

Research on cement clinker calcination in CO₂/O₂ atmosphere

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ABSTRACT: Oxyfuel CO₂ capture technology is one of the key approaches to addressing CO₂ emissions in cement production, offering advantages such as low capture cost and high efficiency, which highlight its strong application potential. However, research on the effect of oxy-fuel combustion technology on cement clinker calcination is insufficient. In this paper, the effects of kiln atmosphere, heating rate, and sintering temperature on the phase composition, microstructure, and resultant properties of cement clinker were analyzed through strength testing, petrographic analysis, f-CaO testing, and X-ray diffraction analysis. The results show that with the increase in the CO₂/O₂ ratio, the C₃S content and strengths at 3-day and 28-day first increase and then decrease. With the increase in lime saturation factor (KH), the content of C₃S increases and the content of C₂S decreases, but excessive KH can lead to incomplete development of alite (A ores) and significant defects. At too low calcination temperatures, the f-CaO content is high, the C₃S content is low, and A ores are scarce, while at too high temperatures, A ores are underdeveloped. Under CO₂/O₂ atmosphere, the optimal calcination conditions are: the volume ratio of CO₂ to O₂ ranges from 0.59:0.41 to 0.69:0.31, KH = 0.90, temperature is 1450°C. This study provides a theoretical basis for achieving low-carbon production in the cement industry.

KEYWORDS: Oxyfuel CO₂ capture technology; cement clinker; mineral composition; calcination atmosphere; low-carbon production

1 Introduction

CO₂ is one of the main greenhouse gases, and large amounts of CO₂ emissions will lead to global warming, glacier melting, sea level rise and other problems [1, 2]. Countries and regions around the world have successively introduced low-carbon production policies. During cement production, both carbonate decomposition and fuel combustion produce large amounts of CO₂ [3–7]. The cement industry is one of the largest sources of carbon emissions, accounting for 6–7% of global emissions during production [8, 9]. Therefore, achieving low-carbon production in the cement industry is an urgent issue [10].

Currently, the low-carbon production pathways in the cement industry mainly include co-disposal of alternative fuels [11, 12], use of decarbonized raw materials [13, 14], improvement of production energy efficiency [15], and carbon capture technologies [16]. The decarbonation of raw materials during clinker production is responsible for 50–60% of the total carbon footprint of cement manufacturing [17], and this portion of emissions inherently resists reduction through improvements in production efficiency or the adoption of alternative fuels. The widespread adoption of low-carbon alternative raw materials

is constrained by the scarcity and uneven geographical distribution of viable resources [18]. Consequently, carbon capture and storage (CCS) must be regarded as an essential pathway for the cement sector to achieve its low-carbon transformation. In current research, diverse CCS technologies have been developed, including but not limited to Oxyfuel combustion [19], the Chilled Ammonia Process [20, 21], CO₂ separation via membrane with liquefaction [22], and the Calcium Looping cycle [23]. Compared to other capture technologies, Oxyfuel capture has over 90% capture efficiency and the lowest capture costs [24, 25], attracting attention from the cement industry.

Oxyfuel CO₂ capture technology involves mixing O₂ with recycled CO₂, creating an environment for clinker calcination and fuel combustion. Following combustion, the flue gas primarily consists of water vapor and CO₂. The subsequent integration of oxy-fuel combustion with the calcination process results in a substantially elevated CO₂ concentration in the resulting gas stream (with a volume fraction exceeding 70%), which greatly reduces the difficulty and cost of capturing high-concentration CO₂ [26–28]. In recent years, this technology has been researched as a frontier technology for achieving low-carbon production

in the cement industry. Experimental research on oxy-fuel combustion in cement production has progressed at various scales. Investigations into its effects on combustion characteristics and gas composition have been conducted [29, 30]. Feasibility was confirmed through a 500-kW pilot-scale trial [31], while Carrasco et al. [32] designed and tested an industrial burner prototype under laboratory conditions. Wang et al. [33] simulated the characteristics of oxy-fuel combustion of coal powder in cement kilns, and the results showed that enhancing the oxygen enrichment rate improves combustion temperature and efficiency, but at the expense of temperature field uniformity. Carrasco-Maldonado et al. [34] confirmed a correlation between the oxy-fuel combustion atmosphere and cement clinker strength, indicating that the combustion environment directly influences the final product's mechanical properties.

In summary, there have been some studies on the feasibility of oxy-fuel combustion technology and its influence on combustion, but there is insufficient research on the impact of oxy-fuel combustion technology on cement clinker calcination. Oxyfuel CO₂ capture technology changes the atmosphere of the cement clinker calcination process from air to CO₂/O₂, and this change in atmosphere will have a certain effect upon calcination of the raw meal to form clinker [35]. Therefore, it is necessary to study the influence of CO₂/O₂ atmosphere on cement clinker calcination and obtain the optimal calcination process for cement clinker under CO₂/O₂ atmosphere.

This study systematically assessed the effects of atmospheric conditions, heating rates, and temperatures on the composition, microstructure, and performance of cement clinker. Experiments were conducted using an atmosphere-controlled furnace, and the resulting clinkers were characterized through compressive strength tests, petrographic analysis, f-CaO content measurement, X-ray diffraction (XRD), and other techniques. The optimal calcination process for cement clinker under CO₂/O₂ atmosphere was derived, providing a theoretical basis for achieving low-carbon production in the cement industry.

2 Materials and methods

2.1 Raw materials

In this paper, the cement raw materials and fly ash used were sourced from a cement plant, with the chemical composition of the raw materials and fly ash shown in Table 1. The raw material lime

saturation factor (KH) was 0.90. The adjustment of the raw material rate was mainly achieved by adding analytical-grade CaO or SiO₂. KH = 0.86 was achieved by adding 0.45% SiO₂ by mass of clinker, while KH = 0.94 was achieved by adding 2.44% CaO. To simulate the ubiquitous influence of trace ash introduced by coal combustion on raw meal composition and the clinkering process in actual industrial production, fly ash was added to all raw meal blends at a proportion of 1.55%, a value derived from the thermal consumption data of the cement plant. Subsequently, CaO or SiO₂ was added according to the design ratio, mixed uniformly in a mixer, and ground to a fineness of 80 µm with a residue of 15–20%. The raw material was mixed with 8 wt% deionized water and homogenized. The mixture was then compacted at 30 MPa into green cakes with a diameter of 30 mm, followed by a drying pretreatment at 65°C for 30 min.

