Academic Journal of Science and Technology
ISSN: 2771-3032 | Vol. 14, No. 3, 2025

Research Progress on the High-Temperature Resistance of Ultra-High Performance Concrete Incorporating Iron Tailings as a Cementitious Material

Haochen Yang, Guowei Ni and Bo Liu

School of Science and Technology, North China University, Tangshan 063210, China

Abstract: Ultra-High Performance Concrete (UHPC) is widely recognized for its superior strength, exceptional durability, and outstanding crack resistance, making it an attractive material for applications in tunnel linings, nuclear power plant structures, industrial furnace linings, and high-rise building firewalls. However, conventional UHPC is prone to spalling and rapid strength deterioration under high-temperature conditions due to internal water evaporation, pressure buildup, and the decomposition of hydration products. In recent years, iron tailings—an abundant industrial solid waste rich in SiO_2, Al_2O_3, and Fe_2O_3—have been investigated as a supplementary cementitious material to partially replace cement. This substitution not only reduces carbon emissions and production costs but also has the potential to improve the high-temperature performance of UHPC through its participation in hydration reactions and the refinement of the pore structure. This review comprehensively summarizes the chemical and physical properties of iron tailings, their inherent cementitious reactivity and activation methods, and discusses the influence of iron tailings on the evolution of UHPC mechanical properties, spalling mechanisms, and fire resistance under high temperatures. Furthermore, engineering applications and environmental safety issues are analyzed, and future research directions are proposed to provide theoretical support and technical guidance for the sustainable utilization of iron tailings in high-temperature UHPC.

Keywords: Iron tailings, Ultra-High Performance Concrete (UHPC), Cementitious material, High-temperature resistance, Sustainable construction.

1. Introduction

With the accelerating pace of urbanization and infrastructure development, the performance requirements for concrete materials have become increasingly demanding, especially for applications in high-temperature and fire-prone environments. UHPC, with its outstanding mechanical properties and durability, has emerged as a high-performance structural material in extreme conditions. However, its dense microstructure also predisposes it to spalling and rapid strength loss when exposed to elevated temperatures. Concurrently, the utilization of industrial solid wastes, such as iron tailings, for green building materials has gained significant attention in response to environmental concerns and resource scarcity. Iron tailings, by-products of the iron and steel industry, are rich in silica, alumina, and iron oxides, which provide them with potential cementitious activity. Researchers have explored the incorporation of iron tailings into UHPC systems to partially replace cement, thereby reducing carbon emissions and possibly enhancing high-temperature performance. This review aims to systematically summarize the current research on the use of iron tailings in UHPC, focusing on its activation methods, influence on high-temperature mechanical behavior, and engineering applications, while also addressing existing challenges and future research prospects.

2. Basic Characteristics of Iron Tailings

2.1. Chemical Composition and Mineral Characteristics

Iron tailings primarily consist of SiO_2, Al_2O_3, and Fe_2O_3, with the content of each component varying significantly depending on the ore source and processing method. Typically, the SiO_2 content ranges from 24% to 75%, Al_2O_3 from 2% to 17%, and Fe_2O_3 from 4% to 47%. X-ray diffraction (XRD) analyses reveal that the main mineral phases in iron tailings include quartz, hematite, and kaolinite. Although quartz is present in high proportions, its chemical inertness limits its contribution to hydration reactions. In contrast, minerals such as kaolinite can exhibit pozzolanic activity after appropriate activation, thereby enhancing the reactivity of iron tailings in UHPC systems. Recent studies have demonstrated that by optimizing activation processes, the reactivity of iron tailings can be significantly improved, rendering them more effective as a supplementary cementitious material.[1]

2.2. Physical Properties and Particle Distribution

The physical properties of iron tailings are also crucial for their application in UHPC. Generally, iron tailings exhibit irregular particle shapes and high specific surface areas, with values ranging from approximately 2640 to 3310 kg/m^3. However, they also possess a relatively high porosity, typically between 33.1% and 50%, and an absorption rate ranging from 0.8% to 9%. These characteristics influence the workability and hydration efficiency of UHPC. A well-controlled particle size distribution and optimized grading are essential to improve the density of the UHPC matrix and enhance the interfacial transition zone (ITZ) between the binder and aggregates.[2]

