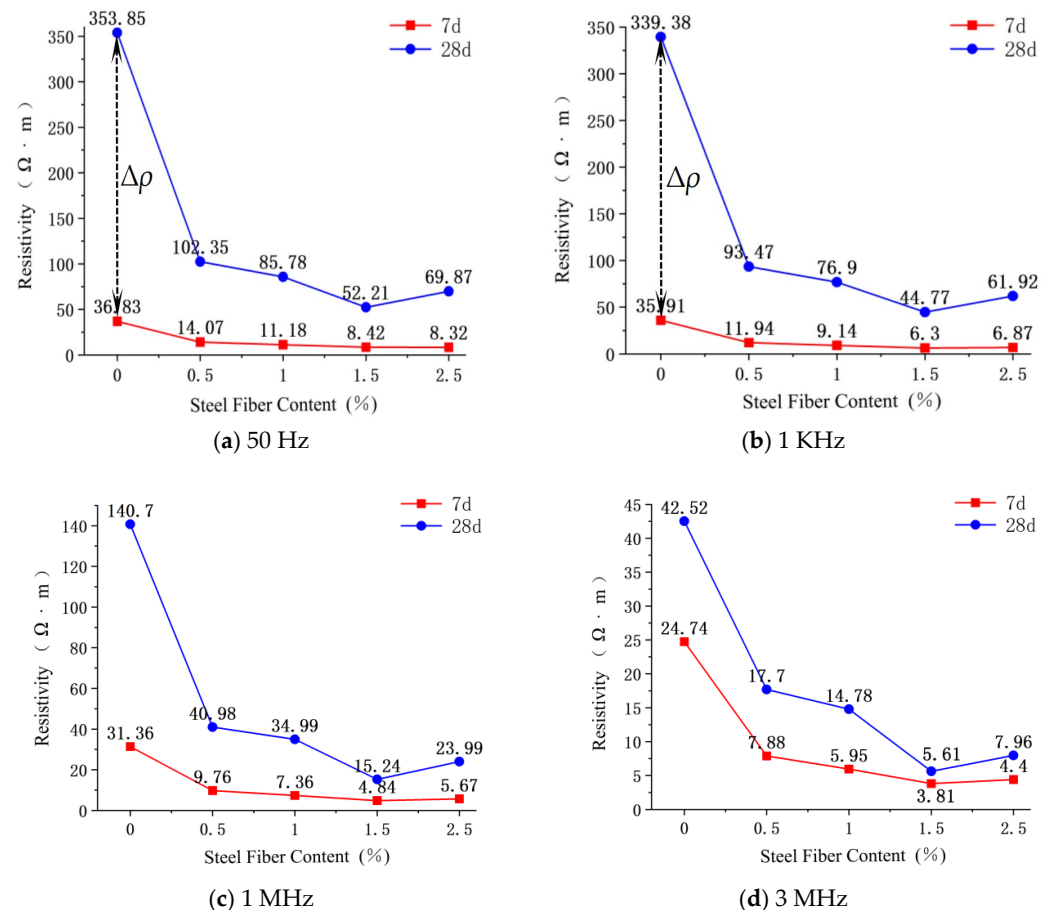


Figure 7. Variation in specimen resistivity with steel fiber content at different test frequencies.

On the other hand, it was observed that the effect of curing age on electrical resistivity and electrothermal performance primarily results in a general change in magnitude, without altering the overall trend. Therefore, based on the principles of hydration reactions and electrical theory (as illustrated in Figure 8), the following inferences can be drawn: In the early stages of curing, the free water content is relatively high, forming continuous electrolyte pathways and conductive networks with the steel fibers, thereby enhancing ion mobility within the pore solution. As the hydration process progresses, the free water content in the iron tailings-based UHPC gradually decreases, leading to a reduction in free ions and disruption of percolated ionic networks, thereby decreasing the number of charge carriers available for conduction. In the later stages of curing, the hydration products predominantly form crystalline and gel-like structures, which impede the movement of charge carriers, thereby reducing their mobility and further increasing electrical resistivity.

Notably, with extended curing durations, the impact of steel fiber dosage on resistivity becomes increasingly pronounced, eventually surpassing the contribution rate of ionic conduction. This phenomenon suggests that at advanced curing ages, steel fiber content, particularly the uniformity of fiber distribution, plays a pivotal role in determining the composite's electrical resistivity characteristics.

Furthermore, the resistivity difference ($\Delta\rho$) between the early and late stages decreases with increasing testing frequency. For a steel fiber content of 1.0%, the resistivity differences ($\Delta\rho$) at 7-day and 28-day curing ages at testing frequencies of 50 Hz, 1 kHz, 1 MHz, and 5 MHz were 74.6 Ω·m, 67.8 Ω·m, 27.6 Ω·m, and 8.8 Ω·m, respectively. This suggests that at higher testing frequencies, the influence of curing age on resistivity is significantly

diminished. In other words, high-frequency testing effectively reduces the impact of moisture content on resistivity.