2.2 Clinker calcination

The cement clinker was calcined in an atmosphere-controlled furnace, specifically a silicon-molybdenum (MoSi₂) furnace, which was programmed to reach the specified temperature. The gas flow rate was regulated by mass flow controllers to achieve different atmospheric ratios. Prior to entering the atmosphere furnace, the gases are thoroughly mixed via a gas blending unit. The gas ratios are precisely regulated by controlling the flow rates using mass flow controllers. The total system gas flow rate is set at 5 ± 0.1 L/min, and the operating pressure is ambient (atmospheric pressure). The mixed gas stream is subsequently preheated to 900°C. The raw material cakes were placed into the furnace chamber at 900°C, then heated to the target temperature at a rate of 5°C/min. They were subsequently held at 1425°C, 1450°C, or 1475°C for 1 h before being rapidly cooled to room temperature by forced-air cooling. The calcined cement clinker samples were prepared according to the testing requirements. Table 2 outlines the detailed experimental design and sample identifiers. The corresponding preparation procedure is schematically shown in Figure 1.

2.3 Material testing and performance characterization

The free calcium oxide content was measured with an FC-6 rapid tester. Petrographic analysis, performed using an Olympus BX-51 polarizing microscope, was employed to characterize

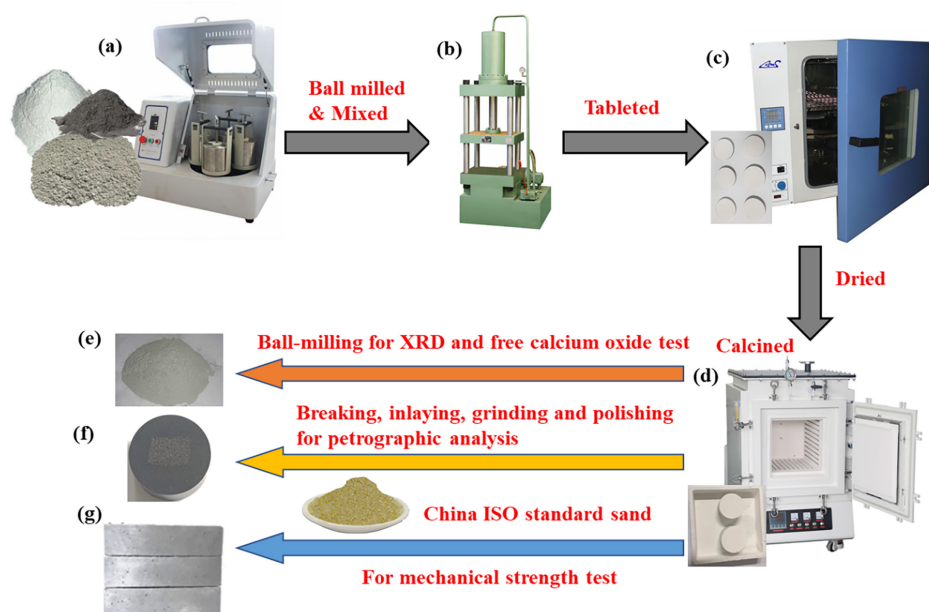
Table 1 Oxide composition (wt%) of the burning raw meal, fly ash, and cement clinker

	CaO	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	MgO	SO ₃	K ₂ O	Na ₂ O	KH	SM	IM
Burning raw meal	62.8	20.62	4.59	3.32	2.54	0.41	0.90	0.24	0.90	2.57	1.44
Fly ash	20.41	42.53	18.44	4.34	2.22	3.54	0.29	0.49			
Cement clinker	62.14	20.96	4.80	3.34	2.54	0.46	0.89	0.24			

Note: KH: Lime Saturation Factor; SM: Silica Modulus; IM: Alumina Modulus. "Cement clinker" refers to the industrial cement clinker used as a reference.

Table 2 Experimental design and sample nomenclature for the cement clinker calcination trials

	Calcination atmosphere					Calcination temperature (°C)	KH
	39% CO ₂ + 61% O ₂	49% CO ₂ + 51% O ₂	59% CO ₂ + 41% O ₂	69% CO ₂ + 31% O ₂	79% CO ₂ + 21% O ₂		
Sample No.	A1	A2	A3	A4	A5	1450	0.86
	B1	B2	B3	B4	B5	1450	0.90
	C1	C2	C3	C4	C5	1450	0.94
	B _{LT} 1	B _{LT} 2	B _{LT} 3	B _{LT} 4	B _{LT} 5	1425	0.90
	B _{HT} 1	B _{HT} 2	B _{HT} 3	B _{HT} 4	B _{HT} 5	1475	0.90

**Figure 1** Schematic diagram illustrating the complete preparation and analysis process: (a) ball-milling, (b) tableting, (c) drying, (d) calcination, (e) samples for XRD/f-CaO testing, (f) sample for petrographic analysis, and (g) mortar specimens

the clinker microstructure. For sample preparation, a planar surface was sectioned from the clinker, mounted in phenolic resin, and subjected to sequential grinding and polishing. Grinding was performed using progressively finer abrasive papers, finishing with a grit no coarser than P2500. Polishing was carried out on a polishing cloth with anhydrous ethanol as the lubricant, followed by etching of the polished surface with a 1.0% ammonium chloride solution.

The compressive strength of cement mortar was tested at 3-day and 28-day ages in accordance with GB/T 17671-2021 “Method for Testing the Strength of Cement Mortar (ISO Method)”. The mixture proportion was set as cement: standard sand: water = 1:3:0.5, and specimens with dimensions of 40 mm × 40 mm × 160 mm were prepared. All specimen groups were cured under standard conditions (20 ± 1°C, relative humidity ≥90%), with no fewer than six valid specimens per group. During strength testing, the loading rate was controlled at 2.4 kN/s.

X-ray diffraction (XRD) analysis was performed on a Bruker D8 Advance diffractometer (Germany)

operated at 40 kV and 40 mA. Data were collected in step-scan mode over a 2θ range of 10° to 70°, with a step size of 0.02° and a counting time of 1 s per step.

Rietveld refinement was carried out using the MAUD software to quantify the mineral phase composition based on the obtained XRD patterns. Rietveld refinement is a precise full-pattern fitting method for quantitative phase analysis, which employs a least-squares approach to model the diffraction profile by incorporating crystal structure data, instrumental parameters, and sample-related effects such as microstrain and preferred orientation [36, 37]. In this work, the background was fitted with a 5th-order Chebyshev polynomial. For the four major crystalline phases—tricalcium silicate (C₃S), dicalcium silicate (C₂S), tricalcium aluminate (C₃A), and tetracalcium aluminoferrite (C₄AF)—both microstrain parameters and atomic positions were refined. A spherical harmonics model was applied to correct for preferred orientation in C₃S. The sample displacement parameter was also included and successfully converged during refinement.

The accuracy of the Rietveld refinements was assessed based on the visual agreement of the fitted spectra and the weighted-profile error factor (Rwp). The obtained Rwp values (all below 10%) confirm high-quality fits [38–40]. Quantitative phase analysis (QPA) was conducted using MAUD software, with the following crystal structures as reference models: Ca_3SiO_5 (monoclinic, Cm) [41], Ca_2SiO_4 (monoclinic, $\text{P2}_1/\text{n}$) [42], $\text{Ca}_3\text{Al}_2\text{O}_6$ (cubic, Pa_3) [43], and $\text{Ca}_2\text{AlFeO}_5$ (orthorhombic, Pbcm) [44]. The experimental XRD patterns of the synthesized samples were then refined against these models.

