



Integrated Modelling and Experimental Analysis of Low-Temperature Hydration Mechanisms in Sustainable Fully Solid Waste Cementitious Materials

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Abstract: A sustainable solid waste-based cementitious system was developed using refining slag, steel slag, desulfurized gypsum, and granulated blast furnace slag (GBFS), and its low-temperature hydration behavior was investigated through a combined experimental and modelling approach. The strength development and microstructural evolution of the quaternary system under different curing temperatures were systematically analyzed. A temperature-dependent hydration kinetics interpretation was introduced to explain the variation in mechanical performance. The hydration characteristics were examined using X-ray diffraction (XRD), thermogravimetric–differential scanning calorimetry (TG–DSC), and scanning electron microscopy (SEM). The results indicate that curing temperature plays a dominant role in governing hydration kinetics and strength evolution. The compressive strength shows a clear positive correlation with temperature, which can be attributed to the accelerated formation of hydration products, mainly ettringite (Aft) and calcium silicate hydrate (C–S–H) gel. Under low-temperature conditions, the hydration process is significantly retarded due to reduced ion mobility and suppressed dissolution of solid waste components. The proposed mechanism suggests that refining slag contributes to the activation of the quaternary system by enhancing early-stage hydration reactions and improving structural densification. From a sustainability perspective, the developed system provides an effective pathway for large-scale utilization of industrial solid wastes while reducing dependence on conventional cement. The findings offer both experimental insights and a modelling-oriented interpretation of low-temperature hydration processes, providing a useful reference for the design and optimization of sustainable cementitious systems in cold-region engineering applications.

Keywords: Quaternary solid waste system; Low-temperature curing; Hydration mechanism; Consolidation mechanism

1 Introduction

The iron and steel industry is a vital pillar industry of China’s national economy, and its solid waste output accounts for 15% of the total industrial solid waste in China [1–3]. In accordance with the iron and steel smelting process, the production from iron ore to crude steel mainly involves several key procedures: blast furnace ironmaking, hot metal pre-desulfurization-dephosphorization, converter steelmaking, and secondary refining [4–7]. Statistics show that per ton of crude steel produced generates approximately 0.4 t of granulated blast furnace slag (GBFS), 0.15 t of converter or electric furnace steel slag, 0.05 t of refining slag, and 0.087 t of desulfurized gypsum. The iron and steel industry produces a wide variety of solid wastes with large output and complex compositions, and the industry is facing enormous pressure of emission reduction under the implementation of the current Environmental Protection Law of the People’s Republic of China [8–13].

Metallurgical slags are rich in elements such as calcium, silicon, iron, magnesium, and a small amount of aluminum, manganese, phosphorus and sulfur. The interaction and mutual activation of these solid wastes can be utilized to prepare cementitious materials with low environmental load [14–17]. Such cementitious materials can partially replace Portland cement, which not only reduces the production cost of cementitious materials, but also cuts down carbon emissions during cement manufacturing [18, 19]. Our research group has conducted extensive

mechanism studies on the “steel slag-GBFS-desulfurized gypsum” ternary system. By regulating the double salt effect and silicon tetrahedral isostructuralization, we have developed clinker-free or low-clinker fully solid waste cementitious materials and fully solid waste concrete, which have been applied in the preparation of artificial fish reefs, high-performance concrete, prefabricated components for assembled buildings, filling materials and other fields, with a number of demonstration projects established. Nevertheless, this ternary system suffers from low early strength and slow setting during winter construction. Further improving the early strength of the fully solid waste system at low temperatures is conducive to expanding the applicability of fully solid waste cementitious materials.

At present, the output of refining slag is increasing with the upgrading of iron and steel production processes, while its utilization rate remains relatively low [20, 21]. Refining slag is characterized by low iron content, rapid hydration reaction, and better grindability compared with converter steel slag. Nergis et al. [22] experimentally found that refining slag, as an admixture, can effectively improve the compressive strength and durability of concrete materials. Feng et al. [23] used refining slag as fine aggregate for concrete, and the results showed that fresh concrete mixed with refining slag presented fast early hydration and excellent physical and mechanical properties after hardening.

