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Research on Low-Temperature Regeneration Process of Waste Foundry Clay Sand Based on Catalytic Oxidation

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Abstract: With the increasing stringency of environmental regulations, the efficient reclamation of used clay-bonded sand has become a crucial pathway for the sustainable development of the foundry industry. Traditional reclamation processes, which combine high-temperature roasting with mechanical attrition, suffer from prominent issues such as high energy consumption and long processing cycles. To address these challenges, this paper proposes a novel low-temperature and rapid reclamation method for used clay-bonded sand based on catalytic oxidation with potassium nitrate (KNO₃). This method leverages the property of potassium nitrate to release active oxygen upon thermal decomposition. By introducing it as an additive during the roasting process of used clay-bonded sand, the aim is to enhance oxygen mass transfer, thereby promoting the low-temperature oxidative combustion of coal powder components within the clay film coating the sand grains. Experimental results demonstrate that the complete thermal decomposition temperature of coal powder in the used sand is significantly lowered, and the heat treatment time is considerably shortened. The mechanisms by which the additive facilitates oxygen transfer and catalyzes low-temperature decomposition are further elucidated. Under optimized process conditions (KNO₃ concentration of 6%, addition amount of 4%, roasting temperature of 550°C, and roasting time of 30 min), the reclaimed sand exhibits an acid demand value below 5 mL, electrical conductivity below 100 μS/cm, loss on

ignition $\leq 0.05\%$, and the shattering rate decreases from 14.6% for the original used sand to below 3%. These properties fully meet the requirements for cold-box core making processes, enabling the reuse of waste foundry sand, offering an efficient, economical, and feasible pathway for the green and low-carbon transformation of the foundry industry.

Key words: Green foundry; Waste clay sand; Low-temperature pyrolysis; Composite additives;

Introduction

The foundry industry represents a fundamental pillar of manufacturing and plays a critical role in sustaining modern industrial systems. Annually, this sector generates hundreds of millions of tons of solid waste, among which waste clay sand constitutes the largest proportion [1–3]. Green sand, one of the most extensively employed molding materials in foundry production, is primarily composed of silica sand, bentonite, carbonaceous additives, and moisture. Although foundries commonly recycle clay sand within their production processes, it can only be reused for a finite number of casting cycles before its properties degrade beyond acceptable quality thresholds. As core sand and new sand are continuously introduced into the system, a portion of sand must be routinely discharged, thereby classified as Waste Clay Sand (WCS) [4,5]. Currently, the predominant disposal method for WCS remains landfilling, with only a minor fraction being repurposed in concrete production, low-strength controlled materials, and road paving applications [6–10]. Failure to effectively reclaim and reuse WCS would not only result in significant wastage of silica sand resources but also pose substantial environmental risks associated with its accumulation and disposal [11–13]. Therefore, advancing the resource-efficient recycling of WCS has emerged as both a central challenge and a necessary pathway for the industry to transition toward green and sustainable development.

The primary challenge in recycling WCS arises from the robust, deactivated dead coating adhering to its surface, which primarily comprises an oolitic layer accumulated over multiple casting cycles and embedded organic materials such as

coal dust [14–16]. To obtain high-quality reclaimed sand suitable for advanced core-making processes, such as cold box cores, it is essential to effectively remove coal dust and the oolitic layer from the sand surface [17,18]. Currently, the regeneration of WCS in the foundry industry relies predominantly on an integrated thermal-mechanical treatment process involving high-temperature calcination followed by mechanical grinding. This process subjects the sand to calcination at 690 °C for over 4 h, promoting the combustion of coal dust and embrittlement of the consolidated clay layer. Subsequent mechanical grinding is then employed to detach the surface coatings [19–22]. However, owing to the encapsulation of coal powder within a dense clay matrix, oxygen diffusion is significantly hindered during calcination, leading to inefficient pyrolysis. Consequently, the process necessitates prolonged exposure to elevated temperatures. This results in significant drawbacks, including high energy consumption, substantial capital investment in equipment, strict infrastructural requirements, and elevated operational costs. Moreover, excessively high calcination temperatures can induce further sintering of residual active clay, forming new oolitic layers that ultimately compromise the quality of the regenerated sand [23,24].

To address the aforementioned technical challenges, both academia and industry have engaged in extensive explorations. For instance, the implementation of a three-step process involving "pre-grinding, roasting, and secondary grinding" aims to enhance roasting efficiency by partially exfoliating clay layers in advance [25]. Alternatively, various chemical additives have been tested to facilitate the regeneration of WCS. However, these methods either fail to fundamentally reduce roasting energy consumption or introduce new issues, such as high reagent costs and secondary pollution [26–28]. Therefore, the development of a regeneration technology that significantly lowers energy consumption while effectively disrupting clay encapsulation and catalyzing coal powder decomposition is of substantial theoretical significance and engineering application value.

This study proposes an innovative technology for the regeneration of waste clay-bonded sand through low-temperature pyrolysis using KNO_3 as an additive.

