



Activation of Low-Quality Coal Gangue Using Suspension Calcination for the Preparation of High-Performance Low-Carbon Cementitious Materials: A Pilot Study

Hongbo Zhang ^{1,2}, Shaowu Jiu ^{1,*}, Qianwen Gao ¹, Sijun Zhao ¹, Yanxin Chen ^{1,*}, Feng Cheng ¹, Ding Han ¹, Ruihong Shi ¹, Kaixin Yuan ¹, Jiacheng Li ¹, Yuxin Li ¹, Zichun Wang ¹ and Bo Zhao ¹

- ¹ School of Materials and Engineering, Xi'an University of Architecture and Technology, Xi'an 710055, China
- ² Anhui Conch Group Co., Ltd., Wuhu 241004, China
- * Correspondence: jiushaowu@xauat.edu.cn (S.J.); chenyanxin@xauat.edu.cn (Y.C.)

Abstract: Although the calcination-based activation of coal gangue is important for its valorization in the form of cementitious materials, the related works mainly focus on high-quality coal gangue, neglecting its low-quality counterpart. To bridge this gap, we herein conducted the pilot-scale suspension calcination of low-quality coal gangue; explored the effects of calcination temperature, particle size, and O₂ content on the phase composition of the calcined product, kaolinite decomposition, decarbonization, and silica/alumina dissolution; and evaluated calcination-product-based cementitious materials. Under optimal conditions (temperature = 875–900 °C; particle size = 39.71–46.84 μ m; and O₂ content = 12–14%), the carbon content of the calcined product equaled 1.24–1.87 wt%, and the dissolution rates of activated alumina and silica were 77.6–79.5% and 49.4–51.1%, respectively. The 28 d compressive strength (50.8–55.7 MPa) and true activity index (98.8–108.4%) of the cementitious material prepared at a calcination product dosage of 30–38 wt% met the standard of 42.5 grade cement. This study demonstrated the suitability of suspension calcination for the preparation of high-performance low-carbon cementitious materials from low-quality coal gangue, thus providing a basis for further industrialization and technological development.

Keywords: low-quality coal gangue; suspension calcination; decarbonization; process optimization; cementitious material

1. Introduction

Coal mining generates large amounts of coal gangue. China alone discharges 300– 500 million tons of coal gangue annually, and the corresponding historical stockpiles exceed 7 billion tons [1]. Given that the massive accumulation of coal gangue results in resource wastage and severe environmental pollution, the valorization of this material has drawn considerable attention [2,3]. High-quality coal gangue can be calcined to prepare low-carbon cementitious materials, which can be used to reduce the consumption of cement clinker and increase the durability and late strength of the corresponding mortar specimens [4–7]. Although numerous studies have confirmed the feasibility of preparing low-carbon cementitious materials from coal gangue, the large differences in the nature of coal gangue, the uneven distribution of high-quality coal gangue, and the immaturity of large-scale industrialization technologies limit the related practical application of this approach [8,9]. In particular, coal gangue is difficult to utilize because of its considerably low quality, low content of active substances, and low performance of activated products [10]. Therefore, the efficient activation of low-quality coal gangue is important for developing large-scale application technologies.

The activity of calcined coal gangue can be increased in two ways. Methods of the first type, which rely on the calcination, beneficiation, and ultrafine grinding of raw materials, involve chemical reactions, beneficiation, and enrichment or mechanochemistry to