3 Results and discussion

3.1 Influence of KH value on clinker calcination under CO_2/O_2 atmosphere

The KH value not only directly affects the mineral composition of cement clinker but also determines the performance and quality of the final product [45–47]. Therefore, in-depth exploration and precise control of KH are important for optimizing the performance of cement clinker. Through fine-tuning of KH parameters, the quality of the clinker can be effectively improved, ensuring the durability and stability of cement materials.

3.1.1 Influence of KH value on clinker performance
In this paper, the calcination experiments of cement clinker with different KH values were carried out under CO_2/O_2 atmosphere. The calcined cement clinker was subsequently subjected to a series of characterizations. The resulting free CaO content and compressive strength, as functions of varying KH values and calcination atmospheres, are presented in Figures 2 and 3, respectively. Further statistical analysis of the strength data revealed that significant differences exist in the clinker strengths obtained under different calcination atmospheres and varying KH values.

As can be seen from Figure 2, with the CO_2/O_2 ratio increases, the f-CaO content in the clinkers first decreases and then increases, reaching a minimum when the CO_2/O_2 ratio is 59/41. With the increase of KH value, when $\text{KH} = 0.94$, the f-CaO content significantly increases, which is attributed to the relatively high content of CaO in the system when KH is too high, making it difficult for free calcium in the clinker to be fully absorbed.

Comparing the strengths of clinkers calcined under different atmospheres, as the CO_2/O_2 ratio increases, the strengths at 3d and 28d follow a

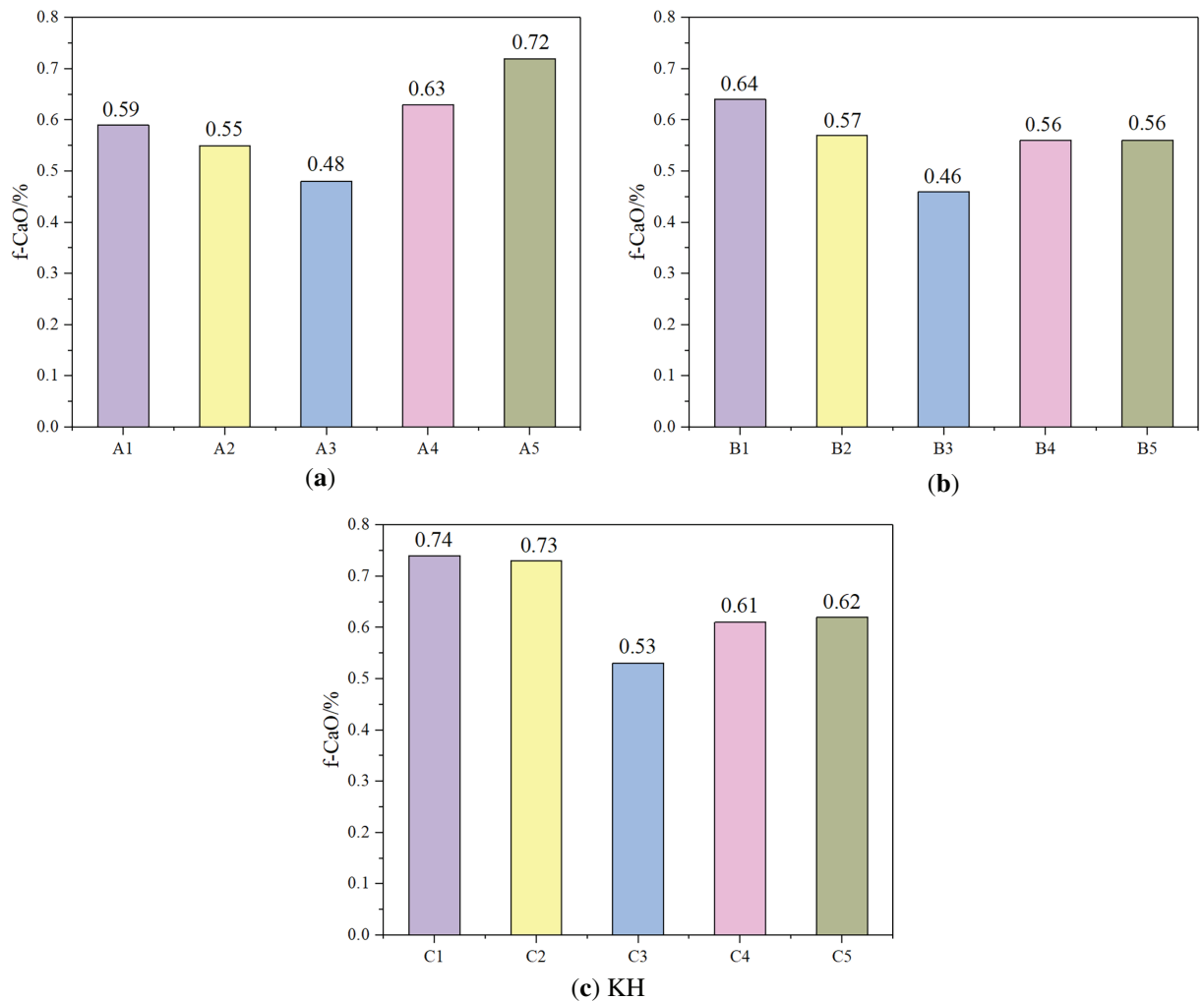


Figure 2 Effect of heating rate on the free CaO content of cement clinker: (a) KH = 0.86; (b) KH = 0.90; (c) KH = 0.94