This paper focuses on the hydration and consolidation characteristics of the “refining slag-GBFS-steel slag-desulfurized gypsum” quaternary system under low-temperature conditions. Through single-factor experiments, the effects of refining slag dosage and curing temperature on the mechanical properties of fully solid waste cementitious materials are studied. Macro and micro characterization methods including X-ray diffraction (XRD), thermogravimetric–differential scanning calorimetry (TG–DSC) and scanning electron microscopy (SEM) are employed to analyze the chemical changes and micro-morphology evolution of the quaternary cementitious system during low-temperature hydration, and the low-temperature hydration and consolidation mechanism of the refining slag modified fully solid waste cementitious system is proposed. The research results of this paper provide a reference for the modification of other cementitious systems with refining slag, and lay a theoretical foundation for the development of fully solid waste concrete materials with early strength at low temperatures.

2 Materials and Experimental Methods

2.1 Raw Materials

The main raw materials used in the experiment include GBFS, steel slag, desulfurized gypsum and refining slag. GBFS powder was supplied by Zhengzhou Longze Water Purification Material Co., Ltd. (Henan Province), while refining slag, steel slag and desulfurized gypsum were all provided by Handan Iron and Steel Group Co., Ltd. (Hebei Province). All raw materials were dried in an oven at 40 °C to constant mass to ensure a moisture content of no more than 0.2%. The chemical compositions of the raw materials were tested by X-ray fluorescence (XRF) spectrometry, and the results are listed in Table 1. The specific surface area of GBFS is 400 cm²/g, with a density of 2.7 g/cm³ and a quality coefficient (ratio of the total mass of CaO, MgO and Al₂O₃ to the total mass of SiO₂, MnO and TiO₂) of 2.14. The specific surface area of refining slag is 444.85 cm²/g and its density is 3.09 g/cm³. Desulfurized gypsum has a specific surface area of 430 cm²/g and a density of 2.5 g/cm³. Steel slag has a specific surface area of 570 m²/g, a density of 3.37 g/cm³ and an alkalinity coefficient (ratio of CaO mass to the total mass of SiO₂ and P₂O₅) of 2.20.

Table 1. Chemical compositions of raw materials (wt.%)

Chemical Composition	CaO	Fe ₂ O ₃	Al ₂ O ₃	SiO ₂	MgO	MnO	F
Refining Slag	44.31	14.74	14.11	11.68	8.54	1.71	1.02
Steel Slag	39.78	20.79	2.24	15.71	9.31	5.12	— ^a
GBFS	40.99	0.39	13.93	29.84	10.85	0.24	—
Desulfurized Gypsum	47.4	1.14	0.91	3.22	0.60	0.07	—
Chemical Composition	P ₂ O ₅	SO ₃	V ₂ O ₅	Cr ₂ O ₃	K ₂ O	Na ₂ O	TiO ₂
Refining Slag	1.00	0.85	0.35	0.22	0.10	0.09	1.02
Steel Slag	2.36	0.21	1.50	0.502	0.11	0.1	2.10
GBFS	0.02	1.83	—	0.009	0.51	0.48	0.66
Desulfurized Gypsum	0.02	45.80	—	0.11	0.18	0.11	0.07

Note: GBFS = granulated blast furnace slag

2.2 Preparation and Curing Conditions of Cementitious Materials

Paste specimens were prepared with a fixed mass ratio of GBFS to steel slag of 3:1, a desulfurized gypsum dosage accounting for 20% of the total mass, and variable parameters including refining slag dosage (0%, 5%, 10%, 20%) and curing temperature (0 °C, 10 °C, 20 °C). The water-binder ratio of the cementitious material was set at 0.3. The relevant operations of the normal consistency test and paste test were carried out in accordance with the

national standard GB/T 1346—2011 Test Methods for Water Requirement of Normal Consistency, Setting Time and Soundness of the Portland Cement.

Raw material mixing was performed in an NJ-160 cement paste mixer. The uniformly mixed materials were placed into standard paste molds (size: 30 mm × 30 × 50 mm) for molding, and then cured in environments at 0 °C, 10 °C and 20 °C respectively for 1 d before demolding. The demolded specimens were further cured in environments at 0 °C, 10 °C and 20 °C with a relative humidity of 99% until the curing ages of 3 d, 7 d and 28 d. Standard curing tests were conducted in a BSYH-40B standard curing box, while low-temperature curing tests were carried out in a DW- 40 low-temperature test chamber. Material characterization tests were performed on the prepared specimens. The raw material proportions and curing temperatures of the cementitious materials are listed in Table 2.