3. Cementitious Reactivity and Activation Methods of Iron Tailings

3.1. Cementitious Reactivity and Influencing Factors

The cementitious reactivity of iron tailings depends mainly on the content of active oxides, particularly SiO_2 and Al_2O_3, as well as on the particle size and specific surface area. Due to the inherently low pozzolanic activity of natural iron tailings, direct incorporation into UHPC often fails to contribute significantly to strength development. Therefore, activation treatments are necessary to enhance their reactivity. A higher specific surface area and finer particle size promote the dissolution of reactive components, while the addition of chemical activators can further accelerate the hydration reactions. However, the relatively high water absorption of iron tailings may also affect the hydration process, necessitating a careful balance in mix design.

3.2. Physical Activation Methods

Physical activation of iron tailings is mainly achieved through ultra-fine grinding, which increases the specific surface area and reduces particle size. Studies indicate that mechanical milling can improve the reactivity index of iron tailings by more than 20%, thereby enhancing their ability to participate in the hydration process. In addition, optimizing the post-grinding particle size distribution helps to ensure uniform dispersion within the UHPC matrix, contributing to an overall denser microstructure.[3]

3.3. Chemical Activation Methods

Chemical activation involves the use of alkaline activators (such as NaOH or KOH) or sulfate-based compounds to stimulate the dissolution of active SiO_2 and Al_2O_3 in iron tailings. This process enhances the secondary hydration reaction, leading to increased formation of calcium silicate hydrate (C-S-H) gel, which is critical for the strength and durability of UHPC. The effectiveness of chemical activation is further improved when iron tailings are used in conjunction with other high-activity mineral admixtures, such as silica fume and fly ash.

3.4. Thermal Activation Methods

Thermal activation, or calcination, involves heating iron tailings at temperatures ranging from 600°C to 800°C to alter their mineralogical composition. Such heat treatment can transform part of the quartz into a more reactive amorphous phase, thereby significantly enhancing the pozzolanic activity of the tailings. In some cases, combining thermal activation with chemical activation (for example, subsequent treatment with sodium silicate) can further improve the overall cementitious performance, making iron tailings more suitable for UHPC applications.

4. Evolution of UHPC Performance under High-Temperature Exposure

4.1. Physical and Chemical Changes at Elevated Temperatures

Under high-temperature conditions, UHPC undergoes a series of complex physical and chemical changes that affect its mechanical properties and fire resistance. At temperatures between 30°C and 105°C, water in the capillary pores gradually evaporates, potentially leading to the initiation of microcracks. In the range of 110°C to 170°C, decomposition of hydration products such as ettringite and gypsum begins, causing a gradual reduction in matrix strength. Between 180°C and 300°C, partial dehydration of the C-S-H gel occurs, resulting in a progressive loosening of the microstructure. At 450°C to 550°C, the decomposition of calcium hydroxide ($Ca(OH)_2$) significantly increases porosity and leads to a marked decline in compressive strength. Between 700°C and 900°C, the decomposition of calcium carbonate ($CaCO_3$) and further phase transformations cause severe microstructural damage, and temperatures above 900°C typically lead to complete structural disintegration.[4]

4.2. Spalling Mechanisms and Fire Resistance Issues

The phenomenon of explosive spalling in UHPC at high temperatures is primarily attributed to the combined effects of thermal gradient stress, pore pressure buildup, and phase transformation stress. Due to the low porosity of UHPC, water vapor generated during heating cannot escape quickly, leading to rapid pressure buildup within the matrix. Simultaneously, the differential thermal expansion between aggregates and the binder creates significant internal stresses, especially in the interfacial transition zone (ITZ). Furthermore, the decomposition of hydration products induces volumetric changes that exacerbate crack propagation, ultimately resulting in spalling. Recent research has proposed various strategies, including optimizing the concrete mix, incorporating fibers, and employing combined curing methods, to mitigate these spalling risks.[5]