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Copyright: © 2024 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https:// creativecommons.org/licenses/by/ 4.0/). remove harmful components and improve the reactivity of active minerals [11–14]. Calcination is typically conducted in muffle furnaces, vertical furnaces, and rotary kilns [15,16]. This type of equipment is difficult to popularize and apply because of its low calcination efficiency. Although processes based on efficient calcination technologies, such as those using fluidized or suspended beds, have attracted widespread attention, large-scale production has not yet been realized. Flotation, electrical separation, gravity separation, magnetic separation, and other mineral processing methods enable the efficient removal of coal, organic matter, iron ore, and other impurities from coal gangue [13]. However, the beneficiation method is very expensive and therefore mostly used to prepare high-value products. Ultrafine grinding does not purify coal gangue and fails to achieve activation, despite destroying the crystal structure of constituent minerals and increasing the specific surface area [17]. Methods of the second type involve the chemical activation of coal gangue components and thus facilitate their participation in the hydration reaction of cement, thereby improving the performance of cementitious materials [18–20]. Common strategies include alkali, acid, and composite (multicomponent) excitation. Alkali and acid excitations are mostly used in academic research because of their high cost and limited practical applications [21–24]. Composite excitation typically involves multicomponent batching methods to promote the hydration of active admixtures [25–27]. This strategy has been extensively researched by Scrivener and Dhandapani, who prepared a material with excellent properties by batching calcined clay with limestone powder and increasing blend content to 45 wt% [5]. Liu and Jiu et al. prepared cementitious materials with superior properties using components such as desulfurized gypsum, limestone powder, and fly ash to activate calcined coal gangue [28,29]. Current research on coal gangue activation largely focuses on high-quality coal gangue, leaving the activation of low-quality coal gangue and its calcination products underexplored.

High-temperature calcination is the most effective method of coal gangue activation. During calcination, kaolin decomposes to metakaolin, which is responsible for the gelling activity of calcined coal gangue [7,9,11,29]. Moreover, calcination can effectively remove carbon from coal gangue, not only utilizing its energy but also eliminating its adverse effects on concrete, such as poor fluidity and additive consumption. Suspension calcination (a gas-solid system), a process recently applied to coal gangue activation, allows powders with particle sizes of $\leq 100 \,\mu\text{m}$ to be calcined in the form of a conveyor bed and offers the advantages of high efficiency, low energy consumption, and high product quality [12,29]. After more than 10 years of research, we have developed a pilot-scale suspension calcination system for the efficient activation of coal gangue and confirmed the effectiveness of this system for the activation of several types of high-quality coal gangue. However, in-depth research on the applicability of our system to the activation of low-quality coal gangue is still lacking. According to previous studies, low-quality coal gangue is very different from highquality gangue in terms of composition, reaction characteristics and kinetics, the hydration mechanism of the corresponding cementitious materials, and product properties [16,29–31]. Thus, the results of research on the suspension calcination of high-quality coal gangue and its conversion to cementitious materials cannot be directly applied to low-quality coal gangue.

To overcome these limitations, the present study investigated the pilot-scale suspension calcination of low-quality coal gangue and the properties of the resulting cementitious materials, improving these properties through multi-solid waste composite excitation. The effects of temperature, particle size, and O_2 content on product composition, kaolinite decomposition, decarbonization, and active substance dissolution were explored to optimize the calcination parameters. The results of gelling material preparation and performance tests revealed that the low-quality coal gangue was effectively activated under the optimized conditions. The dose of the calcination product used to prepare cementitious materials was 30–38 wt%, and the performance of these materials complied with the standard of 42.5 grade cement. Thus, our study bridges a long-standing knowledge gap, demonstrates the feasibility of suspension calcination for the preparation of high-performance low-carbon cementitious materials from low-quality coal gangue, and lays the foundation for the industrialization of this process.

2. Materials and Methods

2.1. Raw Material

Washed coal gangue (30 t) was collected from the coal gangue yard of the Yuanzigou Coal Mine (Linyou County, Baoji, Shaanxi Province, China) using multipoint sampling. This raw material was crushed to a particle size of <10 mm by a jaw crusher and then ground to four fineness levels ($d_{50} = 61.35$, 46.84, 39.71, and 28.06 µm; particle sizes 1, 2, 3, and 4, respectively) using a vertical mill (DL1200, Xi'an University of Architecture and Technology, Xi'an, China). The composition of the raw coal gangue was analyzed through X-ray diffraction (XRD; D/MAX-2200, Rigaku, Akishima, Japan) using a Cu K_{α} target at a tube voltage and current of 45 kV and 40 mA, respectively. The main minerals were identified as kaolinite, quartz, and siderite, and the minor minerals were identified as calcite (Figure 1).



Figure 1. X-ray diffraction (XRD) pattern of raw coal gangue.

