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MnO_2-TiO_2 composite additives driven low-cost fabrication of coal gangue/bauxite ceramic proppants

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ABSTRACT

The urgency of resource utilization for coal gangue has driven innovations toward its high-value processing technologies. Although coal gangue can serve as a low-cost source of silicon and aluminum—reducing raw material costs by 14 % compared to pure bauxite—its direct application in the production of ceramic proppants faces significant challenges. These challenges include an excessively high calcination temperature (e.g. >1450 °C) and compromised mechanical properties. In this study, we designed the fabrication of ceramic proppants by using coal gangue and bauxite as raw materials. By adjusting the dosage of a MnO_2–TiO_2 composite additive (0–7.5 wt%), a dual-phase ceramic proppant composed of corundum and mullite was prepared. The results show that the addition of the MnO_2–TiO_2 can lower the sintering temperature, allowing the proppant to develop a well-dense structure within the temperature range of 1250–1350 °C. However, the composite additive also inhibits the formation of mullite while promoting the development of the corundum phase. This phase transformation enhances the compressive strength of the proppant but simultaneously increases its density. When the composite additive content is 7.5 wt% and the sintering temperature is 1350 °C, the resulting ceramic proppant exhibits a bulk density of 1.88 ± 0.01 g/cm^3 and an apparent density of 3.17 ± 0.02 g/cm^3, with a minimum breakage rate of 2.71 ± 0.32 % under 52 MPa.

1. Introduction

Shale gas reservoirs consist of a matrix and natural fractures, characterized by extremely low permeability. Therefore, horizontal well hydraulic fracturing has become the predominant method for exploiting shale gas reservoirs [1]. Proppants play a crucial role in this process by preventing fracture closure and ensuring sustained high production of shale gas, oil, and gas resources [2]. In 1947, quartz sand was used for the first time as a proppant material, and it was widely adopted due to its low cost and low density [3]. However, since quartz sand has relatively low compressive strength, it is only suitable for service environments where the closure stress is below 28 MPa [4], which severely limits its application. To enhance the compressive strength and overall performance of proppants, two new types of proppants—polymer-coated and ceramic —have been developed successively since the 1980s [5]. Polymer-coated proppants are produced by coating traditional proppants with polymers, offering advantages such as low density, high compressive strength, and excellent flow conductivity. However, under high-temperature and high-pressure conditions, their fracture permeability is significantly reduced, thus limiting their application in deep reservoirs [6]. Ceramic proppants, on the other hand, are artificial fracturing proppants manufactured by granulating aluminosilicate raw materials followed by high-temperature sintering. They possess high strength, high sphericity, and chemical stability, making them ideal for fracturing in unconventional reservoirs. Nevertheless, their production still faces challenges such as high sintering temperatures and high production costs [7].

China's unconventional oil and gas resources are abundant, but the reservoirs have complex structures and are difficult to exploit, which imposes higher demands on the mechanical properties and conductivity of proppants [8]. In addition, the mining and transportation costs of bauxite have been rising in recent years, which limits its application in

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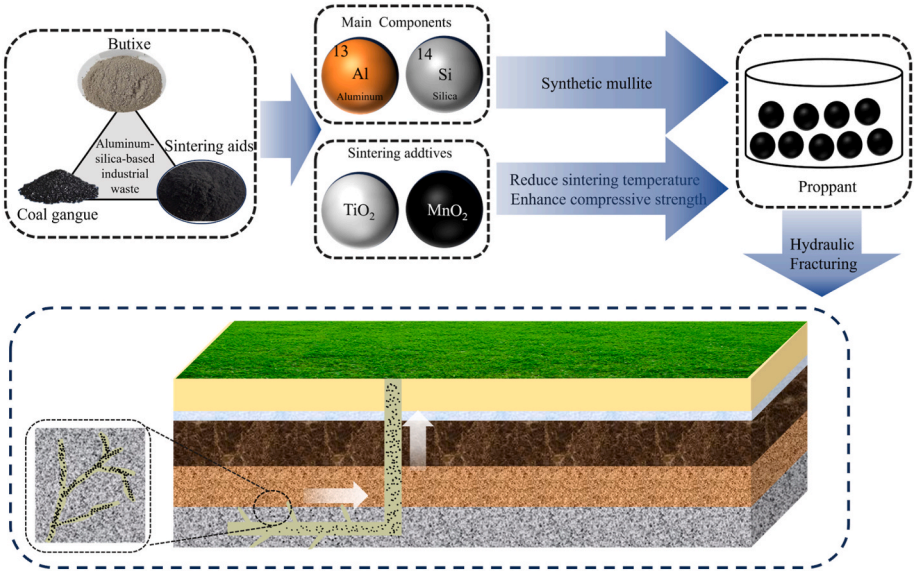