Leveraging the stepwise thermal decomposition characteristics of KNO_3 , the process achieves a synergistic effect involving catalytic oxidation, pore formation, and chemical bond cleavage. This synergy reduces both the temperature and time required for the complete pyrolysis of coal powder, thereby significantly lowering energy consumption. In addition, it effectively disrupts the Al–O–Si bonds within the oolitic layer, weakening its mechanical strength and facilitating subsequent grinding. As a result, high-quality reclaimed sand suitable for cold-box core-making processes can be obtained. These integrated steps constitute a comprehensive, low-energy, and cost-effective technical route that supports the sustainable recycling of foundry clay-bonded sand and promotes the green transformation of the industry.

2. Experimental

2.1 Materials

The WCS sample used in this study was sourced from a foundry enterprise in Changchun, Jilin Province, China, which specializes in automotive casting production. The enterprise employs green sand molding and hot-box coated sand for core making. Consequently, the resulting waste sand is a mixed type, consisting of approximately 82% waste clay-bonded sand and about 18% waste coated sand. Its main chemical composition is presented in Table 1. The relatively high content of Al_2O_3 primarily originates from the bentonite binder. The Loss on Ignition (LOI) mainly reflects the content of coal powder and a small amount of residual organic matter. The Acid Demand Value (ADV) is an important quantitative indicator reflecting the alkaline substance content in foundry sand, commonly used to evaluate the reactivity of foundry sand to acid-curing agents. The initial ADV of this batch of waste clay-bonded sand was measured to be as high as 30 mL. The Oolitic Content (OC) is a parameter used to quantitatively characterize the mass percentage of the deactivated clay layer in waste foundry sand. The OC of this WCS sample was 14.6%, indicating a relatively thick inert layer coating the sand surface and suggesting greater difficulty in regeneration.

The results of the X-ray diffraction (XRD) and particle size analysis of the WCS

samples are presented in Fig. 1. The XRD pattern reveals that silica (SiO_2) and aluminosilicate (Al_2SiO_5) are the predominant phases within the WCS. The cumulative volume distribution demonstrates that the particle size of WCS is concentrated, with D_{50} and D_{90} values measured at 311.46 μm and 543.68 μm , respectively. The potassium nitrate (KNO_3) reagent used in the experiment is of analytical grade (Sinopharm Chemical Reagent Co., Ltd.). Throughout the experimental process, all aqueous solutions were prepared using deionized water. In addition, Fig. 1(c)-(e) show the SEM images of WCS samples and EDS analysis results of the selected area. It can be observed from Fig. 1(c) that the original waste sand surface is wrapped by a layer of dense and continuous covering without visible pores.