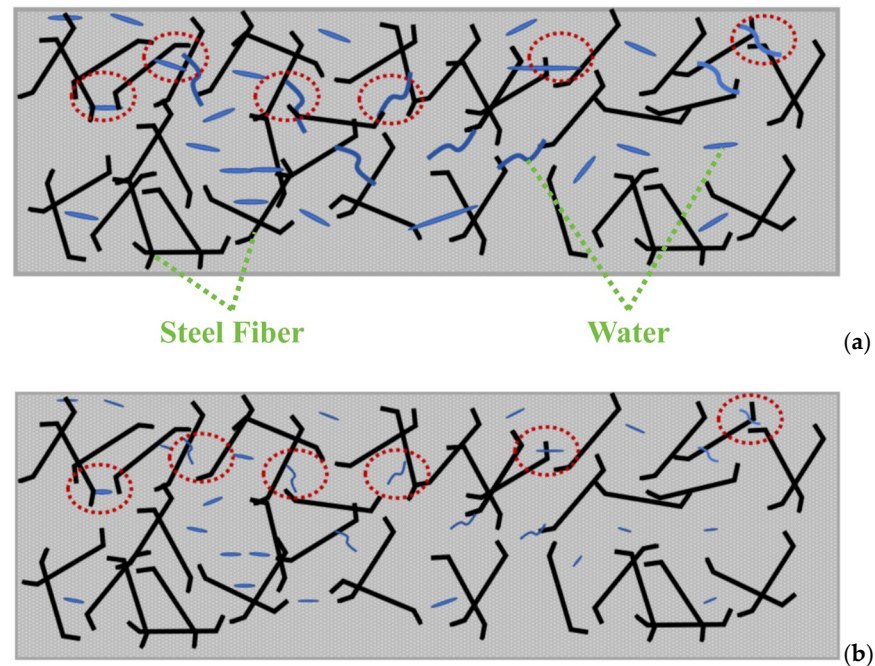


Figure 8. Variation of moisture content during early (a) and later (b) curing stages, along with a schematic of the conductive network. The red dashed circles denote the places where the conductive channels were cut off due to reduction in the water connecting adjacent steel fibers with the progress of hydration reaction.

Figure 9 illustrates the variation in resistivity with testing frequency for iron tailings UHPC at different steel fiber contents. From the figure, the following observations can be made:

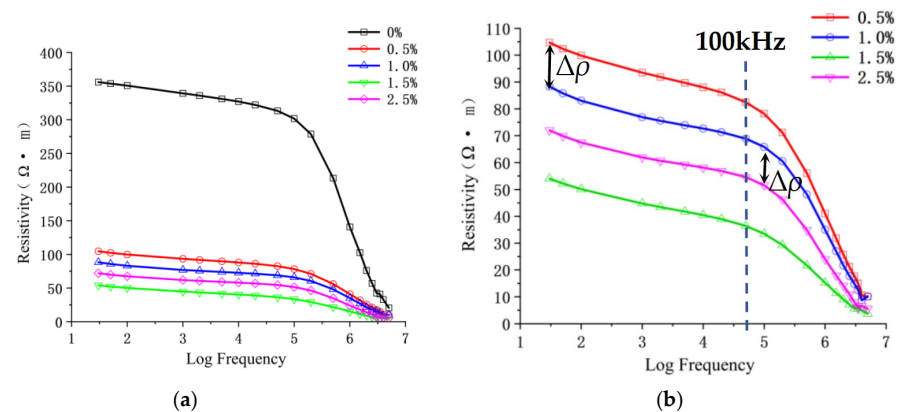


Figure 9. Resistivity–frequency curves for materials with different steel fiber contents (28-day curing age): (a) 0–2.5% steel fiber content, including the curve for 0% steel fiber content to illustrate the effect of steel fiber incorporation on resistivity variation, and (b) 0.5–2.5% steel fiber content, omitting the curve for 0% steel fiber content to emphasize the variation patterns of the remaining curves.

The incorporation of steel fibers has been observed to significantly decrease the resistivity of the material when compared to specimens without fiber reinforcement. For instance, under a testing frequency of 100 kHz and a curing age of 28 days, the resistivity of the specimen without steel fibers was measured at 305 $\Omega \cdot m$, whereas the specimen with 0.5% steel fiber exhibited a significantly lower resistivity of 78 $\Omega \cdot m$.

The resistivity–frequency trends for materials with different steel fiber contents exhibit similar patterns, with resistivity decreasing as testing frequency increases. When the testing frequency is below 100 kHz ($\text{Log Hz} < 5$), the rate of resistivity reduction is relatively small. However, once the testing frequency exceeds 100 kHz ($\text{Log Hz} > 5$), the rate of resistivity decrease becomes significantly more pronounced.

In the low-frequency range ($\text{Log Hz} < 5$), the resistivity differences ($\Delta\rho$) between materials with different steel fiber contents are substantial. Conversely, under high-frequency ($\text{Log Hz} > 5$) testing conditions, these differences ($\Delta\rho$) diminish rapidly. This suggests that in the low-frequency range, material resistivity is more sensitive to variations in steel fiber content than in the high-frequency range. Therefore, lower testing frequencies should be utilized when differentiating between material resistivities, whereas higher alternating current frequencies should be selected to enhance material conductivity and optimize electrothermal conversion efficiency.

During the transition from low to high frequencies, the magnitude of resistivity variation decreases as steel fiber content increases. However, incorporating excessive steel fibers leads to poor dispersion within the UHPC matrix, introducing numerous internal voids, which consequently increase resistivity. As a result, the resistivity change amplitude for the material with 2.5% steel fiber is greater than that for the material with 1.5% steel fiber, as evidenced by the curve for 2.5% steel fiber lying above the curve for 1.5% steel fiber.