Fig. 1. Process strategy Diagram for preparing ceramic proppants from coal gangue waste.

large-scale ceramic proppant production. To overcome the resource and cost limitations, many researchers have explored the use of solid waste to replace bauxite, such as oil-based drilling cuttings [9], fly ash [10], coal gangue, and waste ceramic sand [11]. Moreover, some studies have begun to focus on utilizing biomass materials, such as rice husk ash [12], to develop low-cost, high-performance ceramic proppants. This approach not only helps reduce the environmental pollution caused by solid waste but also promotes the secondary utilization of resources.

Coal gangue, an industrial solid waste generated during coal production, mainly consists of Al_2O_3 and SiO_2, which are similar to the composition of bauxite [13]. Numerous studies have explored the process of using coal gangue to partially replace bauxite in the preparation of ceramic proppants [14]. However, the ceramic proppants produced using coal gangue still face challenges such as low compressive strength and high sintering temperatures. Lei et al. [15] replaced bauxite with 20 wt% coal gangue and added 20 wt% potassium feldspar as an additive; the proppants sintered at 1260 °C exhibited a breakage rate of 5.12 % under 28 MPa. To further increase the coal gangue content, Zhao et al. [16] used 40 wt% coal gangues; under a sintering temperature of 1450 °C, the ceramic proppants achieved a minimum breakage rate of 7.0 % under 35 MPa. Subsequently, Hao et al. [17] found that at the same sintering temperature, increasing coal gangue content results in a reduced apparent density and a significant decline in the compressive strength of the ceramic proppants. Most studies indicate that when the coal gangue content exceeds 30 wt%, the proppants can withstand closure stresses of only up to 35 MPa [18]. To address these issues, researchers have proposed various strategies to enhance the compressive strength of ceramic proppants and reduce the sintering temperature, among which the use of additives has received considerable attention. The commonly used additives are mainly divided into high-temperature liquid-phase sintering aids (such as MgO [19] and CaO [20]) and lattice distortion sintering aids (such as Fe_2O_3 [21], V_2O_5 [22], TiO_2 [23], and MnO_2 [9]). Studies have shown that the incorporation of additives can effectively reduce the formation temperature of the ceramics and enhance grain growth. For example, the addition of 5 wt% $CaCO_3$ at 1350 °C generates a large amount of liquid phase, leading to a change in the mass transfer mode, which in turn promotes the growth of mullite grains and sintering densification [24]. In addition, MnO_2 and TiO_2 not only reduce the formation temperature of mullite but also improve the mechanical properties of ceramics [25,26]. Moontoya et al. [27] suggested that the enhancement of the mechanical properties of alumina-mullite ceramics by TiO_2 could be attributed to the incorporation of Ti^{4+} ions into the secondary mullite phase, which promotes nucleation and crystal growth. Chen et al. [28] found that TiO_2 can significantly enhance the compressive strength by forming an interlocking rod-like mullite structure; however, when its content reaches 6 wt%, the increase in the glassy phase leads to a higher breakage rate. Furthermore, Lahiri et al. [29] compared the applications of MgO and TiO_2 in alumina ceramics and found that titanium oxide forms a solid solution in Al_2O_3, thus enhancing the densification of α-alumina and promoting grain growth, while magnesium oxide forms magnesium aluminate spinel with alumina at low temperatures, which has less impact on densification and grain growth. Yang et al. [30] discovered that the introduction of MnO_2 in silicate systems not only effectively lowers the formation temperature of mullite, promoting the nucleation and growth of mullite whiskers at low temperatures but also suppresses the abnormal grain growth during low-temperature sintering. Additionally, Majidian et al. [31] introduced manganese oxide as an additive in alumina-mullite-zirconia composite ceramics and found that manganese forms a solid solution in alumina, thereby promoting densification and enhancing the mechanical properties of the ceramics. However, the addition of MnO_2 was also observed to delay the formation of the mullite phase. Although a single additive can improve performance to some extent, the use of composite additives can exert a synergistic effect to further promote sintering densification and enhance mechanical properties. Gnanasagaran et al. [32] added TiO_2 and MnO_2 to Al_2O_3 ceramics, and after sintering at 1250–1300 °C, a relative density of up to 98 % was achieved. In mullite-corundum ceramics, Liu et al. [33] used MnO_2 and CaO as composite additives and found that the composite system was more effective than using CaO alone in reducing the sintering temperature and enhancing the compressive strength; ceramic proppants prepared at 1200 °C exhibited a breakage rate of 2.2–4.5 % under 69 MPa. Similarly, Wang et al. [34] employed K_2O and P_2O_5 as composite additives, which transformed the mullite morphology from equiaxed grains to needle-like and columnar forms; compared with single additives, the composite additives increased the system's liquid phase by 2 wt%. In summary, compared to single additives, composite additives show significant advantages in enhancing the structure and mechanical properties of ceramic proppants. However, there are still few reports on incorporating TiO_2 and MnO_2 as composite additives in the preparation of bauxite–coal gangue ceramic proppants. Further exploration of their application potential for performance optimization and cost control is of great significance.