The chemical composition of coal gangue was analyzed through X-ray fluorescence (XRF) spectrometry (S4 PIONEER, Bruker, Mannheim, Germany) at a power of 4.2 kW and the maximum voltage and current of 60 kV and 140 mA, respectively (Table 1). The raw material was also analyzed according to the Chinese national standard GB/T212-2008 "Industrial Analysis Methods of Coal" [32] (Table 2). The results of XRD, XRF spectroscopy, and industrial analyses were combined to semi-quantitatively estimate the composition of the raw material (Table 3).

Table 1. Coal gangue composition determined using X-ray fluorescence (XRF) spectroscopy (wt%).

SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	CaO	K ₂ O	TiO ₂	MgO	Na ₂ O	SO ₃	MnO	P ₂ O ₅	Total
49.14	28.14	15.93	2.08	1.67	1.05	0.626	0.312	0.286	0.286	0.142	99.66

Moisture	Ash (wt%)	V	olatile (wt%)	Fixed Carbon	Lower Calorific	
$M_{ m ad}$ (%)	A _{ad}	A _d	V_{ad}	V _d	$V_{\rm daf}$	(wt%)	Value (kJ/kg)
0.48	71.82	72.17	14.62	15.18	52.79	13.08	4233.44

Table 2. Coal gangue composition determined using industrial analysis (wt%).

where A_{ad} and A_d are the air dry basis and dry basis ash, respectively; V_{ad} , V_d , and V_{daf} are the air-drying base, dry basis, and dry ash-free basis volatile matter, respectively.

Table 3. Coal gangue composition estimated via combined XRF spectroscopy, XRD, and industrial analysis (wt%).

Kaolinite	Quartz	Siderite	Calcite	Rutile	Coal
52.31	11.77	16.98	2.73	0.77	13.08

2.2. Suspension Calcination System

The suspension calcination system used in pilot-scale tests (Figure 2) was developed by the Xi'an University of Architecture and Technology, China. The pilot system consisted of a feeder, a preheating unit, a suspension reactor, a hot air furnace, a product cooling unit, and a tail gas purification unit. The hot air furnace used pulverized coal as fuel.



Figure 2. (a) Process flow diagram and (b) photograph of the pilot-scale suspension calcination system.

Considering the results of previous tests, we selected the calcination temperature, particle size, and the O₂ content of the calcination atmosphere as the control parameters. The temperature (800–900 °C) in the middle of the suspension reactor was controlled at ± 20 °C. The residence time of the material in the suspension reactor was 5–8 s, and the dosing volume was 320 kg \pm 5 kg per hour. The O₂ content, set at 8%, 10%, 12%, 14%, and 16%, was measured at the outlet of the suspension reactor using an in-line gas analyzer (TESTO340, Testo International Trading Co., Ltd., Shanghai, China).

2.3. Product Analysis

2.3.1. Phase Composition and Dissolution Activity

The phase composition of the calcined gangue was analyzed using XRD (see Section 2.1). Active silica and alumina were quantified using the potassium fluorosilicate volumetric method and ethylenediamine tetraacetic acid (EDTA) complex titration method, respectively [33,34].

2.3.2. Carbon Content and Decarbonization Rate

The following reactions were assumed to occur during calcination [16,29]:

$$Al_2O_3 \cdot 2SiO_2 \cdot 2H_2O \rightarrow Al_2O_3 \cdot 2SiO_2 + 2H_2O_{(g)}, \tag{1}$$

$$C + O_2 \rightarrow CO_2,$$
 (2)

$$KAl_2(Si_3Al)O_{10}(OH)_2 \rightarrow KAl_2(Si_3Al)O_{11} + H_2O_{(g)}, \qquad (3)$$

$$CaCO_3 \rightarrow CaO + CO_2.$$
 (4)

The main processes corresponded to Reactions (1) and (2). Reaction (1) represents the decomposition of kaolinite and is mainly affected by the temperature and diffusion of $H_2O_{(g)}$ during suspension calcination [16]. Reaction (2) represents the combustion of coal in the gangue, requires a long time at later stages, and is influenced by O_2 content, temperature, and CO_2 diffusion [16].

A high-sensitivity high-frequency infrared carbon and sulfur analyzer (HW2000B, Nanjing Qilin Scientific Instrument Group Co., Ltd., Nanjing, China) was used to analyze the carbon content (%, measurement range = 0.00001–99.999%) of the calcined gangue products.