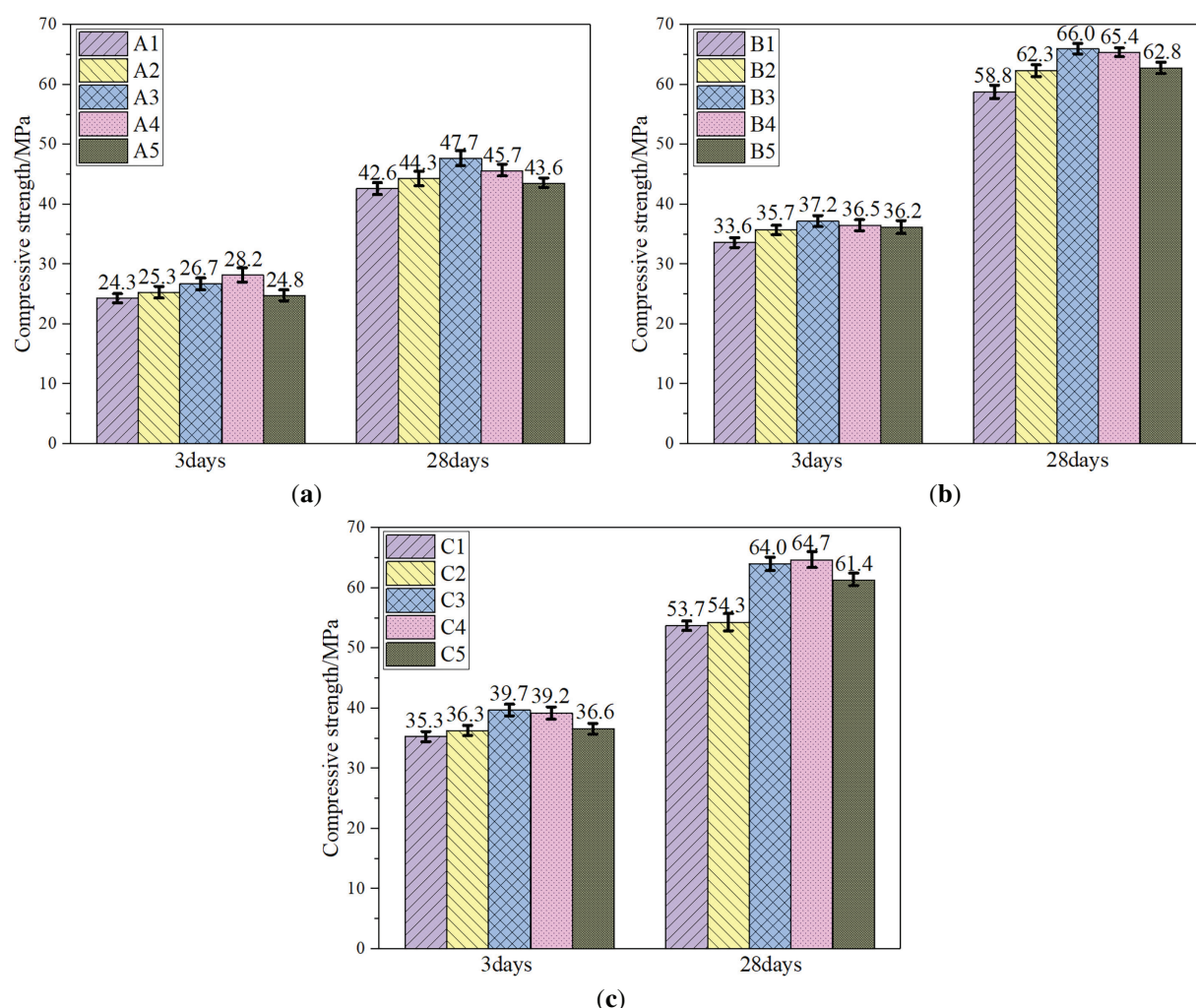


Figure 3 Compressive strength of cement clinker with different rate values: (a) KH = 0.86; (b) KH = 0.90; (c) KH = 0.94

trend of first increasing and then decreasing, indicating that a suitable CO_2/O_2 ratio is beneficial for enhancing the strength of cement clinker. In this paper, under different KH values, the volume ratio of CO_2 to O_2 ranges from 0.59:0.41 to 0.69:0.31, showing a significant increase in cement clinker strength, indicating that the optimal CO_2/O_2 ratio lies within this range. Under the same atmosphere, comparing the effects of different KH values on clinker strength, it can be observed that increasing KH leads to an increase in 3d strength, whereas 28d strength first increases and then decreases, with the best 3d strength occurring at KH = 0.94 and the best 28d strength at KH = 0.90.

In summary, under CO_2/O_2 atmosphere, the best 3d strength occurs at KH = 0.94, and the best 28d strength occurs at KH = 0.90. Considering the calcination of cement clinker, KH = 0.90 is optimal, and the best CO_2/O_2 ratio lies between 0.59/0.41 and 0.69/0.31.

3.1.2 Influence of KH value on clinker composition

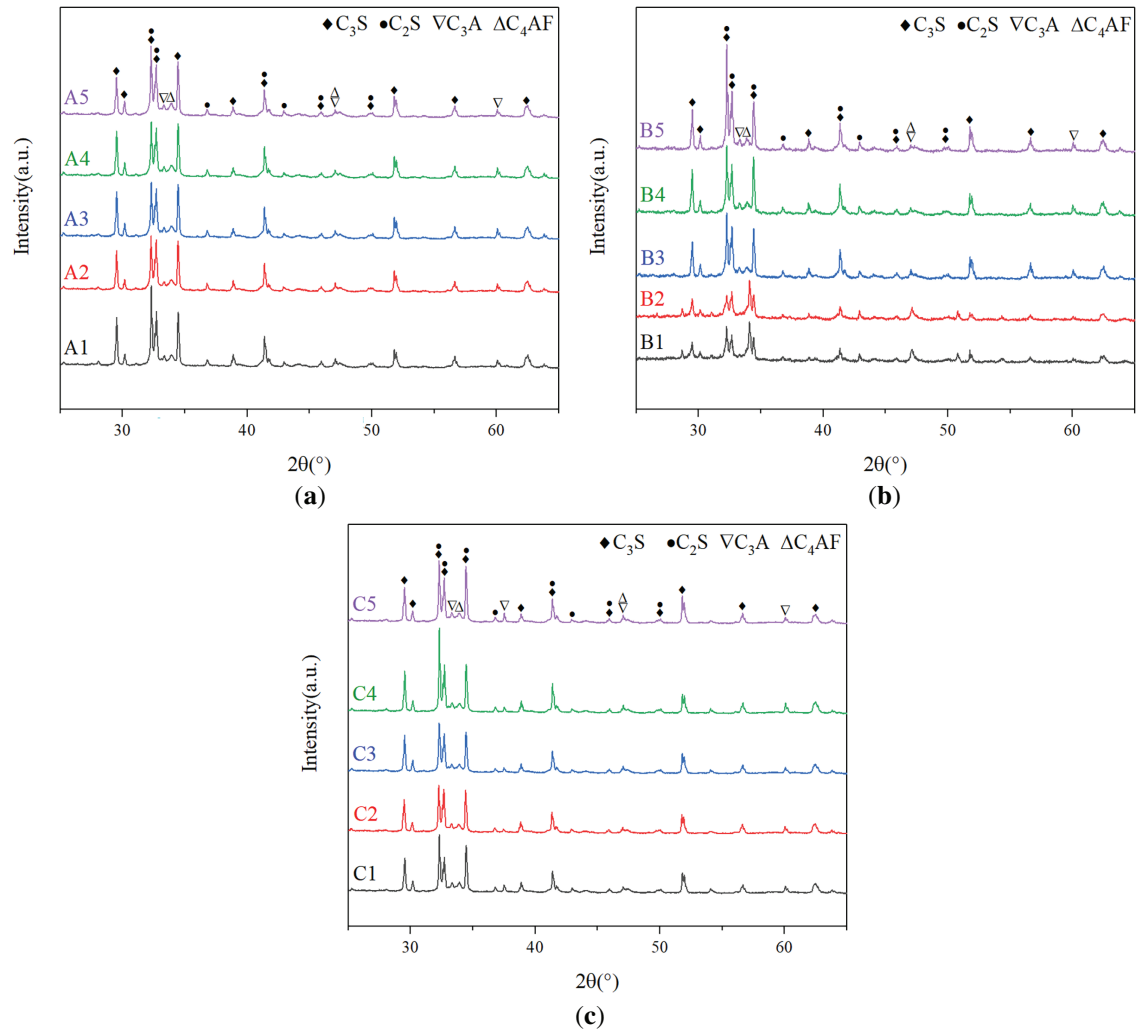
To investigate the intrinsic factors affecting clinker strength, XRD analysis was conducted on the clinkers. Figure 4 shows the XRD diffractograms

of clinker samples obtained under different KH values and atmospheres.