This study applied a composite additive strategy to prepare ceramic

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

	Al_2O_3	SiO_2	TiO_2	Fe_2O_3	K_2O	CaO	MgO	other
Bauxite	77.675	13.138	5.407	1.385	1.066	0.271	0.268	0.79
Coal Gangue	32.246	48.163	0.653	5.892	2.254	0.384	0.392	10.016
Calcined Coal Gangue	34.13	51.66	0.57	8.44	2.42	0.37	0.312	2.098

proppants from silicon-rich aluminous coal gangue waste (see Fig. 1), promoting the high-value utilization of solid waste resources. Pre-calcined coal gangue and pre-mixed bauxite were used as the base materials to tailor the physical and chemical properties of the ceramic proppants. MnO_2 and TiO_2 were selected as composite additives. The effects of coal gangue pre-calcination, sintering temperature, and composite additives on the phase composition, microstructure, and mechanical properties of the ceramic proppants were systematically investigated. In addition, an evaluation of the proppant production cost was conducted to assess the economic feasibility of the process.

2. Experimental section

2.1. Experimental materials

The skeletal materials used included clinker bauxite (300 mesh, Henan Borun Foundry Materials Co., Ltd.) and coal gangue (300 mesh, Shanxi Changqing Petroleum Fracturing Proppant Co., Ltd.), with their specific chemical compositions listed in Table 1 Chemical Composition of Raw Materials (wt%). The additives included MnO_2 (analytical grade, Chengdu Kelong Chemical Reagent Factory) and TiO_2 (analytical grade Chengdu Kelong Chemical Reagent Factory). Polyvinyl alcohol (PVA, AR, Chengdu Kelong Chemical Reagent Factory) was used as the binder.

2.2. Preparation process

Table S1 lists the composition ratios of different proppant samples. Samples Z1-Z4 were sintered at a fixed temperature of 1450 °C with composite additive content ranging from 0 to 7.5 wt%. Samples Z5-Z8 maintained a fixed composite additive content of 7.5 wt%, with sintering temperatures ranging from 1250 to 1400 °C. Based on literature research [35], when the coal gangue content exceeds 30 %, the mullite phase inside the ceramic proppant grows abnormally, accompanied by pore formation, leading to an increased breakage rate. Therefore, in this study, the mass ratio of bauxite to coal gangue in the framework material was fixed at 7:3, and the mass ratio of MnO_2 to TiO_2 in the composite additive was fixed at 3:1. The raw materials were wet-milled using a planetary ball mill (QM-QX04, Zhejiang Jiechen Instrument Equipment Co., Ltd.) at a rotational speed of 400 r/min for 4 h, with a mass ratio of powder, grinding balls, and deionized water set at 1:1:1. The milled slurry was dried at 120 °C for 24 h in an electric blast drying oven (101A-2 ET, Shanghai Experimental Instrument Factory Co., Ltd.). The dried lumps were ground and sieved through a 350-mesh (40 μm) screen. A laser particle size analyzer (Masterizer-2000, Malvern Instruments Ltd) was used to measure the particle size distribution (Fig. S1), revealing a bimodal distribution with an average particle size D_{50} of 2.828 μm. The appropriate amount of powder was placed into a sugar-coating machine (BY-300A, Guangzhou Daxiang Electronic Machinery Equipment Co., Ltd.) for granulation at a rotational speed of 50 r/min. During the process, 1.5 wt% PVA solution and powder were continuously added until the granules grew to the target size. Ceramic proppant green pellets of 30–50 mesh were selected and sintered in a tubular furnace (STG-60-17, Henan Sante Furnace Technology Co., Ltd.). The sintering process involves heating at 5 °C/min from room temperature to 1000 °C, followed by 3 °C/min from 1000 °C to the final sintering temperature, with a holding time of 90 min at the final temperature. The preparation process is shown in Fig. S2.