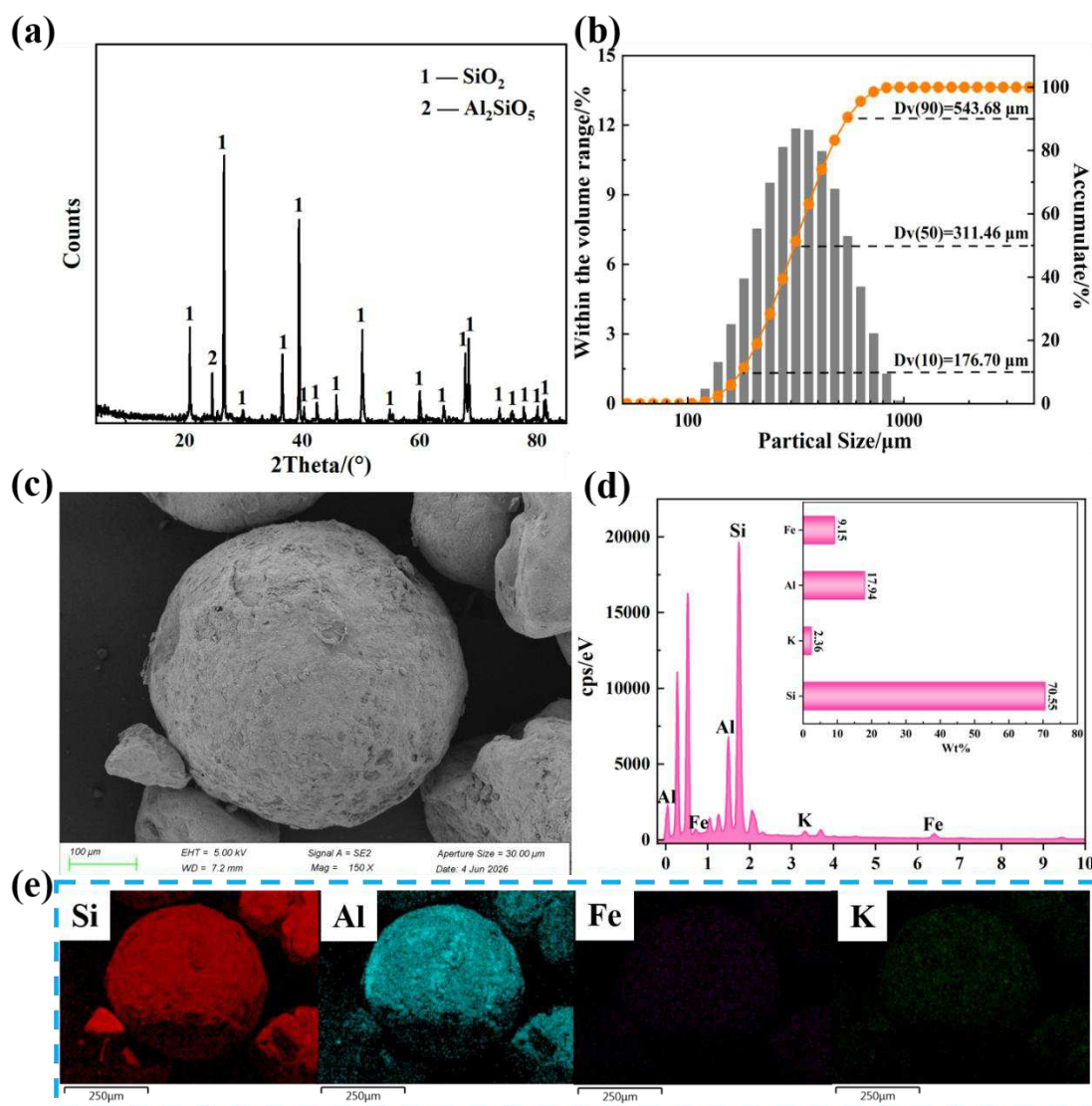


Fig. 1. The characterizations of WCS sample: (a) XRD, (b) particle size distribution,

(c) SEM micromorphology, (d)-(e) EDS analysis.

Table 1. The phase content and chemical composition of the clay waste sand sample

(wt.%)									
Chemical analysis				Components analysis					
Si	Al	Fe	Ca	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	LOI (%)	ADV (mL)	Other impurities
41.89	3.60	0.43	0.28	80.2	12.2	0.6	4.6	30.1	1.0

2.2. Experimental procedure

The regeneration process of the WCS was depicted in Fig. 2. A series of KNO₃ solutions with concentrations of 2%, 4%, 6%, 8% and 10% were prepared by analytically pure reagents and deionized water. Subsequently, 100 g samples of pre-treated WCS (after crushing and magnetic separation) were weighed, and different additive solutions were incorporated at respective dosages of 1%, 2%, 3%, 4%, and 5% relative to the sand mass. The mixtures were homogenized in a sand mixer for 60 min, followed by static conditioning at room temperature for 12 h to facilitate thorough penetration of the additive solution into the clay and oolitic layers on the sand surface.

After standing, the samples were transferred into ceramic crucibles and placed in a box-type muffle furnace for roasting in an air atmosphere. Five roasting temperatures (450 °C, 500 °C, 550 °C, 600 °C, and 650 °C) were employed in this experiment, with five roasting durations (5 min, 15 min, 30 min, 45 min, and 60 min) set for each temperature. The heating rate of the muffle furnace was maintained at 5 °C/min to systematically investigate the effects of roasting parameters on the regeneration behavior of WCS. Following the roasting process, the samples were allowed to cool to room temperature and subsequently subjected to mechanical grinding using a ball mill with a ball-to-material ratio of 1.2 for 5 h. The ground product was then sieved using a vibrating screen, and reclaimed sand particles within the 20–200 mesh range were collected. Finally, the acid demand value, conductivity, and loss on ignition of the reclaimed sand were measured according to relevant standard methods. These performance indicators were utilized to comprehensively

evaluate the regeneration effectiveness of the WCS under various additive systems and processing conditions.

Table 2. The experimental design of WCS regeneration.

Variable	Temperature, °C	Time, min	Reagent concentration, %	Reagent addition, %
Temperature	450/500/550/600/650	30	6	4
Time	550	5/15/30/45/60	6	4
Reagent concentration	550	30	0/2/4/6/8/10	4
Reagent addition	550	30	6	1/2/3/4/5

The reclaimed sand sample was placed in an oven and dried to a constant weight at 105 °C. After removal, it was cooled to room temperature in a desiccator. A precise mass of 2.0000 g of the dried reclaimed sand sample was weighed and evenly distributed in a porcelain crucible that had been pre-ignited to a constant weight. The crucible was subsequently placed in a muffle furnace, where the temperature was increased from room temperature to 1000 °C at a heating rate of 10 °C/min. It was maintained at this temperature for 60 min to ensure the complete decomposition and removal of organic matter and volatile components. Following ignition, the crucible was transferred to a desiccator and allowed to cool to room temperature, after which the mass of the ignited sample was accurately measured. The loss on ignition (LOI) of the reclaimed sand sample was calculated using Eq. (1).

$$E = \frac{m_1 - m_2}{m_1} \times 100\% \quad (1)$$

Where E is the LOI of reclaimed sand, %; m_1 is the sample mass before roasting, g; and m_2 is the sample mass after calcination, %.