Table 2. Raw material proportions and curing temperatures of materials

No.	Refining Slag (wt.%)	GBFS (wt.%)	Steel Slag (wt.%)	Desulfurized Gypsum (wt.%)	Curing Temperature (°C)
J1	0	60	20		
J2	5	56.25	18.75		
J3	10	52.5	17.5	20	0/10/20
J4	20	45	15		

Note: GBFS = granulated blast furnace slag

2.3 Material Characterization Tests

The density of each raw material was measured using a pycnometer. Kerosene was added into the pycnometer, which was then placed in a 20 °C curing box for constant temperature control to stabilize the kerosene volume, and the scale reading was recorded. After adding raw material powder, the pycnometer was placed in the constant-temperature curing box again, and the scale was recorded once the volume stabilized; the volume difference between the two readings represented the volume of the raw material under the corresponding mass.

The specific surface area of raw materials was determined by a DBT-127 Blaine specific surface area tester and an FBT-9 fully automatic specific surface area tester. The specific surface area of powder was measured by calculating the resistance change when air passed through a powder layer with a certain mass and porosity. The calculation formula for the mass of powder is shown in Eq. (1):

$$W = \rho V(1 - \varepsilon) \quad (1)$$

where, W is the mass of powder for specific surface area measurement (g); ρ is the density of the tested powder (g/cm^3); V is the volume of the sample layer (cm^3); ε is the porosity, set as 0.5 in this study.

X-ray fluorescence (XRF) spectrometry tests were conducted at the State Key Laboratory of Advanced Metallurgy, University of Science and Technology Beijing, using an XRF-1800 scanning X-ray fluorescence spectrometer (Shimadzu Corporation, Japan) for material composition analysis.

The mineral compositions of hydrated cementitious materials were determined by a Rigaku D/Max-RB X-ray powder diffractometer. XRD was adopted to analyze the mineral phases in raw materials and hydration products. The tests were entrusted to Beijing Beida Yuanyuan Microstructure Analysis and Testing Center, with a Cu target X-ray source, tube voltage of 40 kV, tube current of 100 mA, 2θ range of 3° – 90° , step size of 0.02° , and dwell time of 0.7 s per step.

Thermogravimetric-differential scanning calorimetry (TG-DSC) was performed using a STA409C high-temperature thermal analyzer to identify hydration products and their contents. The tests were entrusted to Beijing Beida Yuanyuan Microstructure Analysis and Testing Center, with a heating rate of $10^\circ\text{C}/\text{min}$ and a test temperature range of 20 – 1000°C , to reflect the mass change of materials with temperature and endothermic/exothermic phenomena, and analyze the evolution of formed or decomposed products.

The microstructure of hydrated cementitious materials was observed using a SUPRA55 field emission scanning electron microscope. Gold spraying was conducted during sample preparation to improve conductivity. Secondary electron emission signals were used for imaging to observe the internal morphology of materials, and the mineral composition was inferred based on morphological characteristics and energy dispersive spectroscopy (EDS) analysis.

3 Results and Discussion

3.1 Effect of Curing Temperature on Compressive Strength

Figure 1 shows the variation of compressive strength of the “steel slag-GBFS-desulfurized gypsum” ternary cementitious system with curing age under different temperatures. As shown in Figure 1, under 20°C curing, the 3 d,

7 d and 28 d compressive strengths of the ternary system are 12.36 MPa, 13.65 MPa and 23.01 MPa respectively, meeting the requirements for cementitious materials specified in T/CECS 689-2020 Technical Specification for Application of Solid Waste-Based Cementitious Materials, and are suitable for preparing concrete and mortar of grade M15 and below.

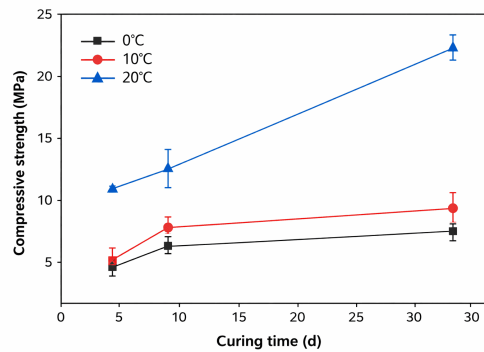


Figure 1. Variation of compressive strength of specimens at different curing temperature

The compressive strength of the ternary cementitious system decreases with the reduction of curing temperature. The 3 d and 28 d compressive strengths of specimens cured at 0 °C are only 34% and 33.5% of those cured under standard temperature (20 °C) at the corresponding ages, respectively. This may be attributed to the fact that lower temperature slows down the hydration reaction rate of the system, thereby weakening its hydration and consolidation performance. This leads to the failure of fully solid waste cementitious materials that meet all performance standards at 20 °C during winter construction.