The thermal decomposition of kaolinite upon calcination resulted in mass loss and composition change. Under the assumption of no Si loss, the decarbonization rate (η) was calculated from the relative carbon content before and after calcination as

$$\eta = \left(1 - \frac{x_i S i_0}{x_0 S i_i}\right) \times 100\%,\tag{5}$$

where x_0 and Si_0 are the carbon and Si contents of raw coal kaolinite (wt%), respectively, and x_i and Si_i are the carbon and Si contents of the product (wt%), respectively.

2.3.3. Kaolinite Decomposition Rate

The amount of constitutional water, calculated by subtracting the carbon content determined in Section 2.3.2 from the weight loss upon calcination, was converted to the amount of undecomposed kaolinite (by molecular weight), and the rate of kaolinite decomposition (η_1) was calculated as

$$\eta_1 = \left(1 - \frac{m_{kt}}{m_{k0}}\right) \times 100\%,\tag{6}$$

where m_{kt} and m_{k0} are the amounts of kaolinite in the product and raw ore (mol), respectively.

2.3.4. System State Parameters

System state parameters were measured under stable operating conditions. Energy consumption per unit mass of product, system efficiency, and other indicators were determined using material- and heat-balance methods.

2.4. Performance Analysis of Cementitious Materials

Calcined coal gangue, limestone powder, and cement clinker were mixed in specific proportions (Table 4), and the flexural and compressive strengths of the resulting cemen-

titious materials were tested on days 3, 7, 14, and 28 according to the Chinese standard GB/T 17671-2021 [35].

Serial Number	Clinker	Desulfurized Gypsum	Calcined Coal Gangue	Limestone	Mixing Material Dosage
0	95	5	0	0	0
1	65	5	20	10	30
2	62	5	22	11	33
3	60	5	25	10	35
4	57	5	24	14	38
5	55	5	30	10	40

Table 4. Compositions of different cementitious materials (wt%).

3. Results and Discussion

3.1. Effects of Temperature on Product Composition and Reaction Conversion

The effects of temperature on product composition and reaction conversion were analyzed for particle size 1 ($d_{50} = 61.35 \ \mu m$) and at an O₂ content of 14%.

3.1.1. Phase Composition

Under the conditions of this paper, the XRD pattern of the calcined product (Figure 3) was not affected by the temperature (800–900 °C), since the reaction of kaolinite to form metakaolin was almost complete. Figure 3 indicates the presence of quartz, muscovite, magnetite, calcium oxide, and rutile in the products.



Figure 3. XRD patterns of the products obtained at different calcination temperatures.

During calcination, kaolinite loses constitutional water to form metakaolin, which cannot be detected using XRD because of its amorphous structure. The absence of kaolinite peaks in the XRD patterns (Figure 3) indicates that this mineral fully decomposed upon calcination. Quartz is a structurally stable mineral that does not undergo phase transformation during calcination. The increased intensity of the quartz peaks observed after calcination was due to the apparent increase of the crystalline phase share due to kaolinite amorphization. The presence of rutile in the calcined product but not in the raw material was attributable to the same reason. The notable decrease in the intensity of muscovite peaks upon calcination indicated that this phase underwent decomposition. Upon calcination in the oxidizing atmosphere, siderite was converted to magnetite and not

hematite (Equations (7) and (8)), a phenomenon commonly observed in the calcination of coal gangue [36].

$$FeCO_3 \rightarrow FeO + CO_2$$
, (7)

$$3FeO + CO_2 \rightarrow Fe_3O_4 + CO. \tag{8}$$

Despite the overall oxidizing atmosphere in the suspension reactor (O_2 content = 8%–14%), the coal inside the gangue particles and CO generated by its incomplete combustion provided a reducing internal environment, which enabled the retention of Fe₃O₄. For coal gangue with a high iron content, iron minerals can be recovered through magnetic separation to further purify the calcination products.

3.1.2. Reaction Conversion

Figure 4 presents the effects of temperature on the carbon content of the calcined product, and the decarbonization and kaolinite decomposition rates.



Figure 4. Effects of temperature on the carbon content of the calcination product, and decarbonization and kaolinite decomposition rates.