Figure 4 shows that with the change in KH value and atmosphere, the main minerals of the samples remain largely unchanged, but the intensity of the diffraction peaks varies, indicating that changes in atmosphere and KH values can affect the mineral composition of the clinker. Further quantitative analysis through XRD full-pattern fitting was conducted, yielding the mineral phase content of each clinker sample. Table 3 presents the mineral composition of cement clinker samples under varying calcination atmospheres and KH values. The weight factor $R_{wp} < 10\%$ indicates that the fitting results are reliable [38–40].

From Table 3, as the CO_2/O_2 ratio increases, the C_3S content first increases and then decreases, with the peak C_3S content occurring at a CO_2/O_2 ratio of 59/41. Compared to C_3S , there is no apparent regularity in the changes of C_2S , C_3A , and C_4AF with changes in atmosphere. C_3S and C_2S are the main components providing strength to cement clinker, and as the CO_2/O_2 ratio increases, the C_3S content first increases and then decreases, leading to the trend of 3d and 28d strength first increasing and then decreasing. The presence of CO_2 can enhance the reaction rate between CaO and SiO_2

Figure 4 XRD diffractograms of cement clinker with different rate values:
(a) KH = 0.86;
(b) KH = 0.90;
(c) KH = 0.94



[48]; as the CO₂ ratio increases, the C₃S content increases. However, with further increases in CO₂ content, the decomposition of carbonates is inhibited, resulting in a decrease in the active CaO content and the rate of C₃S formation. Therefore, when the CO₂/O₂ ratio is between 0.59/0.41 and 0.69/0.31, the C₃S content reaches its peak, and both 3d and 28d strengths are optimal. As seen in Table 3, with changes in KH values, the contents of the main minerals, C₃S and

Table 3 Mineral compositions of cement clinkers with different rate values

KH	Sample No.	Mineral Composition of Clinker (wt.%)				
		C ₃ S	C ₂ S	C ₃ A	C ₄ AF	R _{wp} (%)
0.86	A1	49.2	27.7	7.7	15.4	8.1
	A2	55.1	22.4	6.9	15.6	7.1
	A3	68.7	11.3	7.9	12.1	9.3
	A4	57.3	18.7	8.4	15.6	8.1
	A5	46.2	27.8	7.5	18.5	6.8
0.90	B1	61.9	13.5	8.5	16.1	8.8
	B2	64.7	12.4	8.7	14.2	9.5
	B3	69.1	11.4	8.0	11.5	9.3
	B4	63.3	13.8	8.4	14.5	8.8
	B5	65.9	11.1	8.3	14.7	9.0
0.94	C1	70.8	2.2	8.0	19.0	9.3
	C2	71.2	1.8	8.3	18.7	9.5
	C3	78.2	1.5	9.2	11.1	9.8
	C4	74.7	2.0	8.7	14.6	9.2
	C5	73.4	2.9	10.9	12.8	9.9

C_2S , in the clinker vary significantly. Under the same atmosphere, the difference in C_3S content of clinkers calcined at different KH values can reach 48%. With the increase in KH value, the C_3S content increases significantly, while the C_2S content decreases. This is primarily due to the increase in the ratio of CaO in the raw materials with an increase in KH, and the decrease in the ratio of SiO_2 , leading to more C_2S being converted to C_3S , resulting in the increase of C_3S and the decrease of C_2S . Compared to C_3S and C_2S , the contents of C_3A and C_4AF do not show significant regular changes.

C_3S in cement clinker develops strength more rapidly, exhibiting higher early strength and a larger rate of strength increase; while C_2S hydrates more slowly, initially showing lower strength but catching up with C_3S in later stages [49, 50]. As the KH value of the raw material increases, the C_3S content increases, resulting in enhanced 3d

strength of the clinker. Conversely, the increase in KH value leads to a reduction in C_2S content. When $KH = 0.94$, the C_2S content decreases significantly, so the 28d strength of the clinker does not simply increase with KH.

3.1.3 Influence of KH value on clinker structure

There are general rules regarding the microstructure and strength of cement clinker [51, 52]. To characterize the clinker microstructure, petrographic analysis was conducted. In cement clinker, Alite (A ore) typically crystallizes as hexagonal plates or flakes, while Belite (B ore) commonly presents as rounded particles exhibiting a characteristic cross-hatched twinning pattern. Figure 5 presents the petrographic images of clinker samples prepared under different KH values. Analysis of these images reveals that when $KH = 0.86$, the sample exhibits few voids, with irregular pore sizes