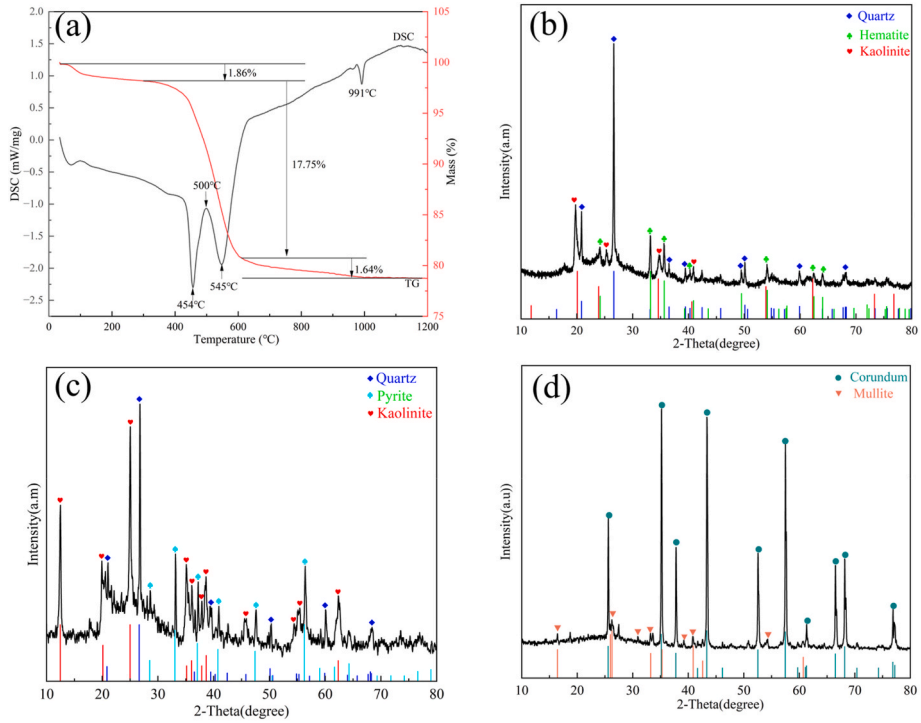

Fig. 2. (a) TG–DSC curve of raw coal gangue. (b) XRD pattern of raw coal gangue. (c) XRD pattern of coal gangue calcined at 700 °C. (d) XRD pattern of bauxite.

2.3. Characterization

Chemical composition analysis of major oxides in bauxite, raw coal gangue, and calcined coal gangue was performed using X-ray fluorescence spectroscopy (Bruker S8 TIGER, Bruker AXS GmbH). The pyrolysis characteristics of coal gangue were investigated via thermogravimetric-differential scanning calorimetry (TG-DSC, NETZSCH STA 449F3) under an air atmosphere with a heating rate of 10 °C/min from 30 °C to 1200 °C. The phase composition of the samples was analyzed by X-ray diffraction (XRD, DX-2007B, Dandong Haoyuan Instrument Co., Ltd.) with a scanning range of 10°–80° (2θ) at a step size of 0.02°. The phase identification and semi-quantitative phase analysis were performed using X'pert HighScore software. Fourier transform infrared spectroscopy (FTIR) was employed to analyze the Z1 and Z5 ceramic proppant samples for the characterization of chemical bonds within the proppants. Macroscopic morphology of proppants was observed through a stereomicroscope (SZM7045, Sunny Optical Technology Co., Ltd.), while cross-sectional microstructure and elemental composition were characterized by field-emission scanning electron microscopy (FE-SEM, Thermo Scientific Apreo 2) coupled with energy-dispersive spectroscopy (EDS, OXFORD ULTIM Max65). Key performance parameters including sphericity, bulk density, apparent density, and breakage ratio under 52 MPa closure stress were measured by the Chinese Petroleum Industry Standard SY/T 5108-2014.