3.2 Effect of Refining Slag Dosage at 20 °C

Figure 2 illustrates the variation of compressive strength of the quaternary cementitious system with different refining slag dosages at 20 °C curing with curing age. It can be seen that at the curing age of 3 d, the compressive strength of the solid waste cementitious system mixed with refining slag is increased by 5 MPa compared with the system without refining slag, indicating that the incorporation of refining slag can enhance the 3 d strength of the “steel slag-GBFS-desulfurized gypsum” cementitious system.

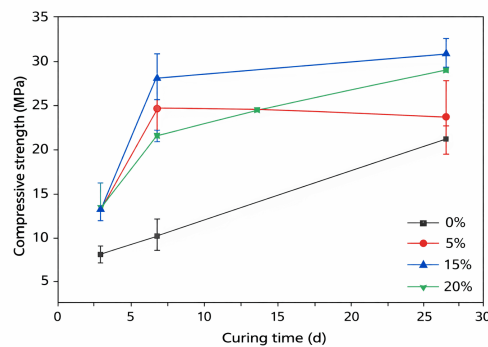


Figure 2. Variation of compressive strength of specimens under curing at 20 °C

The compressive strength of the fully solid waste cementitious system increases with the extension of curing age, and the incorporation of refining slag changes the consolidation rate of the system. Without refining slag, the 7 d compressive strength of the system reaches 13.7 MPa, accounting for 59.6% of the 28 d compressive strength, demonstrating slow early strength growth and rapid late strength growth of the fully solid waste cementitious material. When the refining slag dosages are 5%, 10% and 20%, the 7 d compressive strengths are 25.6 MPa, 28.4 MPa and 23.1 MPa respectively, accounting for 100%, 91.9% and 78.6% of their corresponding 28 d compressive strengths. This indicates that the higher the refining slag dosage, the faster the relative growth rate of early strength.

When the refining slag dosages are 5%, 10% and 20%, the 28 d compressive strengths of the fully solid waste cementitious materials are 24.5 MPa, 30.9 MPa and 29.4 MPa respectively, which are 6.5%, 34.3% and 27.8% higher than that of the system without refining slag. The 28 d compressive strength of the system first increases and then decreases with the rise of refining slag dosage, reaching the maximum at a dosage of 10%.

3.3 Effect of Refining Slag Dosage at 10 °C

Figure 3 presents the variation of compressive strength of the quaternary cementitious system with different refining slag dosages at 10 °C curing with curing age. The compressive strength of the quaternary system increases continuously with the increase of refining slag dosage under 10 °C curing, without the late strength retraction observed at 20 °C curing, suggesting that the optimal dosage of refining slag in fully solid waste cementitious materials is higher under low-temperature curing conditions.

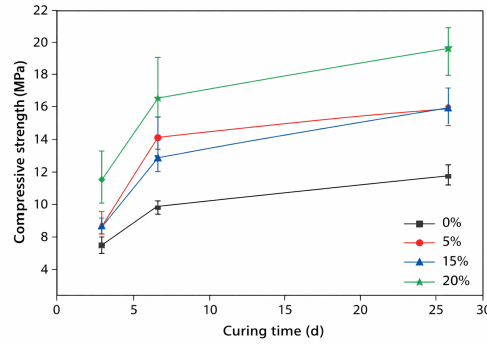


Figure 3. Variation of compressive strength of specimens under curing at 10 °C

When the refining slag dosage is 20%, the 3 d, 7 d and 28 d compressive strengths of the quaternary system cured at 10°C reach 11.0 MPa, 15.5 MPa and 19.1 MPa respectively, which are 93%, 81% and 89.4% higher than those of the ternary system cured under the same conditions, and are comparable to the corresponding age strengths of the ternary system cured at 20 °C (7.7 MPa, 10.1 MPa, 23.0 MPa) with better early strength. Therefore, modifying fully solid waste concrete by adding refining slag can make it more suitable for low-temperature construction.

The compressive strengths of specimens with 5% and 10% refining slag dosages at each curing age show little difference, indicating that the compressive strength of the quaternary system is less sensitive to the change of refining slag dosage within the range of 5–10% at 10 °C curing.