3.2. Electrothermal Performance Analysis

Figure 10 presents the temperature variation curves within iron tailings-based UHPC containing five different steel fiber contents under applied DC voltages of 30 V and 60 V (power on for 30 min, followed by power off). The following observations can be made:

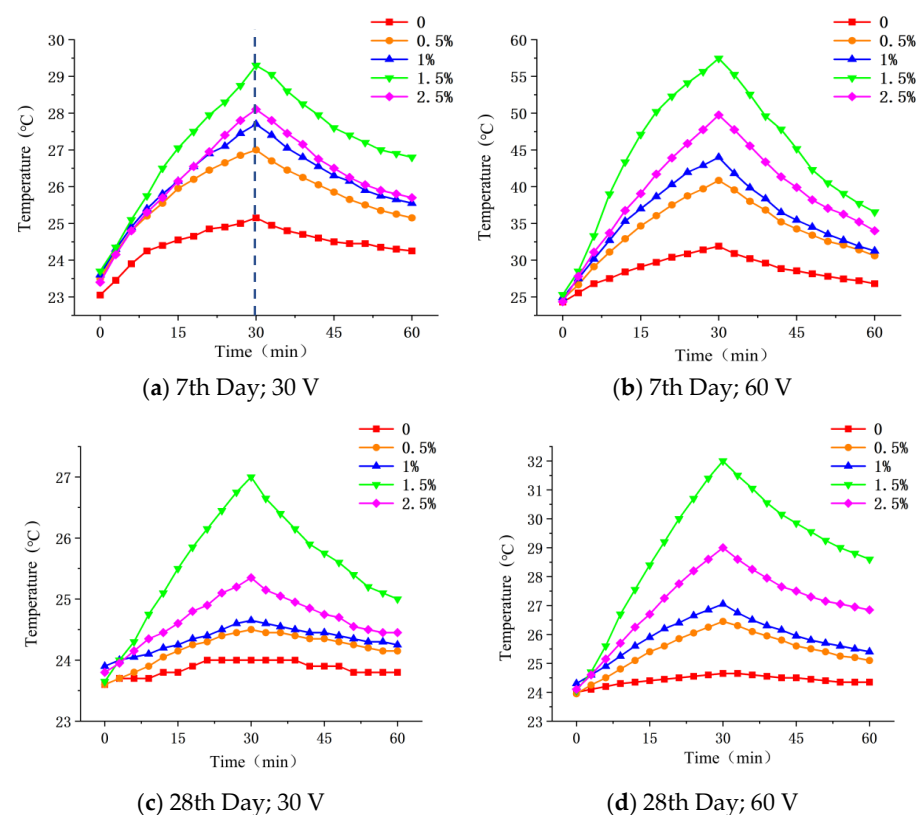


Figure 10. Electrothermal performance of materials with different steel fiber contents at 7 days and 28 days of curing. (a) Measured under 30 V voltage, after 7-day curing; (b) measured under 60 V voltage, after 7-day curing; (c) measured under 30 V voltage, after 28-day curing; and (d) measured under 60 V voltage, after 28-day curing.

Upon voltage application, the internal temperature of steel fiber-based UHPC rises rapidly. After power is turned off, the temperature decreases quickly, although the heating rate exceeds the cooling rate. Even after 30 min of power-off, a significant amount of stored heat remains (i.e., a temperature difference persists between the material and the external environment). Additionally, higher heating leads to greater heat retention within the material.

In general, both the heating rate and temperature increase in steel fiber-based UHPC rise with increasing steel fiber content. However, excessive steel fiber content has negative effects. For instance, the heating rate and temperature increase in UHPC containing 2.5% steel fiber are lower than those in material with 1.5% steel fiber content. This occurs because an optimal steel fiber concentration reduces resistivity effectively, whereas an excessive amount leads to fiber agglomeration, preventing uniform dispersion. Furthermore, it introduces air bubbles into the material, which ultimately increases the composite's resistivity. This trend aligns with the previously established relationship between resistivity and steel fiber content.

The applied voltage significantly influences both heating rate and temperature increase. For example, in UHPC with 1.5% steel fiber content at a 7-day curing age, the heating rates at 60 V and 30 V are 1.08 °C/min and 0.19 °C/min, respectively, with temperature increases of 32.5 °C and 5.6 °C after 30 min of power on. At the same steel fiber content but a 28-day curing age, the heating rates at 60 V and 30 V decrease to 0.27 °C/min and 0.12 °C/min, respectively, with temperature increases of 8.0 °C and 3.5 °C after 30 min of power on.

The curing age significantly affects the thermo-electric properties of materials with different steel fiber contents. At early curing stages, materials exhibit superior thermo-electric performance, characterized by higher heating rates and greater temperature increases. Specifically, for steel fiber contents of 0%, 0.5%, 1.0%, 1.5%, and 2.5%, the temperature increases after 30 min under 60 V voltage are 6.9 °C, 15.8 °C, 19.2 °C, 32.5 °C, and 25.0 °C, respectively, at 7 days of curing age. In contrast, at 28 days of curing age, the corresponding temperature increases are 0.6 °C, 1.5 °C, 2.8 °C, 8.0 °C, and 5.0 °C. The enhanced thermo-electric performance in the early stage can be attributed to incomplete hydration, which leaves a significant amount of moisture and ions inside the material, thereby enhancing conductivity (i.e., lowering resistance R). In theory, according to the general electrothermal energy formula $Q = U^2 \cdot t / R$ (Q is the total thermal energy generated due to electrical resistance, U is the voltage, and t is the duration for which the voltage is applied) and $\Delta T = Q / mc$ (m is the mass of the material, c is the specific heat capacity of the material, and ΔT is the temperature change), it can be concluded that the material exhibits both faster heating rates and greater temperature rise magnitudes in its early stages due to lower resistance R .

In practical applications such as de-icing and snow removal on road surfaces, heat is continuously generated by the material upon the application of an external voltage, resulting in the melting of ice and snow. As a result of this process, the surface moisture content increases, which substantially lowers the material's resistivity and consequently enhances its thermoelectric heating and de-icing performance [48].