The decomposition rate of kaolinite increased from 98.7% to 99.9% with an increase in temperature from 800 to 875 °C. Given that the kaolinite decomposition rate exceeded 99% at 825–900 °C, temperature was found to have a negligible effect on product composition. When finer materials (particle sizes 2–4) were used, kaolinite almost completely decomposed and did not require further in-depth analysis.

Upon an increase in temperature from 800 to 900 °C, the carbon content decreased from 4.42 wt% to 1.24 wt%, and the decarbonization rate increased from 67.3% to 90.9%, which indicated that high temperatures facilitated decarbonization, possibly by accelerating coal combustion [30]. The increase in the decarbonization rate with temperature slowed at high temperatures, i.e., the effect of temperature on decarbonization diminishes with increasing temperature. Given that a carbon content of <3 wt% is required for practical applications, a calcination temperature of \geq 875 °C was needed.

3.2. Effect of Particle Size on Decarbonization Rate

Figure 5 presents the effects of particle size and temperature on the decarbonization rate at an O_2 content of $14 \pm 0.5\%$.



Figure 5. Variation of the decarbonization rate with temperature for particles of different sizes.

At a given temperature, the decarbonization rate increased with decreasing particle size, which was ascribed to the concomitant increase in the specific surface area of the raw material. In turn, this increase in area resulted in an expanded reaction interface, shortened O_2 and CO_2 diffusion paths, and accelerated O_2 and CO_2 diffusion. This effect was most pronounced at low temperatures. For example, the decarbonization rates of 58.4%/83.8%, 67.3%/90.9%, 72.7%/93.7%, and 75.8%/94.1% were observed at 800/900 °C for particle sizes 1, 2, 3, and 4, respectively. At a given particle size, the decarbonization rate increased with increasing temperature. Moreover, the spacing between decarbonization rate-temperature curves decreased with decreasing particle size.

Although high decarbonization rates are advantageous for improving the activity of calcined gangue, complete decarbonization is generally not required. The efficiency of late decarbonization is very low, and complete decarbonization requires long calcination times, which results in increased energy consumption per unit of product and only limited material property improvement. In addition, the products with a carbon content of <1 wt% were off-white or dark red (iron content > 5%), whereas the cement clinker was greenish-gray, which resulted in the poor customer acceptance of the final product. The products with a carbon content of 2-3 wt% were earth gray, resembling cement in color. Thus, the optimal carbon content of the calcined product was determined to be 1-2 wt%.

A smaller particle size results in more efficient decarbonization but does not necessarily benefit production, because the preparation of fine materials requires more grinding power, which results in a higher production cost. Moreover, in the case of suspension calcination, a smaller particle size results in decreased separation efficiency, increased thermal efficiency, and an elevated production cost. Thus, grain size 2 was identified as optimal. If the decarbonization rate does not meet these requirements, a moderate reduction in grain size (e.g., grain size 3) may be required, particularly if fine grain sizes are generally not recommended.

3.3. Effect of O₂ Content on Decarbonization Rate

Although the decarbonization of coal gangue can be effectively promoted by increasing the O_2 content, the latter parameter is typically maintained at certain values because the gas in the suspension reactor is prepared by mixing the flue gases from the hot-air furnace with the air in the cooling unit. The effect of O_2 content on the decarbonization rate was mainly ascribed to the effect of the former on the combustion rate of coal (carbon) and was examined using the industrially acceptable conventional grain size 2 (Figure 6).



Figure 6. Effects of O₂ content and temperature on the decarbonization rate.

At a given temperature, the decarbonization rate increased with increasing O_2 content because of the concomitant increase in the partial pressure of O_2 , the acceleration of O_2 diffusion into the reaction interface, and thus faster carbon combustion. The slope of the decarbonization rate– O_2 content curve increased (i.e., the effect of O_2 content strengthened) with increasing temperature. For example, an O_2 content increase from 8% to 16% resulted in decarbonization rate increments of 11.67%, 14.1%, and 18.67% at 800, 825, and 875 °C, respectively. Therefore, during high-temperature calcination, more attention should be paid to O_2 content measurement and control [30].