3.4 Effect of Refining Slag Dosage at 0 °C

Figure 4 shows the variation of compressive strength of the quaternary cementitious system with different refining slag dosages at 0 °C curing with curing age. Similar to the rule at 10°C curing, the compressive strength of the quaternary system increases continuously with the rise of refining slag dosage at 0 °C curing, and the strength is less sensitive to the dosage change within 5–10% refining slag.

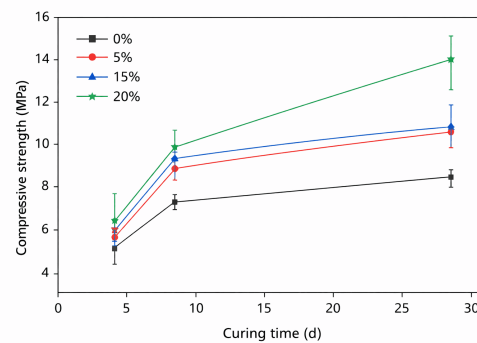


Figure 4. Variation of compressive strength of specimens under curing at 0 °C

Compared with standard curing specimens, the refining slag dosage exerts a more significant effect on the system strength at 0 °C. When the refining slag dosages are 5%, 10% and 20%, the 28 d compressive strengths are increased by 18%, 22.6% and 69.7% respectively. The early strength growth rate of the molded specimens is proportional to the refining slag dosage. It is also found that the “steel slag-GBFS-desulfurized gypsum” ternary system is highly temperature-dependent in low-temperature environments, and refining slag plays a particularly prominent role in improving the strength of the original system. High dosage of refining slag can significantly enhance the compressive strength of the system under low-temperature conditions.

The effect of curing temperature on the compressive strength of the 20% refining slag modified quaternary system is extremely significant, and the compressive strength increases with the rise of curing temperature. Although the solid waste-based cementitious material can undergo continuous hydration at low temperatures, the reaction rate is extremely low. Low temperature inhibits the hydration of solid wastes, reduces the activity of various ions, weakens the synergistic effect between ions, and slows down the formation of ettringite (AFt), thus decelerating strength growth. Higher curing temperature accelerates the pozzolanic reaction of the system and boosts the strength growth rate.

3.5 X-ray Diffraction Analysis

Figure 5 shows the XRD patterns of the quaternary cementitious material paste specimens cured at 20 °C for 28 d with different refining slag dosages. It can be observed that hydration products such as AFt and dicalcium silicate (C_2S) are formed in the quaternary system at different refining slag dosages, and the formation of AFt and C-S-H gel is the main contributor to the strength growth of the system. The hydration reaction rate accelerates and the generation amounts of AFt and C-S-H gel increase with the rise of refining slag dosage, which is consistent with the compressive strength test results of paste specimens. Gypsum diffraction peaks still exist after 28 d of hydration, indicating unreacted gypsum remains in the system. All cementitious systems with different refining slag dosages consume a large amount of gypsum during hydration; the 20% refining slag dosage promotes the formation of massive AFt in the early stage by reacting with gypsum, enhancing early strength, but excessive consumption of active gypsum hydrolyzed ions weakens the late strength development of the ternary system, while the 0% refining slag system forms less AFt in the early stage but generates more AFt and C-S-H gel in the later stage, leading to a small strength difference between the four systems.

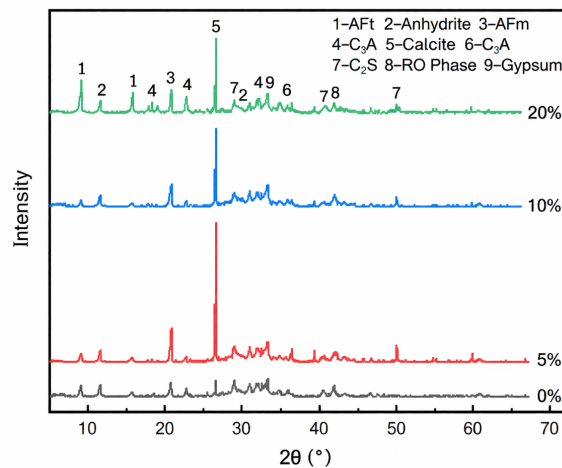


Figure 5. The X-ray diffraction analysis of specimens with different refined slag dosages at 28 days at 20 °C curing

An obvious peak bulge appears in the 2θ range of 27° – 37° , indicating the formation of amorphous gel hydration products in the system. No Ca_2 diffraction peak is detected, demonstrating that OH^- generated from the hydration of steel slag and refining slag is completely consumed in subsequent hydration reactions. The resulting alkaline environment promotes the full hydrolysis of GBFS, facilitating the depolymerization and reconstruction of aluminum-oxygen tetrahedra and silicon-oxygen tetrahedra in the system, and further promoting the formation of AFt and C-S-H gel.