3.3. Thermophysical Performance Analysis

Figure 11 presents the correlation curve between thermal conductivity and steel fiber content for iron tailings-based UHPC at different curing ages. The thermal conductivity of iron tailings-based UHPC initially increases with steel fiber content but declines when the steel fiber content exceeds 1.5%. This trend contrasts with the relationship between resistivity and steel fiber content described earlier (Section 3.1), where the turning point also occurs at 1.5% steel fiber content in both cases.

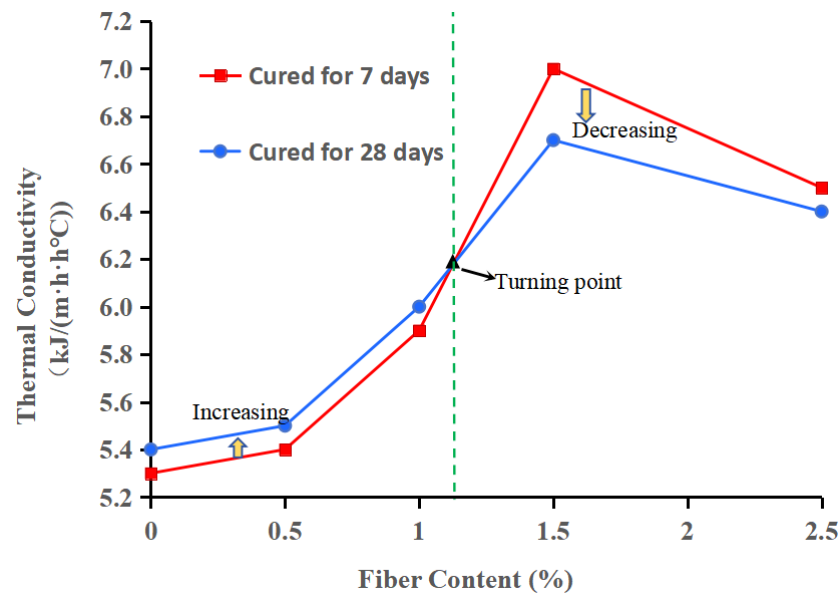


Figure 11. Relationship between thermal conductivity and steel fiber content.

This trend is primarily governed by the four key constituents of iron tailings-based UHPC: steel fibers (SF), iron tailings mortar (M), water in pores (W), and air (A). Their thermal conductivities range from 16–20 W/m·K for steel fibers to 0.01–0.04 W/m·K for air, with steel fibers exhibiting the highest and air the lowest values. When an optimal amount of steel fibers is uniformly dispersed throughout the matrix, the composite's thermal conductivity increases, as their inclusion enhances the material's heat transfer capability. However, excessive fiber addition compromises mixture homogeneity, leading to greater pore formation. These pores, filled with low-conductivity substances such as water and air, diminish the overall thermal conductivity of the composite. Consequently, the influence of steel fibers transitions from enhancing to impairing thermal conductivity.

Regarding the effect of curing age on thermal conductivity, a comparison of thermal conductivity–steel fiber content curves for 7-day and 28-day curing periods reveals that when the steel fiber content is below 1.1%, the thermal conductivity of the material at an early curing stage is lower than that at a later curing stage. Conversely, when the steel fiber content exceeds 1.1%, the opposite occurs. In other words, increasing curing age reduces the thermal conductivity of composites with high steel fiber content (>1.1%) but enhances it in composites with lower steel fiber content (<1.1%). This behavior arises because as curing progresses, the degree of cement hydration increases, producing hydration products that reduce both the size and quantity of internal pores, thereby enhancing material density. Simultaneously, hydration reduces water content, leading to a higher proportion of air within pores.

Therefore, when the steel fiber content is low (<1.1%), steel fibers disperse easily and uniformly, resulting in fewer and smaller pores within the composite. As hydration progresses, most small pores are filled with hydration products, increasing material density and thereby boosting thermal conductivity [49].

However, when the steel fiber content is high (>1.1%), the difficulty in achieving uniform dispersion increases, leading to the formation of more and larger pores. While some small pores become filled with hydration products over time, many large pores remain, and the water inside these pores is gradually replaced by air. Since air has a significantly lower thermal conductivity than water, the thermal conductivity of the composite at later curing stages becomes lower than that at earlier stages.

3.4. Steel Fiber Distribution and Mechanism Analysis

Since steel fibers are chemically stable and do not participate in hydration reactions, their dosage does not influence the formation of hydration products such as C_2S , C_3S , and ettringite. As a result, X-ray diffraction (XRD) analysis was not employed to assess the effect of steel fiber content on the electrical, electrothermal, and thermal conductivity properties of iron tailings-based UHPC in this study. Figure 12 presents SEM micrographs showing the distribution of steel fibers and iron tailings within the UHPC matrix. The images illustrate that both steel fibers and iron tailings exhibit strong interfacial bonding with the matrix. However, given the macroscopic dimensions of the steel fibers (13 mm in length and 0.3 mm in diameter), their spatial dispersion can be effectively evaluated through visual inspection aided by a magnifying lens, rendering SEM-based analysis unsuitable for this aspect of the investigation. Therefore, a statistical analysis approach was employed to examine the spatial distribution of steel fibers within the iron tailings-based UHPC, thereby enabling a quantitative correlation between fiber content and the material's electrical and thermal multifunctional properties.