3. Results and discussion

3.1. Raw material analysis

Fig. 2 shows the TG–DSC results of coal gangue over the temperature range of 30 °C–1200 °C, alongside the XRD patterns of coal gangue before and after calcination as well as the XRD pattern of bauxite. The TG–DSC data (Fig. 2(a)) indicate that in the range of 30–290 °C, the coal gangue loses about 1.86 % of its mass, mainly due to the evaporation of free water and the oxidative decomposition of organic matter. When the temperature increases to 300–610 °C, a more significant weight loss of approximately 17.75 % occurs. Chemical composition analysis of coal gangue indicates the presence of combustible components, including carbon and sulfur, which oxidize within the temperature ranges of 500–600 °C and 450–800 °C, respectively. This stage involves the oxidation of both carbon and sulfur [36]. Based on the XRD analysis of coal gangue before and after calcination (see Fig. 2(b and c)), this stage can be attributed to the thermal decomposition of kaolinite, leading to the release of hydroxyl groups from kaolinite followed by its transformation into metakaolin and the oxidation of FeS_2 [37]. The reaction equations (1) and (2) illustrate these processes, which are manifested as endothermic peaks at 454 °C and an exothermic peak at 500 °C on the DSC curve respectively. Regarding the formation mechanism of the endothermic peak at 545 °C, two possible explanations have been proposed: it may result either from the gasification reaction of residual carbon components or the reorganization of the short-range ordered structure within metakaolin [38]. Beyond 610 °C, the TG curve gradually declines, which is attributed to the decomposition of inorganic minerals and the residual organic components [39]. Analysis of the TG curve reveals that most volatile substances in the coal gangue have decomposed before reaching 700 °C, thereby reducing their impact on the densification of the ceramic granule proppant. Therefore, 700 °C was chosen as the calcination temperature for the coal gangue in this study.

$$Al_2O_3 \cdot 2SiO_2 \cdot 2H_2O(Kaolinite) \rightarrow Al_2O_3 \cdot 2SiO_2(Metakaolin) + 2H_2O \quad (1)$$

$$4FeS_2 + 11O_2 \rightarrow 2Fe_2O_3 + 8SO_2 \quad (2)$$

After calcination, the ratio of Al_2O_3 to SiO_2 in the coal gangue is 0.826 (see Table 1), which is higher than that of the raw coal gangue. Fig. 2(b) shows the XRD pattern of the raw coal gangue, where the main phases are quartz, kaolinite, and pyrite. Fig. 2(c) presents the XRD pattern of the coal gangue calcined at 700 °C for 1 h, revealing quartz as the dominant phase along with diffraction peaks corresponding to residual kaolinite and hematite. By comparing the XRD patterns before and after calcination, it can be observed that the diffraction peak of kaolinite at 12.46° disappears, indicating that the structure of the coal gangue has been disrupted and that kaolinite has transformed into metakaolin. In addition, the relative intensities of the remaining kaolinite diffraction peaks are significantly reduced, indicating that a large amount of kaolinite has decomposed [40]. XRD pattern of the clinker bauxite shows that corundum and mullite are its primary crystalline phase. (Fig. 2(d)).