4.3. Regulatory Effects of Iron Tailings on UHPC High-Temperature Performance

The incorporation of iron tailings into UHPC has been shown to improve its high-temperature performance through several mechanisms. First, ultra-fine iron tailings act as fillers, reducing overall porosity and mitigating the buildup of pore pressure under thermal loading. Second, activated iron tailings can participate in secondary hydration reactions to form additional C-S-H gel, enhancing the stability of the matrix at elevated temperatures. Third, the presence of iron oxides, particularly Fe_2O_3, promotes the formation of high-temperature stable phases such as mullite, which further improves the fire resistance of UHPC. Experimental results suggest that replacing approximately 20%–30% of the binder with iron tailings can lead to a temporary increase in strength between 200°C and 400°C; however, residual strength tends to decrease markedly when temperatures exceed 600°C. Therefore, optimizing the dosage and activation conditions of iron tailings is essential for maximizing their beneficial effects. [6]

5. Optimization Strategies for High-Temperature UHPC and Engineering Applications

5.1. Discussion on Optimization Strategies

Enhancing the high-temperature performance of UHPC incorporating iron tailings requires an integrated approach. Current research focuses on three main strategies: fiber reinforcement, combined curing methods, and multi-admixture techniques. Fiber reinforcement involves the use of polypropylene (PP) fibers in conjunction with steel or natural fibers (e.g., flax fibers). PP fibers melt in the range of 160°C to 200°C, creating microchannels that help relieve pore pressure, while steel fibers act as crack bridges to improve tensile and flexural strength. Combined curing methods, such as initial heat-water curing at approximately 90°C followed by dry-air curing at 200°C to 250°C, have been shown to promote the formation of a denser network of hydration products, reducing large capillary pores and enhancing overall fire resistance. Additionally. multi-admixture strategies—incorporating iron tailings alongside silica fume, fly ash, and granulated blast furnace slag—exhibit synergistic effects that optimize hydration reactions and microstructural development.[7]

5.2. Engineering Application Cases

Iron tailings-based UHPC demonstrates promising potential in various high-temperature applications. In tunnel fire protection linings, the optimized combination of fibers and curing methods can effectively mitigate explosive spalling, ensuring that the lining maintains sufficient load-bearing capacity during a fire. In nuclear power plant shielding structures, the use of combined curing techniques has been shown to enhance long-term durability under conditions of high temperature and radiation. High-rise building firewalls also benefit from the improved fire resistance of UHPC, with studies indicating that an optimized mix can retain over 50% of its compressive strength even after exposure to extreme temperatures. These engineering cases illustrate that, with proper mix design and processing, iron tailings-based UHPC can meet the demanding requirements of high-temperature environments.[8]

5.3. Analysis of Suitability and Future Prospects

From an engineering perspective, the application of iron tailings-based UHPC offers significant advantages, including improved high-temperature resistance and environmental sustainability. However, challenges remain in terms of material variability due to regional differences in tailings composition, the need for standardized activation processes, and the development of long-term durability data under cyclic and extreme thermal conditions. Future research should focus on multi-scale experimental studies and pilot projects to validate performance under real-world conditions. Establishing a unified evaluation system and standardized protocols for industrial application will be critical to promoting the widespread use of this green building material.[9]

6. Environmental Impact and Sustainability Assessment

6.1. Reduction in CO_2 Emissions and Carbon Footprint

The high energy consumption and carbon emissions associated with cement production are major environmental concerns in the construction industry. Replacing a portion of cement with iron tailings not only reduces production costs but also significantly lowers CO_2 emissions. Several studies have reported that substituting up to 30% of the cementitious binder with iron tailings can reduce the overall carbon footprint by as much as 27.7%. This reduction is highly significant in the context of sustainable construction and supports the transition toward low-carbon building materials.