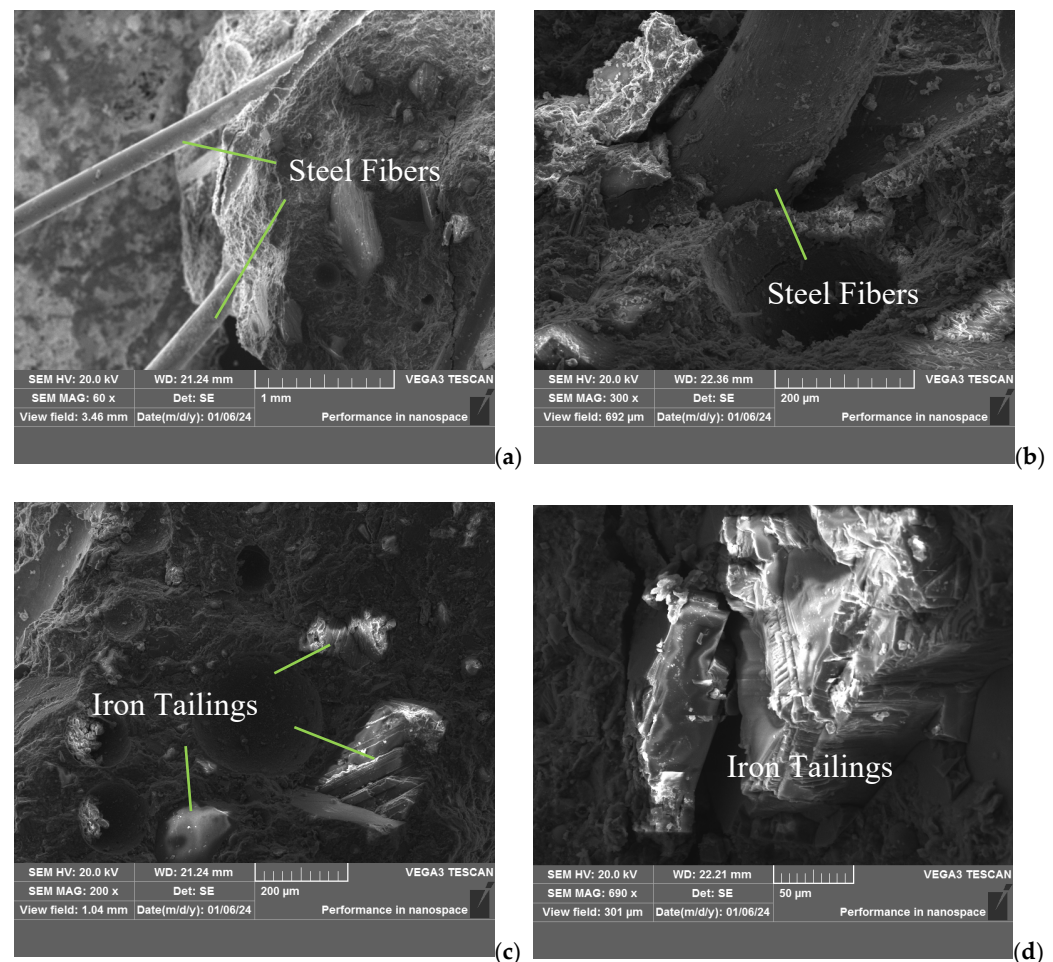


Figure 12. SEM micrographs of steel fiber and iron tailings distributions in the UHPC matrix: (a,b) morphology and dispersion of steel fibers at (a) 60× and (b) 300× magnification, highlighting fiber-matrix interactions; (c,d) morphological features of iron tailings at (c) 200× and (d) 690× magnification, showing their integration within the matrix.

To statistically analyze the spatial distribution of steel fibers within iron tailings-based UHPC and examine the effect of steel fiber content on their dispersion, specimens with varying steel fiber contents were transversely cut, and the distributions of steel fibers

at different cross-sectional positions (from the casting surface to the bottom layer) were compared. As illustrated in Figure 13a, the cross-section was divided into nine equal square units, each assigned a numerical label: the upper layer was numbered 1, 2, and 3; the middle layer was numbered 4, 5, and 6; and the lower layer was numbered 7, 8, and 9. The number of steel fibers in each unit of the cross-section was counted for each group of iron tailings-based UHPC specimens (Figure 13b,c display the steel fiber distribution in specimens containing 1.5% and 2.5% steel fibers, respectively), and the results are presented in Table 1.