Thus, O_2 content increases upon introducing more air into the cooling unit. Given that the air in the cooling unit is cooler than that in the hot-air furnace, the introduction of the former decreases the temperature. Thus, to maintain high calcination temperatures at elevated O_2 content, the burning of substantially larger amounts of coal is necessary, which unreasonably increases the production cost. According to numerous tests, the optimal O_2 content at which a high decarbonization rate is guaranteed without increasing the difficulty of temperature control was found to be 12–14%.

3.4. Dissolution Rate Analysis

The effects of temperature on the dissolution rates of activated alumina and silica in the suspension-calcined coal gangue are shown in Figure 7.



Figure 7. Dissolution rates of activated alumina and silica as functions of temperature.

Alumina and silica, two of the active components of calcined gangue, can be dissolved in alkali solutions, with higher dissolution rates indicating higher gelling activities. Herein, the dissolution rates of these two components (i.e., the activity of the calcined product) increased with increasing temperature. Specifically, the alumina and silica dissolution rates of 77.6–79.5% and 49.4–51.1%, respectively, were obtained above 875 °C. The higher dissolution rates of alumina and silica indicating that calcined coal gangue was involved in cement hydration to a greater extent, therefore has a higher gelling activity [31].

In summary, the optimal calcination parameters were identified as temperature = 875-900 °C; particle size (d_{50}) = 39.71-46.84 µm; and O₂ content = 12-14%. Under these conditions, production control was easy to realize, the carbon content of the calcined product ranged from 1.24 wt% to 1.87 wt%, and the dissolution rates of activated alumina and silica were 77.6–79.5% and 49.4–51.1%, respectively. The corresponding products had high reactivities and good colors close to those of cement.

3.5. Material and Energy Balance

Thermal measurements were carried out at a temperature of 875 °C, particle size 2 ($d_{50} = 46.84 \,\mu\text{m}$), and an O₂ content of 14%. The mass and heat balances of the system are summarized in Tables 5 and 6, respectively. The material balance reference was 1 kg of raw ore, and the reference temperature of the heat balance was 0 °C.

Mass of Input	kg/kg	Percentage/(%)	Mass of Output	kg/kg	Percentage/(%)
Coal gangue	1.000	19.16	Products	0.527	10.10
Ăir	1.848	35.41	Exhaust gas	4.371	83.75
Pulverized coal	0.068	1.30	Fly ash	0.321	6.15
Air into the cooler	2.105	40.33			
Air leakage	0.198	3.79			
Total mass of input	5.219	100.00	Total mass of output	5.219	100.00

Table 5. Mass balance of the employed system.

Table 6. Heat balance of the employed system.

Heat of Input	kJ/kg	Percentage/(%)	Heat of Output	kJ/kg	Percentage/(%)
Sensible heat of coal gangue	23.2	0.51	Sensible heat of products	55.1	1.20
Combustion heat	2860.7	62.36	Sensible heat of exhaust	1013.2	22.09
Sensible heat of air	1.7	0.04	gas Sensible heat of fly ash	88.0	1.92
Sensible heat of pulverized coal	1581.0	34.46	Reaction heat absorption	1818.9	39.65
Sensible heat of air into the cooler	61.4	1.34	Surface heat dissipation	1612.5	35.15
Sensible heat of air leakage	59.7	1.30			
Total heat of input	4587.7	100.00	Total heat of output	4587.7	100.00

The system feeding capacity, roasting mineral output, coal consumption, temperature of the exhaust gas exiting the preheater, system resistance, outlet temperature of the hotair furnace, and temperature in the middle of the suspension furnace equaled 319 kg/h, 160 kg/h, 0.068 kg_{coal}/kg_{raw ore}, 258.8 °C, ~3700 Pa, 1100–1200 °C, and 870–880 °C, respectively. Owing to the weak insulation effect, the surface heat dissipation of the pilot-scale system accounted for 35.15% of the total heat consumption (4587.7 kJ/kg). This value considerably exceeded the actual industrial production value of 10–15%. In industrial production, the heat of the exhaust gas can be used for material drying or power generation, with waste heat recycling efficiencies reaching 60–70%. According to this calculation, the actual energy cost of handling one ton of Yuanzigou coal gangue is less than that of handling 20 kg of standard coal.