3.6 Thermogravimetric–Differential Scanning Calorimetry Analysis

Figure 6 shows the TG-DSC curves of the quaternary cementitious material system with 0% and 20% refining slag dosages cured at 20 °C for 28 d. Obvious mass loss occurs during the heating process of both samples, with a total mass loss of approximately 13.8% for both specimens, indicating that excessive refining slag has no significant effect on the late strength of the system and only promotes early hydration.

The DSC curves present two endothermic peaks below 200 °C, corresponding to the dehydration of hydration products AFt and C-S-H gel, and the dehydration of unreacted gypsum respectively, confirming that gypsum is not completely consumed in both systems under standard curing. Distinct endothermic peaks of hydration products appear at 99.6°C for the 0% refining slag sample and 101.9°C for the 20% refining slag sample. By comparing the mass loss and endothermic peak areas, it is found that the 20% refining slag system generates more AFt and C-S-H gel than the 0% system.

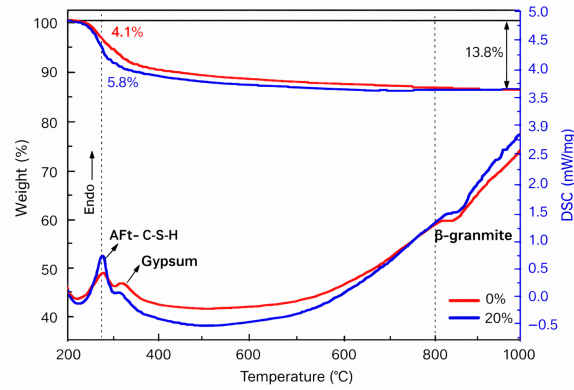


Figure 6. Thermogravimetric–differential scanning calorimetry (TG–DSC) curves of cementitious systems with different refined slag dosages at 28 days

Figure 7 shows the TG-DSC curves of the quaternary cementitious material system with 20% refining slag cured at different temperatures for 28 d. The maximum endothermic peaks of DSC curves under all curing temperatures are below 200 °C, with two endothermic peaks corresponding to AFt/C-S-H gel dehydration and gypsum dehydration respectively. The endothermic peak areas shrink with the decrease of curing temperature, proving that lower temperature significantly inhibits hydration and reduces the formation of AFt and C-S-H gel in the late hydration stage, which is consistent with XRD results. The residual gypsum content increases at lower temperatures, indicating that the 20 °C cured system consumes more gypsum and achieves a more complete hydration reaction. An endothermic peak appears at 600–800 °C, corresponding to the thermal decomposition of calcium carbonate formed by carbonation, and the curve tends to be stable at around 800°C due to the exothermic formation of β -wollastonite from C-S-H gel.

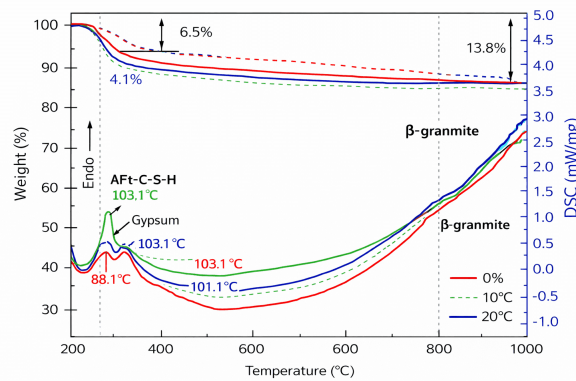


Figure 7. Thermogravimetric–differential scanning calorimetry (TG–DSC) curves of specimens cured at different temperatures for 28 days

The total mass loss of specimens under different curing temperatures is 13.8%, and the 20 °C cured sample shows earlier mass loss, indicating that curing temperature exerts a remarkable effect on the early hydration of the cementitious system.