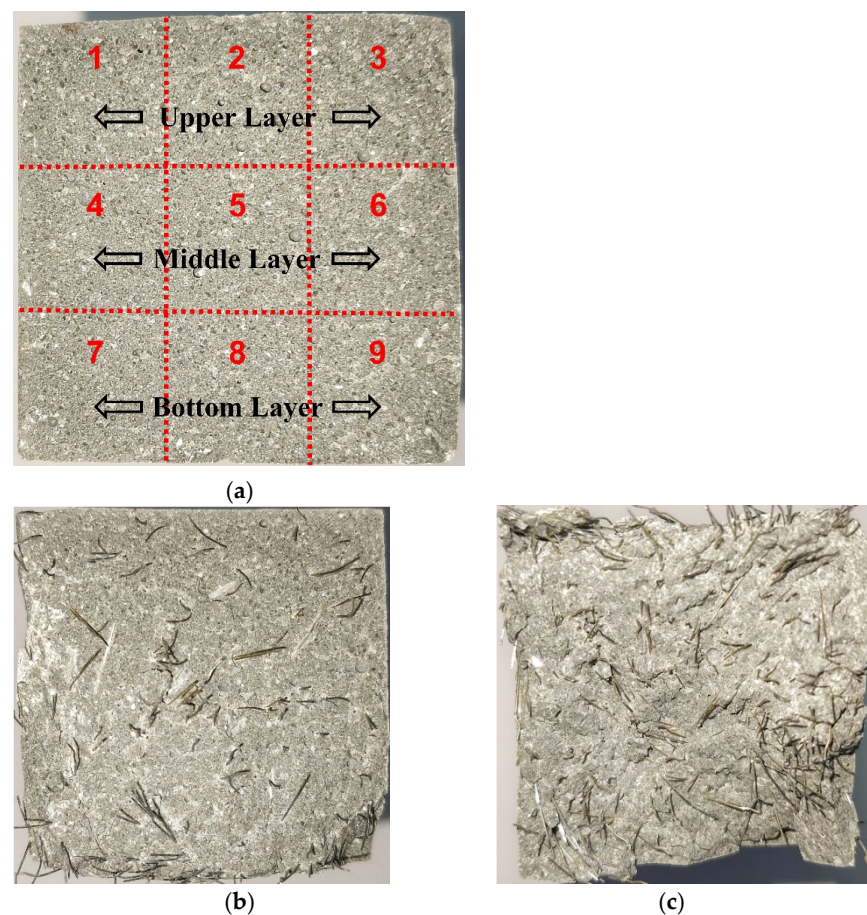


Figure 13. Division and numbering of cross-sectional cells for specimens with different steel fiber contents: (a) 0% steel fiber content; (b) 1.5% steel fiber content; and (c) 2.5% steel fiber content. Notes: To quantify the spatial distribution of steel fibers in iron tailings-based UHPC, the cross-section was stratified into three layers (upper, middle, and lower) perpendicular to the casting direction. Each layer was subdivided into three equal square units, yielding a total of nine sampling zones with the following numbering convention: upper layer (1–3), middle layer (4–6), and lower layer (7–9).

As shown in Table 2, the spatial distribution of steel fibers in different specimens follows a consistent pattern: the number of steel fibers progressively increases from the top to the bottom (i.e., from the casting surface to the bottom layer). Specifically, for specimens with steel fiber contents of 0.5%, 1.0%, 1.5%, and 2.5%, the number of steel fibers in the top layer of the cross-section is 16, 40, 69, and 124, respectively; in the middle layer, it is 35, 67, 84, and 140, respectively; and in the bottom layer, it is 38, 84, 112, and 195, respectively. This phenomenon is attributed to the higher density of steel fibers (7.8 g/cm^3) compared to the mortar matrix (2.0 g/cm^3). During specimen formation, vibration compaction exacerbates the settling of steel fibers, particularly when the slurry viscosity is low, leading to more pronounced fiber accumulation at the bottom layer. Therefore, when fabricating UHPC, if

vibration compaction is used, the vibration intensity should not be excessive, the duration should be controlled, and the slurry should maintain adequate viscosity to minimize fiber segregation.

Table 2. Distribution of steel fibers at different positions on the cross-sections of iron tailings-based UHPC specimens with varying steel fiber contents.

Cell Numbering and Layer Position		Number of Steel Fibers in Each Cell of the Cross-Section for Each Material			
		SF05	SF10	SF15	SF25
1	Upper layer	6	13	24	37
2		5	16	18	57
3		5	11	27	30
4	Middle layer	12	18	23	58
5		9	23	30	39
6		14	26	31	43
7	Bottom layer	10	29	37	66
8		15	23	34	73
9		13	32	41	56
Total number of steel fibers in the cross-section		89	191	265	459
Standard deviation of steel fiber count in the cells σ		3.66	6.79	6.85	13.60
Coefficient of variation δ		0.37	0.32	0.23	0.27

Note: SF05, SF10, SF15, and SF25 correspond to iron tailings-based UHPC specimens with steel fiber contents of 0.50%, 1.0%, 1.5%, and 2.5%, respectively. The standard deviation, σ , is calculated using Equation (2), and the coefficient of variation, δ , is calculated using Equation (3).

To evaluate the dispersion of steel fibers within each unit, statistical methods were employed. The standard deviation (σ) of steel fiber distribution within each unit cell of the material cross-section for different fiber contents was calculated using Equation (2), and the coefficient of variation (δ) was determined using Equation (3). The results are summarized in Table 2. The standard deviation (σ) and coefficient of variation (δ) provide insights into fiber dispersion, with σ representing absolute dispersion and δ indicating relative dispersion. As shown in Table 2, the standard deviation (σ) increases with steel fiber content (i.e., $\sigma_{\text{SF05}} < \sigma_{\text{SF10}} < \sigma_{\text{SF15}} < \sigma_{\text{SF25}}$), with the standard deviation for specimens containing 2.5% steel fibers (13.6) being significantly higher (by factors of 2.0 to 3.7) than those of the other groups. However, the coefficient of variation (δ) initially decreases and then increases with steel fiber content (i.e., $\delta_{\text{SF05}} > \delta_{\text{SF10}} > \delta_{\text{SF15}} < \delta_{\text{SF25}}$), with specimens containing 1.5% steel fibers exhibiting the lowest coefficient of variation ($\delta = 0.23$).

A comparison of the statistical parameters (σ and δ) across various specimens confirms that iron tailings-based UHPC with 1.5% steel fiber content exhibits the most uniform fiber dispersion. This finding further supports the trends observed in the electrical resistivity, electrothermal properties, and thermal performance of iron tailings-based UHPC, as previously discussed.

$$\sigma = \sqrt{\frac{\sum_{i=1}^n (x_i - \mu)^2}{n}} \quad (2)$$

$$\delta = \sigma / \mu \quad (3)$$

In the equation δ —coefficient of variation; x_i —number of steel fibers in the i -th unit cell; μ —average number of steel fibers in all unit cells; and n —number of unit cells.