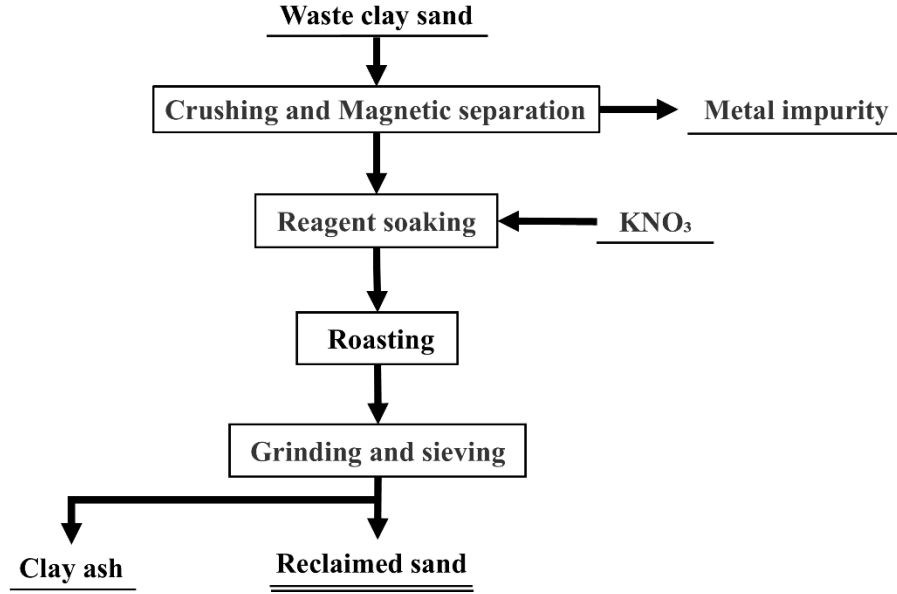


Fig. 2. Flow chart of regeneration process of the WCS.

2.3. Analysis

The experiments encompassed a comprehensive analysis and evaluation of WCS and its intermediate regeneration products. The particle size distribution of the WCS samples was determined using a laser particle size analyzer (Mastersizer 2000, Malvern, England). Thermogravimetric analysis (TG, Netzsch STA 449C) was employed to investigate the pyrolysis process of the mixed additive. During the test, high-purity nitrogen was utilized as the protective gas at a flow rate of 100 mL/min. The acid demand value of the reclaimed sand samples was measured according to the method specified in the foundry industry standard GB/T 2684-2009, which assesses the content of residual alkaline substances in the reclaimed sand. The reclaimed sand was mixed with deionized water at a specified ratio, stirred, and allowed to settle; subsequently, the conductivity of the supernatant was measured using a portable conductivity meter to indirectly evaluate the removal efficiency of soluble salts from the sand. Inductively coupled plasma-atomic emission spectrometry (ICP-AES, PerkinElmer Optima-4300DV) was utilized to analyze the chemical compositions of various samples. X-ray diffraction (XRD, Bruker D8 Advance, Bruker AXS GmbH, Germany) was applied to characterize the phases present in WCS. Scanning electron microscopy (SEM) coupled with energy-dispersive X-ray spectroscopy (EDS, Zeiss

Gemini SEM 300, Carl Zeiss AG, Germany) was employed to analyze the morphology and elemental distribution of WCS and its derived products.

3. Results and discussion

3.1. Thermodynamic analysis

To investigate the influence of KNO_3 as an additive on the pyrolysis process of coal in WCS, thermogravimetric analysis was conducted on three samples: KNO_3 , WCS, and WCS with 10% KNO_3 added. The results are shown in Fig. 3(a). Between room temperature and 541 °C, KNO_3 exhibited only a 1.03% mass loss, attributed to the evaporation of surface-bound water. As the temperature increased from 541 °C to 900 °C, KNO_3 decomposed rapidly, with a significant mass loss of up to 82.31% during this stage. This was attributed to the two-step thermal decomposition reactions of KNO_3 , as shown in Eq. (2) and Eq. (3).



By comparing the pyrolysis curves of WCS before and after the addition of 10% KNO_3 , it can be observed that the addition of KNO_3 significantly reduces the pyrolysis temperature of coal powder to 470.65 °C. The thermal decomposition of KNO_3 provides a continuous and uniform oxygen source, directly acting on the coal powder particles on the surface of WCS and promoting their oxidative decomposition. In addition, the released nitrogen oxides such as NO and NO_2 can act as radical initiators, initiating and accelerating the chain pyrolysis reaction of coal powder macromolecules, thereby reducing reaction activation energy [22]. Simultaneously, the K_2O generated during pyrolysis is highly reactive with water vapor in the environment, either forming KOH or directly releasing K^+ . As a small-radius alkali metal ion, K^+ is inserted into the graphite-like carbon interlayer of coal powder under thermal energy drive, forming potassium-carbon interlayer compounds. This weakens the van der Waals forces between carbon layers, disrupts the stability of C–C bonds, and makes coal powder easier to decompose [24]. In addition, the alkaline environment generated by the decomposition of KNO_3 has a chemical erosion effect

on the layered structure composed of silicon oxygen tetrahedra and aluminum oxygen octahedra of clay minerals. The generated OH^- attack the Si-O-Si and Al-O-Si bonds, causing their bonds to break and transforming the strong ooid layer into a loosely structured potassium/sodium silicate, resulting in a significant decrease in its mechanical strength [25,26].