3.6. Properties of Cementitious Materials

The calcined gangue produced at a temperature of 875 °C, particle size 2 (d_{50} = 46.84 µm), and an O₂ content of 14% was used to prepare cementitious materials; their physical properties are listed in Table 7. The flexural and compressive strengths of the corresponding mortar specimens are listed in Table 8.

Serial Number	Specific Surface Area (m²/g)	Water– Cement Ratio (%)	Initial Setting Time (min)	Final Setting Time (min)	Soundness
0	378.4	28.1	204	224	Qualified
1	377.6	29.2	180	238	Qualified
2	381.8	29.6	194	255	Qualified
3	378.1	29.3	172	257	Qualified
4	378.1	29.4	217	275	Qualified
5	380.5	29.9	204	273	Qualified

Table 7. Physical properties of the cementitious materials.

Table 8. Flexural and compressive strengths of the mortar specimens determined at different times.

	3 d		7 d		14 d		28 d	
Serial Number	Flexural Strength /(MPa)	Compressive Strength /(MPa)	Flexural Strength /(MPa)	Compressive Strength /(MPa)	Flexural Strength /(MPa)	Compressive Strength /(MPa)	Flexural Strength /(MPa)	Compressive Strength /(MPa)
0	8.8	34.8	9.8	41.6	10.6	42.0	11.9	51.4
1	5.9	33.0	7.1	42.8	7.5	49.2	8.1	55.7
2	4.7	27.1	6.6	36.0	7.0	42.3	8.2	52.5
3	4.9	23.9	5.8	36.1	6.8	43.8	6.8	51.7
4	4.8	24.1	6.6	36.4	6.7	42.3	7.7	50.8
5	4.7	22.3	5.5	31.1	6.5	37.9	6.9	46.1

The incorporation of reactive materials increased the amount of water required to reach the standard consistency and the initial and final setting times (Table 7). However, all specimens met the requirements of the Chinese national standard GB175-2023 and passed the stability test [37]. At mixing ratios of 30–38 wt%, the compressive strengths of the 28 d mortar specimens (50.8–55.7 MPa) reached or even exceeded that of pure cement, and the true activity indices of these specimens were 98.8–108.4%. Thus, the suspension-calcined product exhibited high cementitious activity.

Figures 8 and 9 present the effects of active material dosage on the flexural and compressive strengths of mortar specimens based on the data in Tables 7 and 8.



Figure 8. Effect of active material dosage on the flexural strength of mortar specimens.



Figure 9. Effect of active material dosage on the compressive strength of mortar specimens.

Flexural strength considerably decreased with increasing active material content at small hydration ages and rebounded with prolonged hydration. The flexural strength at 28 d was essentially the same at all ratios, except for the 40 wt% admixture. A similar pattern was observed for compressive strength (Figure 9). At 28 d, the compressive strengths in the dosage range of 33–38 wt% were similar and exceeded 50 MPa, complying with the standard of 42.5 grade cement.

In summary, the performance of the calcined gangue prepared using active material dosages of 30–38 wt% was similar to or exceeded that of pure cement, i.e., the suspension calcination of low-quality gangue afforded highly active materials suitable for the production of low-carbon cement.

4. Conclusions

(1) Temperature, particle size, and O_2 content did not considerably influence product composition but strongly affected the decarbonization rate, which was positively correlated with temperature and O_2 content and negatively correlated with particle size.

(2) The optimal calcination parameters were identified as follows: temperature = 875–900 °C; particle size (d_{50}) = 39.71–46.84 µm; and O₂ content = 12–14%. Under these conditions, the carbon content of the calcined product was 1.24–1.87 wt%, the dissolution

rates of activated alumina and silica were 77.6–79.5% and 49.4–51.1%, respectively, and the product color was close to that of cement.

(3) Suspension calcination effectively converted low-quality coal gangue to an activated material for cement production. The mortar specimens prepared using active material dosages of 30–38 wt% and aged for 28 d exhibited compressive strengths of 50.8–55.7 MPa and true activity indices of 98.8–108.4%, thus meeting the standard of 42.5 grade cement.

This paper provided a basis for the industrial application of low-quality coal gangue suspension calcination. Based on this, a 300,000 ton/year industrial production line is under construction.

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