To comparatively analyze the dispersion of steel fibers in specimens with varying fiber contents, this study adopted an exponential attenuation model commonly used in evaluating the dispersion of composite materials. The core principle of this model involves transforming statistical variation parameters (such as standard deviation or coefficient of variation) into a distribution coefficient within the range of 0 to 1 using an exponential function [50,51]. Accordingly, Equation (4) was formulated to calculate the distribution coefficient β , which characterizes the distribution of steel fibers across the specimen cross-section and thereby quantitatively describes their dispersion within the iron tailings-based UHPC matrix. Based on the coefficient of variation (δ) from Table 2 and Equation (4), the distribution coefficient (β) trend curve was plotted, as shown in Figure 14.

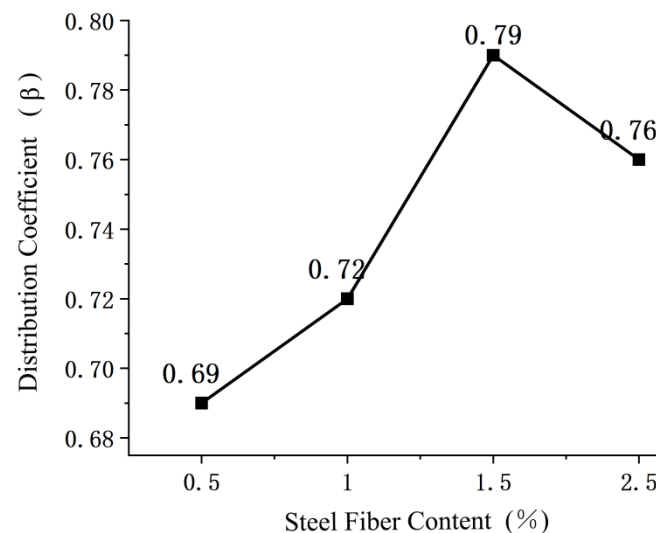


Figure 14. Variation curve of distribution coefficient with steel fiber content.

As illustrated in Figure 14, the distribution coefficient (β) of steel fibers in iron tailings-based UHPC exhibits a non-monotonic relationship with fiber content—initially increasing and then decreasing beyond an optimal threshold. This trend corresponds to thermal conductivity behavior (shown in Figure 11) and shows an inverse correlation with the electrical resistivity curve (shown in Figure 7), indicating a consistent and physically rational pattern. These findings demonstrate that the electrical and thermal performance of iron tailings-based UHPC is influenced not only by the steel fiber dosage but, more critically, by their spatial distribution, as quantified by the distribution coefficient (β) in Equation (4). The coefficient of variation (δ), defined as the ratio of the standard deviation to the mean ($\delta = \sigma/\mu$), provides a dimensionless metric for comparing different physical properties, such as resistivity and thermal conductivity. Notably, the UHPC mixture with 1.5% steel fiber content achieved the lowest δ value (0.23) and the highest β value (0.79), indicating optimal fiber dispersion, maximum thermal conductivity, and minimum resistivity (i.e., superior electrical conductivity). At lower fiber contents (<1.5%), β increases with increasing dosage, reflecting improved fiber dispersibility. However, when fiber content exceeds 1.5%, β begins to decline due to fiber agglomeration, as evidenced by the rising δ values.

$$\beta(\delta) = e^{-\delta} \quad (4)$$

As shown in Figure 15, when the steel fiber content is 0.5% or 1% (Figure 15a), the overall quantity of fibers is low, resulting in a smaller dispersion coefficient β . Due to the limited proportion of steel fibers in the matrix, their impact on overall material performance is minimal, failing to establish an effective conductive network, which leads to only a slight reduction in resistivity and marginal improvements in the electrothermal performance and

thermal conductivity of the iron tailings UHPC. At a dosage of 1.5% (Figure 15b), the quantity of steel fibers reaches the optimal volumetric threshold, achieving a balance between quantity and dispersion, and thus yielding the highest dispersion coefficient β . When uniformly dispersed in the matrix, the copper-coated steel fibers can fully exhibit their intrinsic properties, forming a continuous conductive network with the iron tailings sand, thereby significantly enhancing the electrical conductivity, electrothermal performance, and thermal conductivity of the composite material. At a dosage of 2.5% (Figure 15c), the fiber content exceeds the matrix's load-bearing capacity, leading to agglomeration and sedimentation, which disrupt the internal conductive network and increase porosity, thereby resulting in higher resistivity and reduced electrothermal performance and thermal conductivity.