3.7 Fourier-Transform Infrared Analysis

The FTIR spectra of the cementitious materials at different curing ages and temperatures are shown in Figure 8. The absorption peaks near 3408 cm^{-1} and 1621 cm^{-1} are attributed to the bending and stretching vibrations of OH^- bonds, representing the bound water and crystal water in AFt and C-(A)-S-H gels. These peaks overlap due to the differences in chemical properties and contents of hydration products. The peak width at 3408 cm^{-1} gradually increases with the rise of curing temperature (from 0 °C to 20 °C), indicating more crystal water-containing hydration products are formed at higher temperatures, consistent with XRD and TG-DSC results. The characteristic absorption band at 1477 cm^{-1} , corresponds to CO_3^{2-} , and the varying transmittance under different temperatures reflects the change in CaCO_3 content, proving that lower curing temperature weakens the carbonation reaction of cementitious materials, which is in line with TG-DSC analysis.

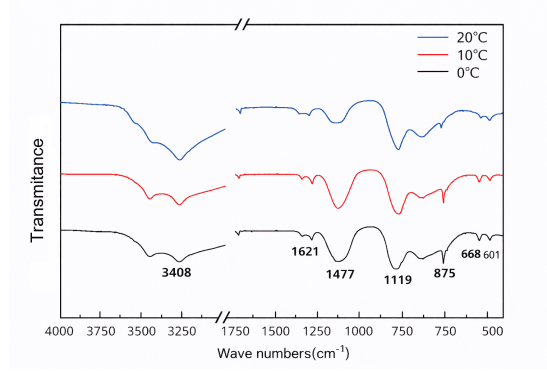


Figure 8. Fourier-transform infrared (FTIR) analysis of specimens cured at different temperatures for 28 days

The absorption peak at 1119 cm^{-1} originates from the asymmetric stretching vibration of $[\text{SO}_4^{2-}]$, mainly from CaSO_4 in raw materials. The absorption band near 985 cm^{-1} is assigned to the asymmetric stretching vibration of Si-O bonds; the characteristic peak sharpens with the increase of temperature, indicating massive Si-O bond breakage and enhanced formation of Aft and C-S-H gel. The absorption peak at 875 cm^{-1} corresponds to the asymmetric stretching vibration of Al-OH bonds, and the peak becomes gentler with higher transmittance as curing temperature rises, demonstrating the depolymerization and reconstruction of aluminum-oxygen octahedra to form Aft.

The symmetric stretching vibration of Si-O-Al bonds linking aluminum-oxygen tetrahedra and silicon-oxygen tetrahedra is observed near 668 cm^{-1} , and the peak becomes gentler with higher transmittance as curing age extends, indicating the migration of Al-O from silicate to Aft. The absorption band at 601 cm^{-1} is caused by the bending vibration of SO_4^{2-} in Aft, and the peak intensity strengthens with age, proving the continuous increase of Aft content in the system.

3.8 Scanning Electron Microscopy Analysis

Figure 9 shows the SEM micrographs of the quaternary system cured for 28 d. Figure 9a and Figure 9b are the micrographs of specimens without refining slag cured at 20°C for 28 d. A large number of acicular-rod shaped Aft crystals are formed, distributed in layers and densely packed to form Aft clusters, providing major strength support for the system. C-S-H gel containing Al and Mg is also generated after 28 d of hydration, and Aft crystals interpenetrate with C-S-H gel to form a compact microstructure.

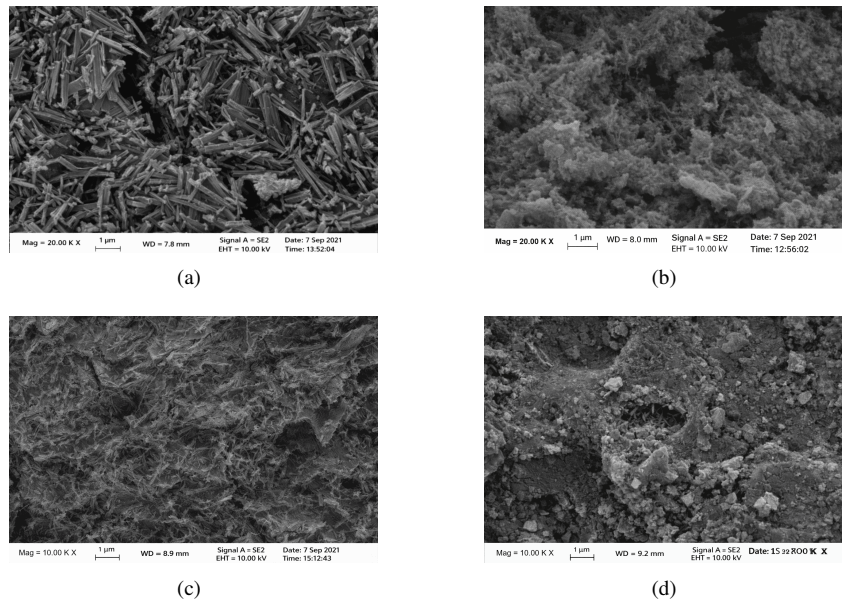


Figure 9. Scanning electron microscopy (SEM) micrographs of cementitious specimens at 28 days