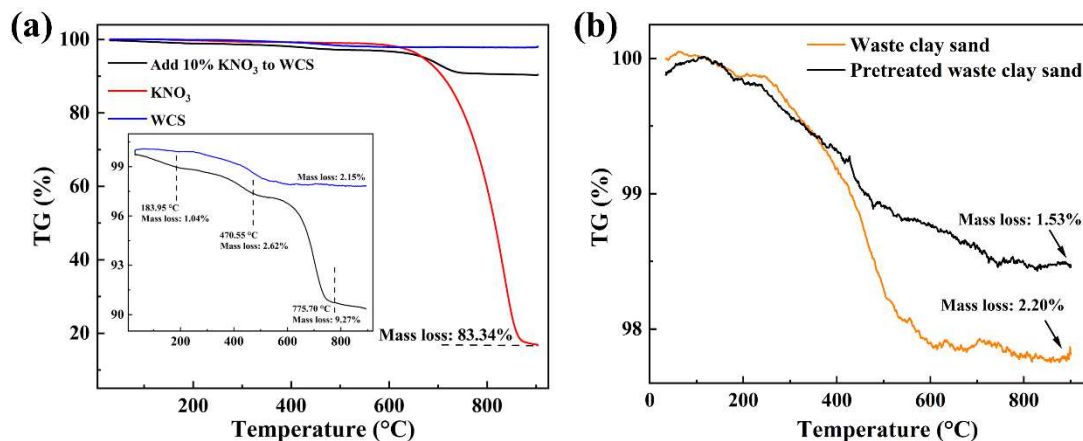


Fig. 3. Thermogravimetric data plots for: (a) KNO₃; Waste clay sand; clay sand with 10% KNO₃ added; (b) Waste clay sand and pretreated waste clay sand.

On the other hand, in order to reduce the amount of additives and decrease reaction time, WCS raw materials are pre-mechanically ground to remove the loose clay layer on the surface. Thermogravimetric analysis was performed on WCS before and after preprocessing, and the results are shown in Fig. 3(b). It can be seen that after mechanical grinding treatment, the quality loss decreased from 2.20% to 1.53%, indicating that the clay layer mixed with coal powder on the surface of the sand particles was effectively peeled off. Furthermore, the micro morphology of the raw material after grinding was characterized, as shown in Fig. 4. The results show that compared with the raw material without grinding (Fig. 1(c)), the sand after grinding is smooth, without obvious attachments, and the contents of Al and Fe are decreased, which also shows that pre-grinding can remove the loose clay layer on the sand surface.

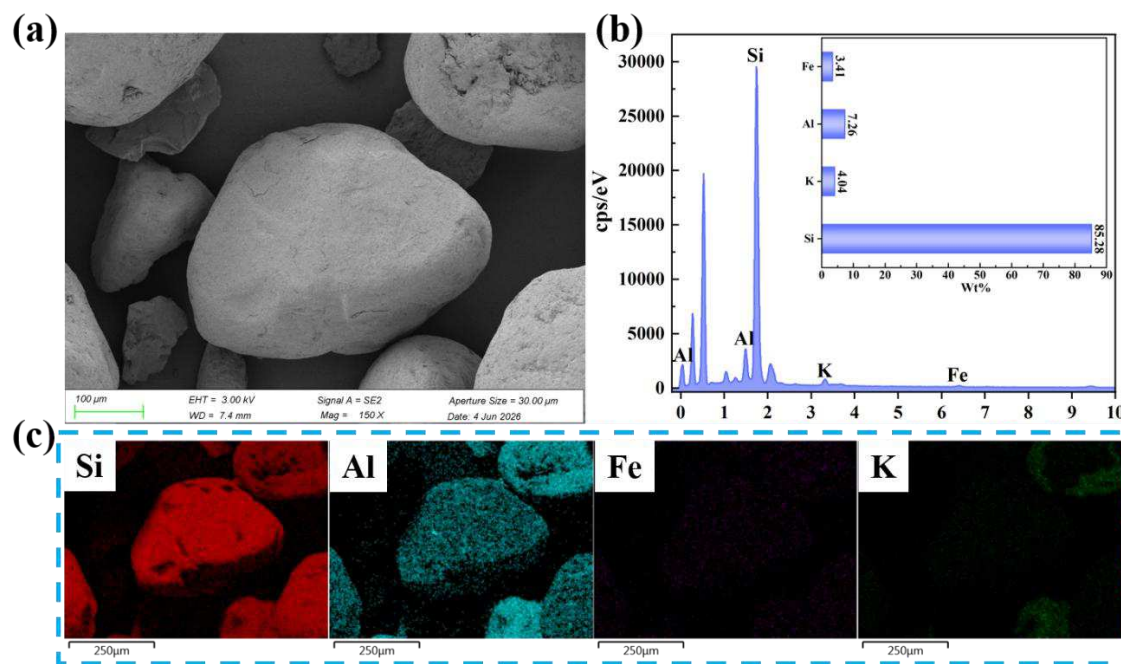


Fig. 4. The characterizations of pretreated waste clay sand: (a) SEM micromorphology, (b)-(c) EDS analysis.

3.2 Analysis of factors influencing the roasting process

3.2.1 Roasting temperature

The influences of roasting temperature on the LOI and ADV of reclaimed sand are shown in Fig. 5, where the temperature is selected to vary between 450 °C and 650 °C, while the reagent addition and time are fixed at 4% and 30 min, respectively. When the roasting temperature increased from 450 °C to 550 °C, the LOI and ADV decreased from 0.54% and 9.8 mL to 0.11% and 4.8 mL, respectively, indicating that the roasting temperature has a significant impact on the properties of reclaimed sand. According to the results of thermogravimetric analysis, this is due to the fact that at lower temperatures, only a small amount of K^+ are released, resulting in incomplete pyrolysis of coal powder and chemical erosion reaction of clay structure. Further, when the temperature exceeds 550 °C, the curve flattens and no longer decreases significantly. when the temperature reaches 550 °C, KNO_3 decomposes significantly, destroying the coal powder and clay structure, leading to a decrease in acid consumption value and ignition loss of sand. As can be seen from Fig. 5, 550 °C is sufficient to complete the core reaction, achieve full decomposition of coal powder

and effective weakening of the clay layer. This temperature is about 130-150°C lower than that of traditional processes (690°C).