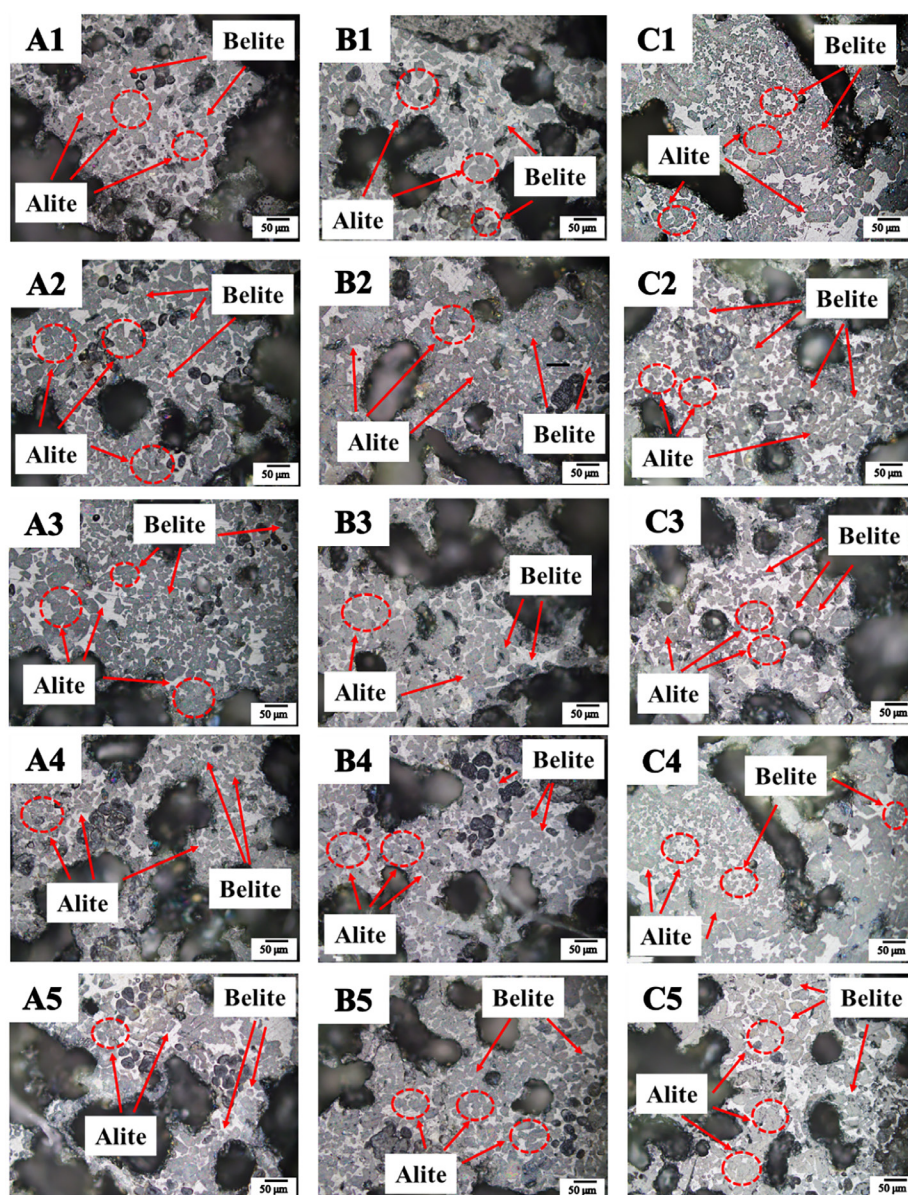


Figure 5 Petrographic diagram of cement clinker with different rate values

and distribution. The majority of the A ore has a regular shape, but the edges are not sufficiently smooth, and both A and B ores showed obvious agglomeration. When $KH = 0.90$, the sample has few voids, with uneven sizes of A ores, which are mostly hexagonal plate-like and flaky, along with some inclusions. B ores exist in a nest-like form with an agglomerated distribution. When $KH = 0.94$, the sample has more voids, a higher density of clinker, and a higher content of A ores, which mostly exist in hexagonal plate-like and flaky forms, but with obvious defects such as adhesion and inclusions. The B ores content is lower, with poor roundness, indistinct crystal boundaries, no cross-twinning, and exists in a nest-like form. The sample exhibits a rim reaction, indicating insufficient liquid phase, which hinders contact between the two mineral phases.

Overall, when the CO_2/O_2 ratio is 59/41 or 69/31, the cement clinker demonstrates superior petrographic characteristics: the alite crystals exhibit regular morphology, uniform size (averaging approximately 30 μm), and fewer structural defects. As KH increases, the content of A ores continues to rise while the content of B ores decreases, which is consistent with the XRD results. When KH is too high, the burnability deteriorates due to insufficient liquid phase, leading to slower growth of A ores. Therefore, although the A ores content increased in Group C samples, there were more instances of

mineral agglomeration and incomplete development of A ores crystals with defects. When KH is low, although the liquid phase and mass transfer efficiency are enough, the insufficient mineral content also makes it difficult to produce ideal clinker. Thus, the best performance of the 28d strength of cement clinker is observed at $KH = 0.90$.

3.2 Influence of temperature on clinker calcination under CO_2/O_2 atmosphere

Changes in calcination temperature can significantly alter the content and crystalline structure of various minerals in the clinker [53, 54], thereby affecting the physical properties of the cement. Therefore, it is essential to study the influence of temperature on clinker calcination under CO_2/O_2 atmosphere.

3.2.1 Influence of temperature on clinker performance

In this paper, cement clinker with $KH = 0.90$ was calcined at 1425°C, 1450°C, and 1475°C, respectively, under CO_2/O_2 atmosphere, and relevant tests were carried out on the calcined cement clinker. Figures 6 and 7 present the free CaO content and strength results of cement clinkers calcined at different temperatures. Further statistical analysis of the strength data revealed that significant differences exist in the clinker strengths obtained under different calcination temperature values.

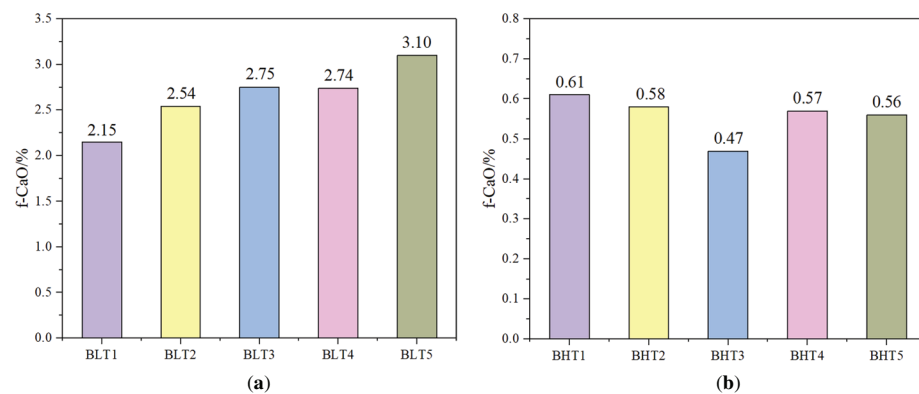


Figure 6 Effect of temperature on the free cao content of cement clinker: (a) 1425°C; (b) 1475°C

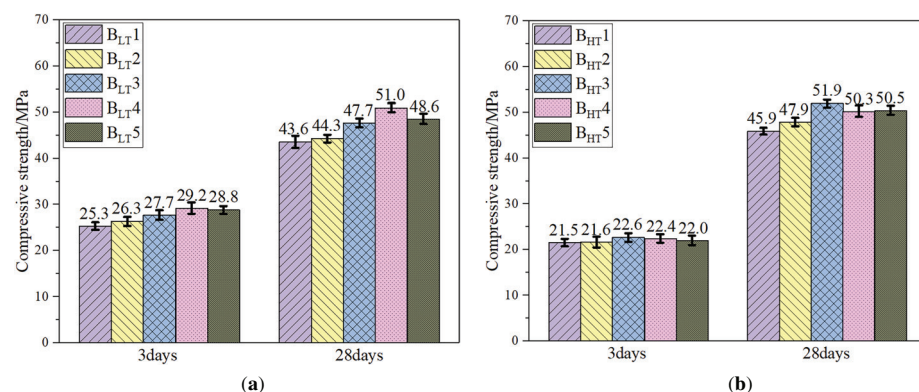


Figure 7 Compressive strength of cement clinker with different temperatures: (a) 1425°C; (b) 1475°C