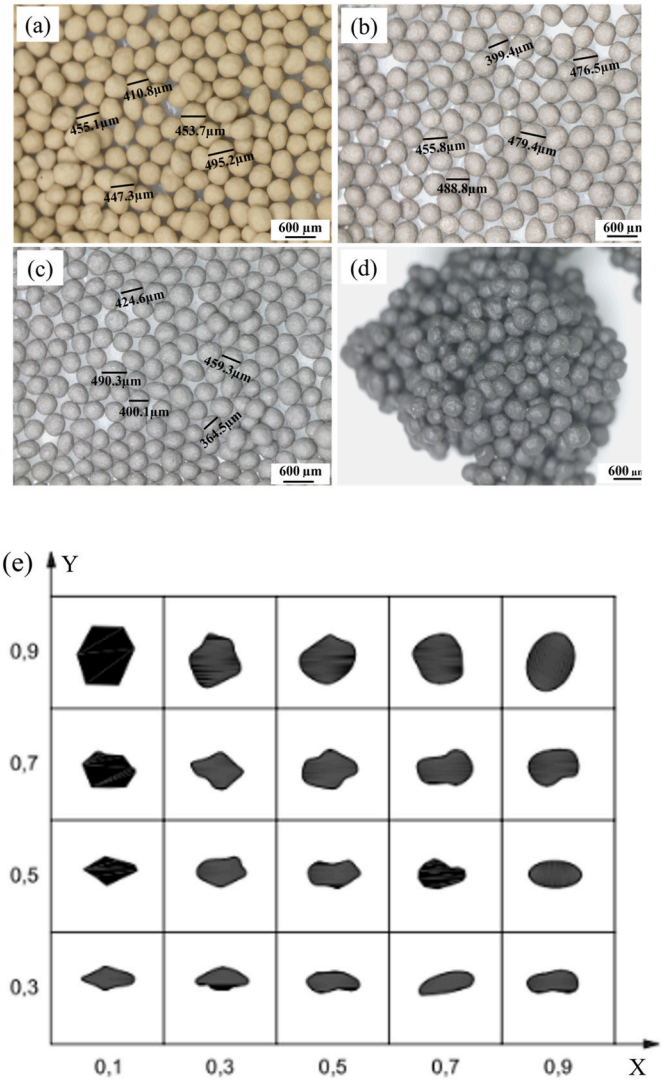

Fig. 3. Macroscopic morphology of Z1-Z4 ceramic proppants and the Krumbein/Slos template. (a) Z1, (b) Z2, (c) Z3, (d) Z4, (e) Krumbein/Slos template.

3.2. The effect of composite additive content on ceramic proppants

The effect of composite additives on the microstructure and mechanical properties of the ceramic proppant was investigated at the sintering temperature of 1450 °C. The resulting ceramic proppants were designated as Z1 to Z4, with the MnO_2/TiO_2 composite additive added at ratios of 0, 2.5, 5, and 7.5 wt%, respectively.

Fig. 3 displays photographs of the ceramic proppants prepared with different additive contents. As the additive content increases, the color of the proppants changes gradually from light yellow to dark gray, and their average diameter is approximately 446.85 μm. The sphericity of

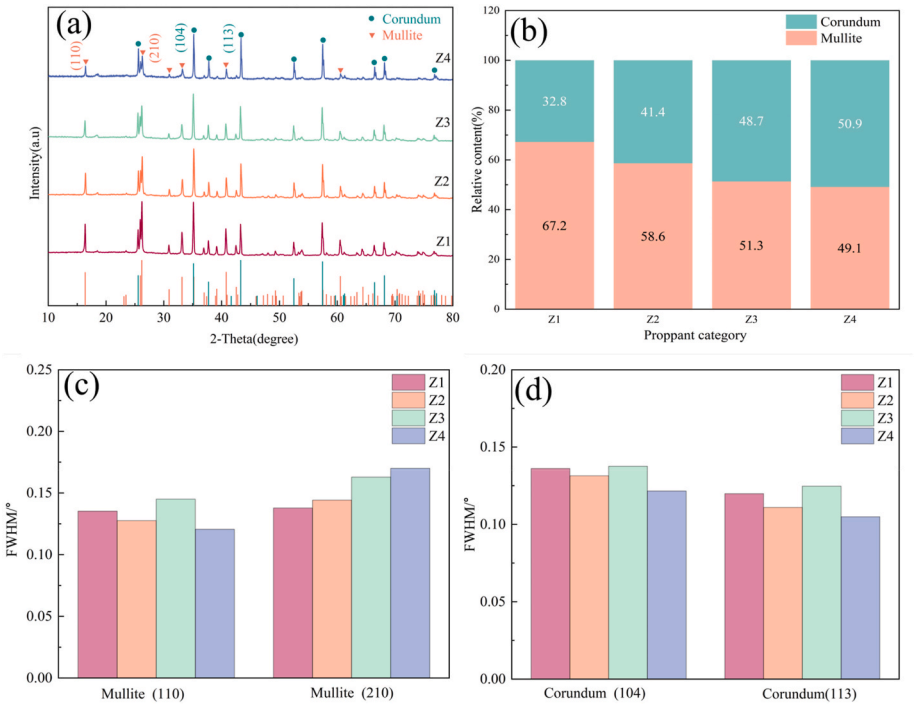

Fig. 4. XRD characterization and phase composition of ceramic proppant samples Z1-Z4. (a) XRD patterns of ceramic proppant Z1-Z4. (b) Semi-quantitative analysis of mullite and corundum phases in Z1-Z4. (c) FWHM of the mullite diffraction peaks in Z1-Z4. (d) FWHM of the corundum diffraction peaks in Z1-Z4.