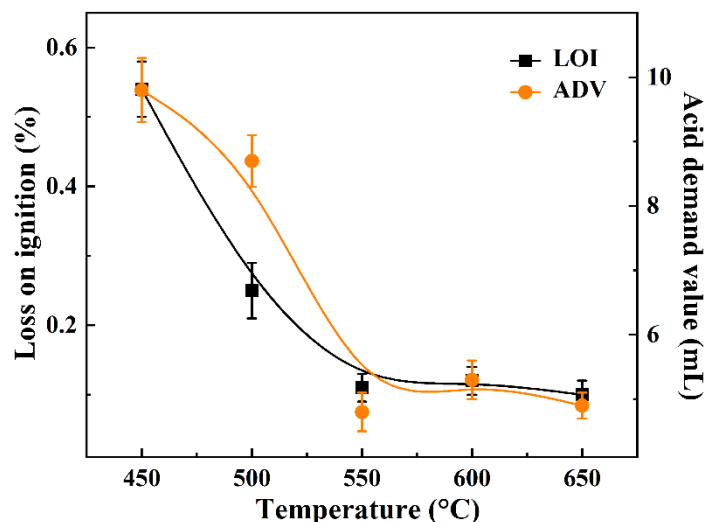


Fig. 5. The LOI and ADV of reclaimed sand at different roasting temperatures.

3.2.2 Roasting time

The effect of roasting time on the properties of reclaimed sand is shown in Fig. 6. The LOI and ADV values were reduced to some extent with the time. When the time varies between 5 min and 30 min, the LOI decreases from 0.23% to 0.11%, and also the ADV decreases from 8.8 mL to 4.8 mL, indicating that the roasting time has a certain impact on the performance of reclaimed sand. Meanwhile, it can be observed that when the roasting time reaches 45 min, the curve flattens and does not decrease significantly. This result indicates that, with the assistance of KNO_3 as an additive, sufficient decomposition of coal powder on the WCS surface and destruction of the clay layer structure can be achieved in 30 min, which is significantly shorter than the over 4 h required by traditional processes.

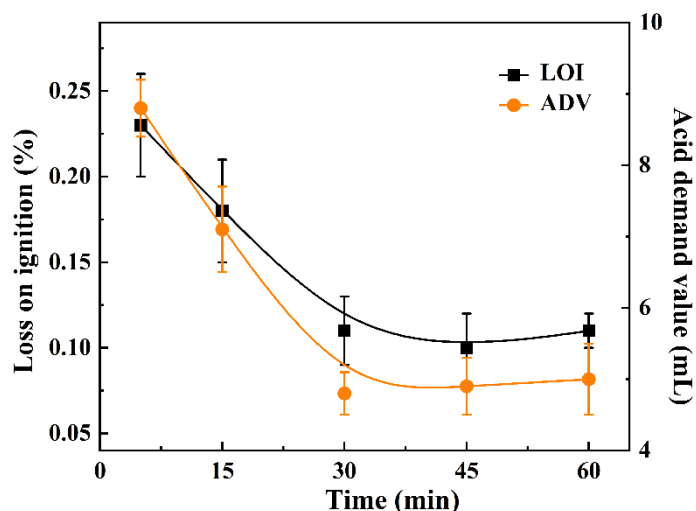


Fig. 6. The LOI and ADV of reclaimed sand at different roasting times.

3.2.3 Reagent concentration

Under the conditions of a fixed roasting temperature of 550 °C, a roasting time of 30 min, and an additive amount of 4%, the effects of different KNO_3 concentrations on indicators of reclaimed sand were systematically studied. The LOI and ADV under different concentration conditions is shown in Fig. 7. Obviously, it can be seen that compared to the case without adding KNO_3 as an auxiliary agent, the LOI and ADV of the reclaimed sand have been significantly improved. When the KNO_3 concentrations increased from 2% to 10%, the ADV decreased from 9.6 mL to 4.9 mL. However, a sudden turning point was found in the LOI at the KNO_3 concentrations of 6%, and the curve shows a certain rebound trend after the turning point, where the LOI increased from 0.11% to 0.28%. Actually, the decomposition of KNO_3 is a strongly exothermic reaction. When the KNO_3 concentration is too high, the local temperature of the sand particles becomes excessively high, leading to compaction or sintering on the surface of the sand particles. This results in unburned coal powder still being encapsulated inside the sand particles. Furthermore, the strongly alkaline oxide (K_2O) produced by excessive decomposition of KNO_3 may react with silicates, similarly leading to sintering phenomenon [27]. Consequently, this leads to a rebound phenomenon in the LOI of the reclaimed sand.