Figure 9c and Figure 9d show the micrographs of specimens with 20% refining slag cured at 20°C for 28 d. Massive Aft clusters are formed, and flocculent Aft wraps around the C-S-H gel, forming a denser microstructure

with almost no pores or cracks compared with the system without refining slag. The intertwined AFt crystals cover the system surface and block micro-cracks, contributing to significant strength growth, which matches the strength test data.

3.9 Hydration and Consolidation Mechanism

In the refining slag-GBFS-steel slag-desulfurized gypsum quaternary cementitious system, refining slag features fast hydrolysis and hydration rates, releasing a large amount of OH^- to create an alkaline environment. This alkaline environment reacts with Ca^{2+} and SO_4^{2-} hydrolyzed from GBFS and gypsum to form AFt, which in turn promotes GBFS hydrolysis and synergistically accelerates the depolymerization and reconstruction of silicon (aluminum) oxygen tetrahedra. The absence of $\text{Ca}(\text{OH})_2$ diffraction peaks in the XRD patterns indicates that $\text{Ca}(\text{OH})_2$ generated from the hydration of refining slag and steel slag is completely consumed by the depolymerization of silicon (aluminum) oxygen tetrahedra in GBFS.

Refining slag provides a large amount of Al^{3+} ions, steel slag supplies divalent metal cations and OH^- ions, and gypsum releases Ca^{2+} and SO_4^{2-} ions, jointly promoting the formation of AFt. However, low-temperature curing reduces the hydrolysis rate of each component and weakens the ion binding capacity. The early hydration of each component releases heat to promote the overall hydration reaction, and a wealth of gel products are formed after hydration, as verified by TG, XRD and SEM analyses.

The early strength growth rate of the system is proportional to curing temperature. The ternary “steel slag-GBFS-desulfurized gypsum” system relies on AFt formation to drive hydration, but low temperature reduces ion migration rate, leading to incomplete hydration, lower strength growth rate and lower peak compressive strength. The incorporation of refining slag optimizes the low-temperature hydration kinetics, providing sufficient early hydration products to stabilize the system structure and improve low-temperature early strength.

4 Conclusions

(1) The uniaxial compressive strength tests of fully solid waste cementitious materials under low-temperature curing show that the compressive strength of paste specimens with the same proportion decreases with the reduction of temperature. The 28 d compressive strength at 0 °C curing is only 33.5% of that under standard curing at the same age, and the early strength growth rate of the system is positively correlated with curing temperature.

(2) Refining slag has excellent hydration activity, and its incorporation can significantly improve the compressive strength of the system under low-temperature curing. At 10 °C curing, the 3 d, 7 d and 28 d strengths of the system with 20% refining slag are increased by 93%, 81% and 89.4% respectively compared with the system without refining slag. The optimal mix proportion of the quaternary system under low-temperature curing is refining slag: GBFS: steel slag: desulfurized gypsum = 20:45:15:20, with the best strength performance.

(3) Microscopic analysis shows that unreacted desulfurized gypsum remains in the system after 28 d of hydration, and low temperature restricts the hydrolysis and hydration process of raw materials, slowing down the reaction rate. No new crystal phases are formed compared with standard curing, fully confirming that low temperature only inhibits the reaction rate of each process without changing the hydration product types.

Author Contributions

Conceptualization, C.R.; methodology, C.R. and L.Y.S.; validation, C.R., H.Z., and Y.H.X.; formal analysis, H.Z. and H.B.J.; investigation, C.R., H.Z., and H.B.J.; resources, C.R., L.Y.S., and Y.B.L.; writing—original draft preparation, C.R., H.Z., and L.Y.S.; writing—review and editing, C.R. and Y.H.X.; project administration, Y.H.X. All authors have read and agreed to the published version of the manuscript.

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Data Availability

The data used to support the research findings are available from the corresponding author upon request.

Conflicts of Interest

The authors declare no conflict of interest.

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