6.2. Heavy Metal Leaching and Environmental Safety

Environmental safety is another critical aspect of utilizing industrial waste in construction materials. Leaching tests conducted on UHPC containing iron tailings have demonstrated that the release of heavy metals such as Mn and Ba is well below national safety limits. This indicates that the potentially hazardous elements in iron tailings are effectively immobilized within the concrete matrix, ensuring that the material is environmentally benign and suitable for long-term applications in sensitive areas.[10]

7. Current Research Status, Challenges, and Future Directions

Despite significant progress in the application of iron tailings in UHPC, several challenges remain. First, the variability in chemical composition and physical properties of iron tailings from different sources leads to inconsistent performance, necessitating the development of standardized pre-treatment and activation protocols. Second, most studies to date have focused on early-age performance or moderate temperature conditions; comprehensive long-term durability assessments under cyclic and extreme high-temperature conditions are still lacking. Third, issues related to cost control, construction process optimization, and quality monitoring in large-scale industrial applications require further exploration. Future research should focus on advanced multi-scale characterization techniques to elucidate the hydration mechanisms and microstructural evolution of activated iron tailings, the development of predictive models for high-temperature performance, and the implementation of pilot-scale projects to validate the practical feasibility and sustainability of iron tailings-based UHPC.

8. Conclusion

This review comprehensively summarizes the progress in utilizing iron tailings as a supplementary cementitious material for UHPC, with a focus on enhancing high-temperature performance. The chemical and physical characteristics of iron tailings, along with various activation methods—including physical, chemical, and thermal treatments—are discussed in detail. It is demonstrated that the incorporation of iron tailings, when optimized in terms of dosage and activation conditions, can effectively improve the density and stability of UHPC under high temperatures, thereby reducing spalling and strength loss. Moreover, the review highlights the environmental benefits of this approach, notably the reduction in CO_2 emissions and the immobilization of heavy metals. Despite the promising potential, challenges related to material variability, long-term durability, and industrial-scale application remain. Future research should address these issues through advanced characterization, standardized testing, and pilot applications, ultimately paving the way for the sustainable and large-scale use of iron tailings in high-performance, fire-resistant concrete.

References

[1] J. Zhao, K. Ni, Y. Su, Y. Shi, An evaluation of iron ore tailings characteristics and iron ore tailings concrete properties, Construction and Building Materials, Vol. 286 (2021) 122968.

[2] J. Shi, W. Pan, K. Zheng, et al., Properties of Ultra-High Performance Concrete incorporating iron tailings powder and iron tailings sand, Journal of Building Engineering, Vol. 83 (2024) 108442.

[3] E. Ghafari, S.A. Ghahari, H. Costa, E. Júlio, A. Portugal, L. Durães, Effect of supplementary cementitious materials on autogenous shrinkage of ultra-high performance concrete, Construction and Building Materials, Vol. 127 (2016) 43-48.

[4] R.-U.-D. Nassar, O. Zaid, F. Althoey, M. A. Abuhussain, Y. Alashker: Spalling behavior and performance of ultra-high-performance concrete subjected to elevated temperature: A review, Construction and Building Materials, Vol. 411 (2024) 134489.

[5] W. Zhuang, S. Li, Q. Yu, The effect of supplementary cementitious material systems on dynamic compressive properties of ultra-high performance concrete paste, Construction and Building Materials, Vol. 321 (2022) 126361.

[6] R. Cai, H. Ye: Clinkerless ultra-high strength concrete based on alkali-activated slag at high temperatures, Cement and Concrete Research, Vol. 145 (2021) 106465.

[7] Sciarretta, F., Briseghella, B., Fava, S., Nuti, C., Ponticelli, L., Caciolai, M.: Ultra-High performance concrete (UHPC) with polypropylene (PP) and steel Fibres: Investigation on the high temperature behaviour, Construction and Building Materials, Vol. 304 (2021) 124608.

[8] G.-F. Peng, X.-J. Niu, Y.-J. Shang, D.-P. Zhang, X.-W. Chen and H. Ding: Combined curing as a novel approach to improve resistance of ultra-high performance concrete to explosive spalling under high temperature and its mechanical properties, Cement and Concrete Research, Vol. 109 (2018) 147-158.

[9] H. Huang, R. Wang, X. Gao, et al.: Improvement effect of fiber alignment on resistance to elevated temperature of ultra-high performance concrete, Composites Part B, Vol. 177 (2019) 107454.

[10] Y. Zhu, H. Hussein, A. Kumar and G. Chen: A review: Material and structural properties of UHPC at elevated temperatures or fire conditions, Cement and Concrete Composites, Vol. 123 (2021) 104212.