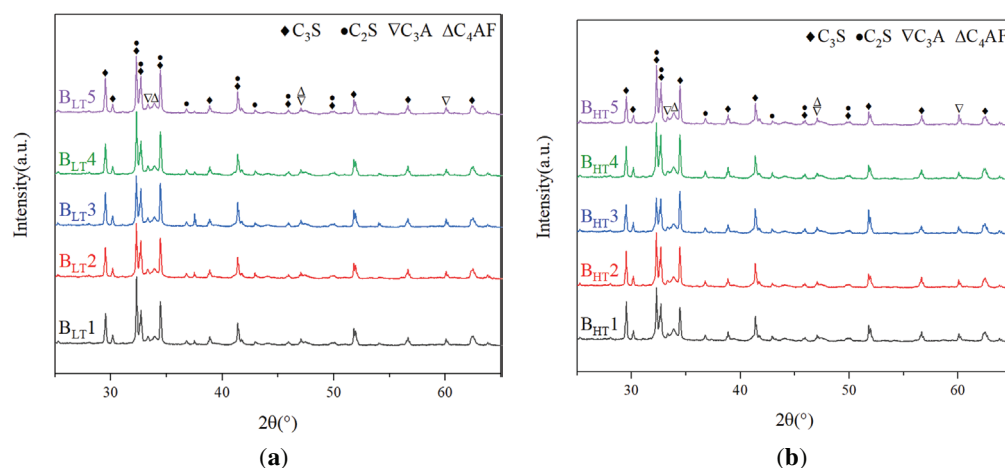


Figure 8 XRD diffractograms of cement clinker with different temperatures: (a) 1425°C; (b) 1475°C

From [Figure 6](#), it can be observed that under CO_2/O_2 atmosphere, the f-CaO content of cement clinker calcined at 1425°C is relatively high and does not meet industry requirements for f-CaO content. This is mainly due to the low calcination temperature, leading to slow formation rates of C_3S and C_2S , resulting in a large amount of unreacted free CaO. Comparing the f-CaO content of clinkers calcined at 1450°C and 1475°C, it can be seen that with further increases in temperature, the f-CaO content remains essentially unchanged. Excessive free CaO content can cause the clinker to react with CO_2 in the air during hydration, forming CaCO_3 , indicating that the calcination temperature for cement clinker under CO_2/O_2 atmosphere should be above 1425°C. As in previous studies, with the increase of CO_2/O_2 ratio, f-CaO first decreases and then increases.

Comparing the strength of clinker calcined under different atmospheres, it can be observed that as the CO_2/O_2 ratio increases, both the 3d and 28d strengths exhibit a trend of first increasing and then decreasing, with the optimal CO_2/O_2 ratio

being between 0.59/0.41 and 0.69/0.31, which aligns with the previous conclusion. Under the same atmosphere, comparing the effects of temperature on clinker strength reveals that as the temperature rises, both the 3d and 28d strengths first increase and then decrease, with the best strength achieved at a calcination temperature of 1450°C.

3.2.2 Influence of temperature on clinker composition

To reveal the intrinsic factors affecting the strength of cement clinker under CO_2/O_2 atmosphere, the phase composition of cement clinker was analyzed by XRD as a function of calcination temperature and atmosphere. [Figure 8](#) shows the XRD patterns of cement clinkers at different temperatures. Subsequently, full-pattern fitting analysis through XRD was performed, yielding the mineral phase content for each clinker sample. [Table 4](#) presents the phase composition of cement clinker samples at different calcination temperatures. A weight factor $R_{wp} < 10\%$ indicates that the fitting results are reliable.

Table 4 Mineral Compositions of Cement Clinkers with Different Temperatures

Temperature (°C)	Sample No.	Mineral Composition of Clinker (wt.%)				
		C_3S	C_2S	C_3A	C_4AF	R_{wp} (%)
1425	B _{L1}	59.9	13.1	9.3	17.7	10.0
	B _{L2}	60.1	13.1	9.6	17.2	9.8
	B _{L3}	62.7	13.3	9.0	15.0	9.7
	B _{L4}	63.1	14.2	9.1	13.6	8.6
	B _{L5}	60.8	14.2	9.3	15.7	9.3
1450	B1	62.3	13.1	8.5	16.1	8.8
	B2	64.7	12.4	8.7	14.2	9.5
	B3	69.1	11.4	8.0	11.5	9.3
	B4	63.3	13.8	8.4	14.5	8.8
	B5	65.9	11.1	8.3	14.7	9.0
1475	B _{HT1}	60.0	14.5	7.6	18.0	8.1
	B _{HT2}	60.6	17.7	6.4	15.4	7.2
	B _{HT3}	63.3	15.9	6.2	14.6	9.4
	B _{HT4}	63.1	13.9	7.2	15.8	8.1
	B _{HT5}	60.9	18.4	6.1	14.6	6.9

From Table 4, consistent with the mineral composition patterns of cement clinkers with different KH values, as the CO_2/O_2 ratio increases, the C_3S content first increases and then decreases. The peak C_3S content occurs at a CO_2/O_2 ratio of 0.59/0.41 or 0.69/0.31. Comparing the mineral composition of cement clinkers calcined at different temperatures, the C_3S content is highest at 1450°C and the C_2S content is lowest. The C_3A content decreased with increasing temperature, while the C_4AF content showed no significant changes. Under CO_2/O_2 atmosphere, as the calcination temperature rises to 1450°C, the rate of C_3S formation increases, leading to an increase in C_3S content in the clinker and consequently enhancing the strength of cement clinker. When the calcination temperature reaches 1475°C, overburning occurs, leading to a reduction in the effective mineral content of the final clinker, thus decreasing the strength of cement clinker.

3.2.3 Influence of temperature on clinker structure
This study further carried out petrographic analysis of cement clinkers calcined at different temperatures. Figure 9 shows the petrographic diagram of cement clinker samples at different temperatures. From Figure 9, it can be observed that at a

temperature of 1425°C, the samples have larger and more numerous voids, with free CaO observable. The A ore shapes are incomplete, the crystal sizes are uneven, and crystal development is poor, with various shapes including long columnar, square, and hexagonal forms. There are some interconnected crystal structures, but the crystal boundaries are not distinct. The B ore content was relatively high and clearly visible, with crystal sizes around 10–30 μm , few inclusions and fluffy crystals, distributed in a circular form, with some clustering around the voids, and most displaying crystal patterns. The intermediate phase shows an uneven distribution, mostly between A and B ores, with few sporadically dispersed around the voids. There are very few crystals that are partially corroded by the liquid phase, with incomplete edges and instances of mineral agglomeration. At a temperature of 1475°C, the samples have fewer voids, a higher A ore content, but clear defects such as adhesion and inclusions, and uneven distribution of A ore sizes, with a large number of small crystals; the B ore showed poor roundness and has not formed nest-like structures.