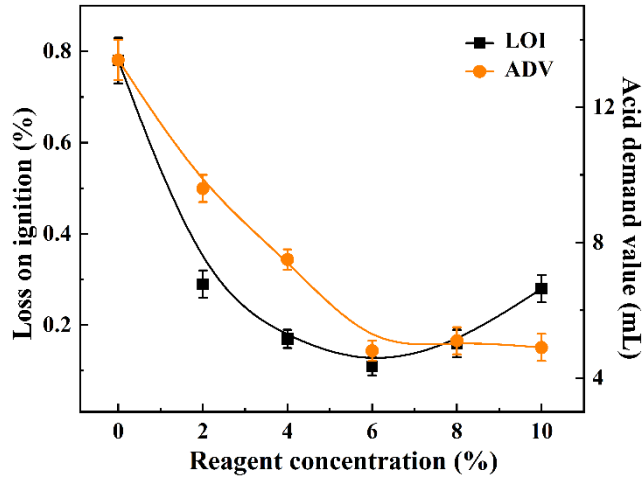


Fig. 7. The LOI and ADV of reclaimed sand at different KNO_3 concentrations.

3.2.4 Additive amount

The LOI and ADV under different additive dosages are shown in Fig. 8. As the amount of additive increases, both LOI and ADV values decrease accordingly. It can be observed that when the additive dosage reaches 4%, the LOI and ADV exhibit significant variations with 0.11% and 4.8 mL, respectively. The ADV value change in the stage where the additive amount continues to increase is not significant, indicating that the decomposition reaction has essentially been completed at this point (4%). However, a slight increase in LOI was also observed, which is consistent with the aforementioned excess KNO_3 concentration. This is primarily due to the excessive addition which reacts with the aluminosilicate in the sand, leading to sintering and hindering the complete combustion of coal powder. Therefore, considering all factors, an additive amount of 4% is an economical and effective choice.

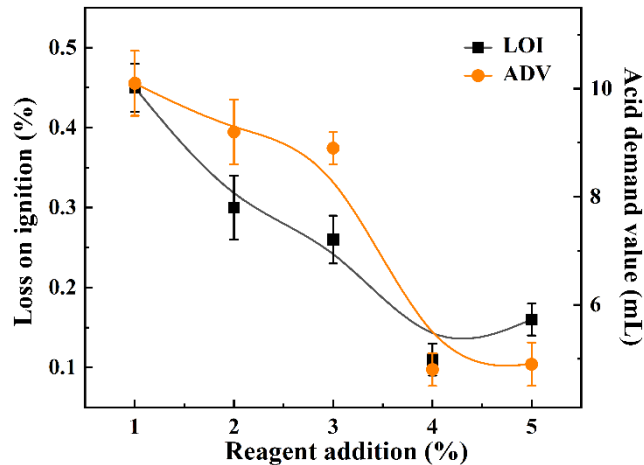


Fig. 8. The LOI and ADV of reclaimed sand at different additive amounts.

3.3 Microscopic mechanism

The changes in microstructure are crucial for the depth of the roasting process. Further observe the evolution of the microstructure of the sand particle surface through SEM to verify the mechanism of the KNO_3 additive. Fig. 9 shows the micro morphology of ungrounded sand after roasting, and reclaimed sand after treatment. Compared with the original waste sand (Fig. 1(c)), after calcination at 550°C with the additive and without grinding (Fig. 9(a)), the surface of the sand can be observed to become loose and porous, with a large number of holes and staggered cracks, and the original dense structure is completely destroyed. These holes and cracks provide a channel for the oxidation decomposition of the internal pulverized coal, and also greatly weaken the adhesion between the coating and the sand matrix. In addition, Fig. 9(b) shows the reclaimed sand after final treatment. After slight grinding, the loose overburden layer basically falls off, and exposing smooth silica sand body, with only a small amount of residue locally. This result is consistent with the LOI and ADV analysis results obtained in the previous section.

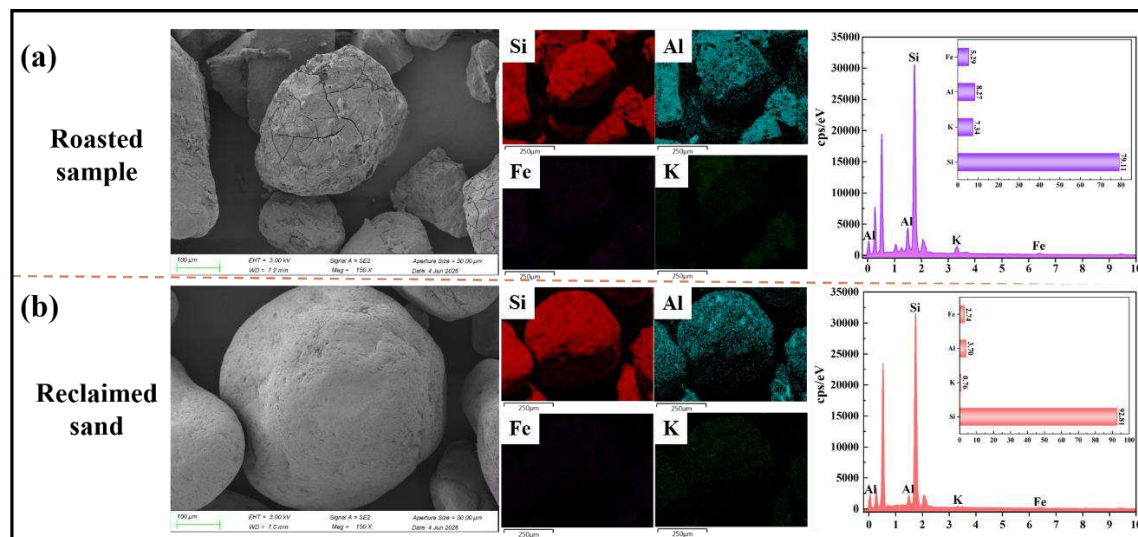


Fig. 9. SEM-EDS analysis of the samples (a) ungrounded sand after roasting, (b) reclaimed sand.