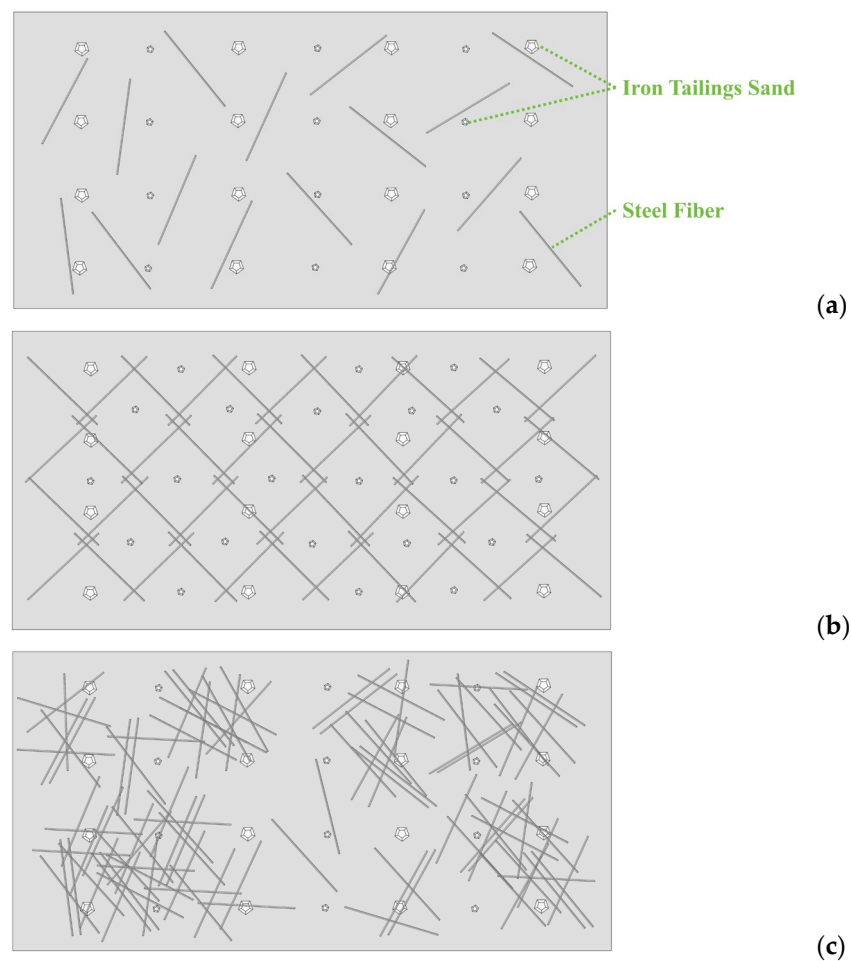


Figure 15. Schematic illustration of the internal conductive network within the matrix at low (a), optimal (b), and excessive (c) steel fiber dosages without considering the influence of moisture in matrix.

The trends observed in electrical, electrothermal, and thermal conductivity properties in this study closely align with the variation of the distribution coefficient (β) with steel fiber content, providing insight into the underlying mechanisms influencing the material's electrical and electrothermal behavior. Therefore, enhancing the electrical and electrothermal properties of iron tailings-based UHPC requires not only optimizing the content of conductive and thermally conductive materials (such as steel fibers) but also improving their dispersion within the matrix.

4. Conclusions and Prospects

4.1. Conclusions

This study systematically investigates the influence of steel fiber content, dispersion uniformity, and curing age on the electrical, electrothermal, and thermal conductivity properties of iron tailings-based UHPC. The findings provide a comprehensive understanding of how these variables interact and affect the multifunctional performance of UHPC. These insights offer a theoretical basis for engineering applications involving functional concrete materials with electrothermal capabilities. Key conclusions are as follows:

(1) The resistivity of iron tailings-based UHPC initially decreases and then increases as steel fiber content increases, reaching its minimum value at 1.5% steel fiber content. Curing age has a substantial effect on resistivity: in the early stages (7 days), the high moisture content results in a greater number of conductive ions, leading to lower resistivity. However, as curing progresses, hydration reactions consume free ions, causing a gradual increase in resistivity. Under high-frequency testing conditions, the influence of curing age on resistivity diminishes, indicating that high-frequency conditions effectively mitigate the impact of moisture on resistivity.

(2) The incorporation of steel fibers significantly enhances the electrothermal performance of iron tailings-based UHPC, with the optimal temperature elevation performance observed at 1.5% volumetric content. In terms of curing age effects, the lower resistivity and higher conductivity of the material in the early stages result in superior electrothermal performance under a given voltage (60 V). For example, at a 7-day curing age, iron tailings-based UHPC achieves a temperature increase of 32.5 °C within 30 min, whereas at a 28-day curing age, the temperature increase is only 8.0 °C within the same duration.

(3) Thermal conductivity of iron tailings-based UHPC initially increases and then decreases with rising steel fiber content, reaching its peak at 1.5% steel fiber content. The effect of curing age on thermal conductivity is closely related to steel fiber content. At lower fiber contents (<1.1%), an increase in curing age enhances thermal conductivity, whereas at higher fiber contents (>1.1%), an increase in curing age reduces thermal conductivity.

(4) The uniformity of steel fiber dispersion within the matrix plays a critical role in determining the electrical, electrothermal, and thermal conductivity properties of iron tailings-based UHPC. Specimens with 1.5% steel fiber content demonstrate the most uniform dispersion, lowest resistivity, and optimal electrothermal and thermal conductivity properties. However, excessive steel fiber content leads to fiber agglomeration and uneven distribution, resulting in a decline in material performance.

4.2. Limitations and Future Work

This study employs a statistical analysis method to evaluate the spatial distribution uniformity of steel fibers in iron tailings-based UHPC and quantifies fiber dispersion by calculating the distribution coefficient (β) using an exponential decay model. Although this approach supports the findings, certain limitations exist: (1) The statistical analysis is based solely on the number of fibers within cross-sectional units, without accounting for the influence of fiber orientation on the continuity of electrical and thermal pathways; (2) Micro-CT scanning and 3D reconstruction techniques have not yet been integrated with macro-scale statistics. Incorporating multi-scale analysis methods could significantly enhance the accuracy of statistical evaluations in assessing the effects of fiber dispersion.

Building on these findings, future research will tackle the following critical challenges to enhance the theoretical depth and practical relevance of this study: (1) A multi-scale analysis framework will be developed that integrates micro-CT scanning, 3D reconstruction, and macroscopic statistical methods to build predictive models linking steel fiber dosage to UHPC multifunctional performance. (2) Thermal field simulations will be conducted using

numerical methods to explore the interactions between steel fibers and iron tailings [52]. (3) Additional studies are required to evaluate the corrosion risks of steel fibers under cyclic electrothermal loading; (4) The combined effects of environmental factors (e.g., humidity and temperature fluctuations) and mechanical stress on long-term degradation of UHPC performance will be evaluated.

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