Compared with the petrographic diagram of cement clinkers at different temperatures, at a calcination temperature of 1425°C, the low temperature leads to a slow conversion rate of C_2S to C_3S , resulting in high f-CaO and B ore content with poorly developed A ores. At a calcination temperature of 1475°C, the high temperature accelerates densification during the calcination process, leading to underdeveloped A ores, smaller crystal sizes, and more defects. Therefore, the optimal calcination temperature for cement clinker under CO_2/O_2 atmosphere is 1450°C.

In summary, under a CO_2/O_2 atmosphere, as the KH value increases, the C_3S content in the clinker increases while the C_2S content decreases. When the KH value rises to 0.94, alite exhibits incomplete crystallization with noticeable defects. This explains why the specimen with KH = 0.90 shows the best 28-day strength. Furthermore, with increasing calcination temperature, the C_3S content first increases and then decreases. At 1470°C, alite crystallization is poorly developed and crystal defects become more pronounced. Overall, the clinker calcined at 1450°C exhibits the most favorable mechanical properties.

4 Conclusion

In this paper, under CO_2/O_2 atmosphere, cement clinker was obtained by varying KH values and calcination temperatures using an atmosphere furnace. The influence of KH values and calcination temperature on the performance of cement clinker was elucidated. XRD and petrographic analysis were employed to investigate the intrinsic factors influencing clinker performance. The conclusions of this study are as follows:

- 1) Under CO_2/O_2 atmosphere, as the CO_2/O_2 ratio increased, the content of f-CaO in the clinker

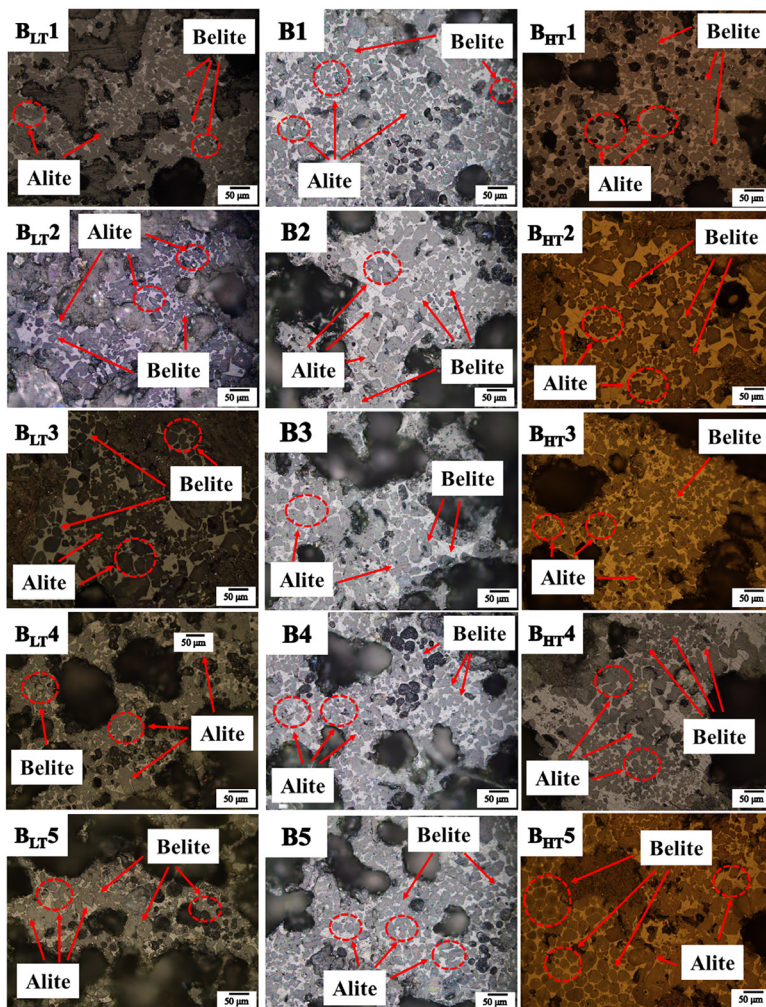


Figure 9 Petrographic diagram of cement clinker with different temperatures

first decreased and then increased, while the content of C_3S first increased and then decreased. As a result, the 3d strength and 28d strength first increased and then decreased, and the optimal CO_2/O_2 ratio was 0.59/0.41~0.69/0.31.

- 2) Under the CO_2/O_2 atmosphere, as the KH value increases, the content of C_3S rises while that of C_2S decreases, resulting in an increase in alite content and a reduction in belite content. At $KH = 0.94$, alite exhibits underdeveloped crystallization with noticeable defects. In terms of mechanical performance, the specimen with $KH = 0.94$ achieves the highest 3-day strength, while the specimen with $KH = 0.90$ demonstrates the optimal 28-day strength. Taking all factors into account, $KH = 0.90$ is identified as the most favorable modulus for calcining cement clinker under these conditions.
- 3) Under CO_2/O_2 atmosphere, the calcination temperature is $1425^\circ C$. The calcination temperature is too low, resulting in a high f-CaO, a low content of C_3S , and less A ore. When the calcination temperature is $1475^\circ C$, the A ore is underdeveloped and has many defects. The optimal calcination temperature for cement clinker is $1450^\circ C$.

This study primarily investigates the influence of temperature and KH values on the structure, mineral composition, and properties of cement clinker under CO_2/O_2 atmospheres following the adoption of oxyfuel CO_2 capture technology. However, the intrinsic mechanisms underlying how atmospheric variations affect the clinker calcination process—including related kinetic and thermodynamic aspects—have not yet been deeply explored. Furthermore, the impacts of changes in parameters such as silica modulus and alumina modulus have not been systematically examined. Future research could focus on further exploring these mechanisms and parameter systems. Additionally, the current work is confined to laboratory-scale investigations, lacking validation through industrial trials. It is recommended that subsequent studies incorporate pilot-scale or industrial-scale experiments to facilitate the effective translation of this technology from laboratory research to complex industrial systems.

Given the increasingly urgent need for low-carbon transformation in the cement industry, oxy-fuel CO_2 capture technology holds significant application potential in this field.

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Author Contributions

The authors confirm contribution to the paper as follows: conceptualization, Hu Yang and Feng He; methodology, Junlin Xie and Feng He; software, Shuxia Mei; validation, Hu Yang, Quanliang Li and Yumei Li; formal analysis, Hu Yang and Junlin Xie; investigation, Hu Yang and Junlin Xie; resources, Feng He and Shuxia Mei; data curation, Hu Yang and Quanliang Li; writing—original draft preparation, Hu Yang; writing—review and editing, Feng He and Junlin Xie; visualization, Hu Yang and Shuxia Mei; supervision, Feng He and Junlin Xie; project administration, Junlin Xie and Shuxia Mei; funding acquisition, Shuxia Mei. All authors reviewed and approved the final version of the manuscript.

Availability of Data and Materials

The authors confirm that the data supporting the findings of this study are available within the article.

Ethics Approval

Not applicable.

Conflicts of Interest

The authors declare no conflicts of interest.

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