In a word, the gas generated by the thermal decomposition of KNO_3 forms microbubbles in the dense clay layer and generates expansion pressure, thus opening micron sized holes and cracks in the covering layer [23]. This establishes a key channel for the diffusion of external oxygen to the inside and the escape of internal pyrolysis gas, and effectively solves the core problem that the internal pulverized coal

is difficult to pyrolysis due to the lack of oxygen.

3.4 Comprehensive evaluation of reclaimed sand performance

Under the optimal process conditions (additive concentration 6%, dosage 4%, roasting at 550 °C for 30 min), the properties of the obtained reclaimed sand were systematically analyzed and compared with the waste clay sand. The results are listed in Table 3.

Table 3. Performance comparison between reclaimed sand and waste clay sand.

Performance index	Waste clay sand	Reclaimed sand	Cold box sand requirements
Acid demand value (mL)	30.10	4.80	≤ 5.0
Conductivity ($\mu\text{S}/\text{cm}$)	—	62	≤ 100
Loss on ignition (%)	4.60	0.11	≤ 0.30
Grain shape factor (%)	14.60	2.90	—
Clay content (%)	—	0.12	≤ 0.30

By comparison, it can be found that the key indexes of clay sand have been obviously improved after low temperature pyrolysis regeneration treatment. The acid consumption decreased from 30 mL to 4.8 mL, which fully met the requirement of standard sand below 5 mL. The low ignition loss and clay content also prove that the organic matter and loose impurities in wasted sand are removed efficiently. In addition, the conductivity value is also lower than the standard value, indicating that soluble salt impurities are effectively controlled. And the oolitic rate decreased from 14.6% to 2.9%, which also showed that most of the refractory inert layers were successfully peeled off.

3.5 Economical benefits analysis

The low-temperature pyrolysis technology developed in this study is compared with the traditional high-temperature roasting process (see Table 4). From the temperature and time perspective, the roasting conditions of this work (550 °C, 0.5 h) is lower than the conditions of traditional process (690 °C, >4 h), which show lower energy consumption. From the process perspective, this work avoids the expensive

high-temperature heat-resistant alloy for the core thermal equipment (baking furnace), and the requirements for heat preservation and refractory materials are correspondingly reduced, which means lower equipment manufacturing and installation costs. At the same time, the whole process has no toxic and harmful gases and solid waste emissions, which is environmentally friendly.

Table 4. Comprehensive comparison between low-temperature pyrolysis process and traditional high-temperature roasting process.

Performance index	Low-temperature pyrolysis process	Traditional roasting process
Roasting parameters	550 °C, 30 min	690 °C, > 4 h
Natural gas consumption	7.8-10.3 m ³ /t sand	10-13 m ³ /t sand
Roasting equipment	Austenitic stainless steel	Iron-nickel base alloy

Conclusions

This article proposes a low-temperature pyrolysis regeneration process for WCS treated with KNO₃ additive. The additive can provide oxygen source and chemical etching during the roasting process with waste clay sands, effectively destroying the surface structure of coal powder and clay, and achieving the regeneration treatment of waste clay sands. The main conclusions are as follows:

1. The addition of KNO₃ significantly lowers the pyrolysis temperature of coal powder in waste clay sand to 470.65 °C by providing a continuous oxygen source and radical initiators (NO, NO₂), while its decomposition products (K⁺ and OH⁻) chemically disrupt both the carbon layers of the coal and the Si-O/Al-O bonds of the clay matrix.
2. The optimal conditions for the regeneration process were determined to be a KNO₃ concentration 6%, an additive dosage of 4%, and roasting temperature at 550 °C for 30 min. Under these conditions, the regenerated sand, after grinding and sieving, exhibited an acid demand value of 4.8 mL, and a loss on ignition as low as 0.03%. These results fully comply with the stringent requirements for raw sand in high-end core-making processes, such as cold-box core production.

3. After treatment with the low-temperature pyrolysis regeneration process, all key performance indicators showed remarkable improvements. Compared with the conventional high-temperature roasting process (690°C, >4 h), the process in this study reduced the roasting temperature by approximately 140 °C and shortened the roasting time by over 87.5%. This results in notable advantages in terms of energy savings, reduced consumption, lower equipment investment, and decreased carbon emissions, demonstrating significant economic and environmental benefits.

CRedit authorship contribution statement

Shengli Hu: Writing–original draft, Validation, Supervision. **Ge Hui:** Conceptualization, Methodology, Validation, Formal analysis, Investigation, Data curation, Writing–original draft. **Wu Shaohua:** Validation, Supervision. **Xiaolong Gong:** Methodology, Writing-review & editing

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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