the proppants was evaluated using the Krumbein/Slos template method [41], as shown in Fig. 3. The results indicate that the average sphericity of the proppants exceeds 0.9, which satisfactorily meets the requirements of the oil and gas industry standard SY/T5108-2014. However, when the additive content is increased to 7.5 wt% and sintered at 1450 °C, severe agglomeration occurs on the particle surfaces, resulting in poor particle dispersion (see Fig. 3). Analysis suggests that this phenomenon is due to the excessive additive content (7.5 wt%) at this temperature, which produces a large amount of liquid phase during high-temperature sintering, causing the particles to stick together. Therefore, for the ceramic proppants prepared with this formulation at 1450 °C, only XRD analysis was performed, and no further evaluation of other properties was conducted.

Fig. 4 presents the XRD patterns of the ceramic proppants prepared with different additive contents at a sintering temperature of 1450 °C, along with the semi-quantitative analysis and FWHM (full width at half maximum) analysis results of the mullite and corundum phases. From Fig. 4, it can be observed that the main diffraction peaks correspond to the corundum phase (PDF#00-046-1212) and the mullite phase (PDF#01-015-0776). Although the XRD patterns of the proppants prepared with different additive contents are similar, there are significant differences in the diffraction peak intensities. Analysis indicates that the diffraction peak intensity of the corundum phase gradually increases with increasing additive content, while that of the mullite phase decreases. Semi-quantitative analysis using HishScore software (Fig. 4(b)) confirms this trend, showing a clear decrease in mullite content and a corresponding increase in corundum. This phenomenon is likely due to enhanced glass phase formation induced by the additives, which consumes more Si and thus reduces the availability of Si for mullite crystallization. Furthermore, FTIR and EDS mapping analyses of Z1 and Z5 samples before and after corrosion (see Figs. S3–S7) suggest that increased Mn content may interfere with the participation of Si in mullite formation, further contributing to the observed reduction in mullite phase.

Further analysis shows that the mullite and corundum phases exhibit their strongest diffraction peaks at the (210) and (104) planes, respectively. The FWHM reflects the crystallinity of the crystals, where a smaller FWHM corresponds to higher crystallinity. By analyzing the FWHM of the mullite (210) and corundum (104) phases in the ceramic proppants prepared with different additive contents (see Fig. 4(c) and (d)), the anisotropy of crystal growth can be inferred [19]. As shown in Fig. 4(c) and (d), with 2.5 wt% additive content, the FWHM of mullite at the (110) plane and corundum at the (104) and (113) planes narrow, indicating improved crystallinity of mullite at (110) and corundum at (104). However, when the additive content rises to 7.5 wt%, the FWHM of mullite at the (210) plane widens, suggesting that the 7.5 wt% additive restricts the crystallization of mullite at the (210) plane. At the same time, the FWHM of mullite at the (110) plane and corundum at the (104) plane reduces significantly, indicating enhanced crystal growth in these specific planes.

Fig. 5(a and b) shows the cross-sectional microstructures of the ceramic proppants prepared under a sintering temperature of 1450 °C with different additive contents, along with the curves of bulk density, apparent density, and breakage rate. According to Fig. 5 (Z1a and Z1 b), the cross-section of the Z1 proppant (without additives) exhibits numerous irregulars, interconnected pores, and a distinct layered structure, lacking a dense structure. Pore size analysis was performed using ImageJ Pro Plus software, where the black areas represent the pores, with pore sizes ranging from 2.5 to 18 μm, as shown in Fig. S8. This indicates that when no additive is incorporated, a minimal liquid phase is generated to effectively fill the internal pores of the ceramic proppant, resulting in low bulk and apparent densities and a high breakage rate of 20.7 %. When 2.5 wt% of the composite additive is added, the cross-section of the Z2 proppant displays a well-densified outer layer with only a few small pores, while the central region still contains larger pores, with sizes ranging from 0.2 to 20 μm. This may be due to the inadequate binding between the mother pellet and the later-added powder during granulation. Compared to the Z1 proppant, the Z2 proppant shows a significant increase in both bulk density and apparent density. Within the Z2 proppant, an interwoven structure of rod-shaped mullite and alumina particles is formed, which further enhances its compressive strength and markedly reduces the breakage rate. After adding 5 wt% of the composite additive, the cross-sectional center of the Z3 proppant still contains large pores, and, compared to the Z2

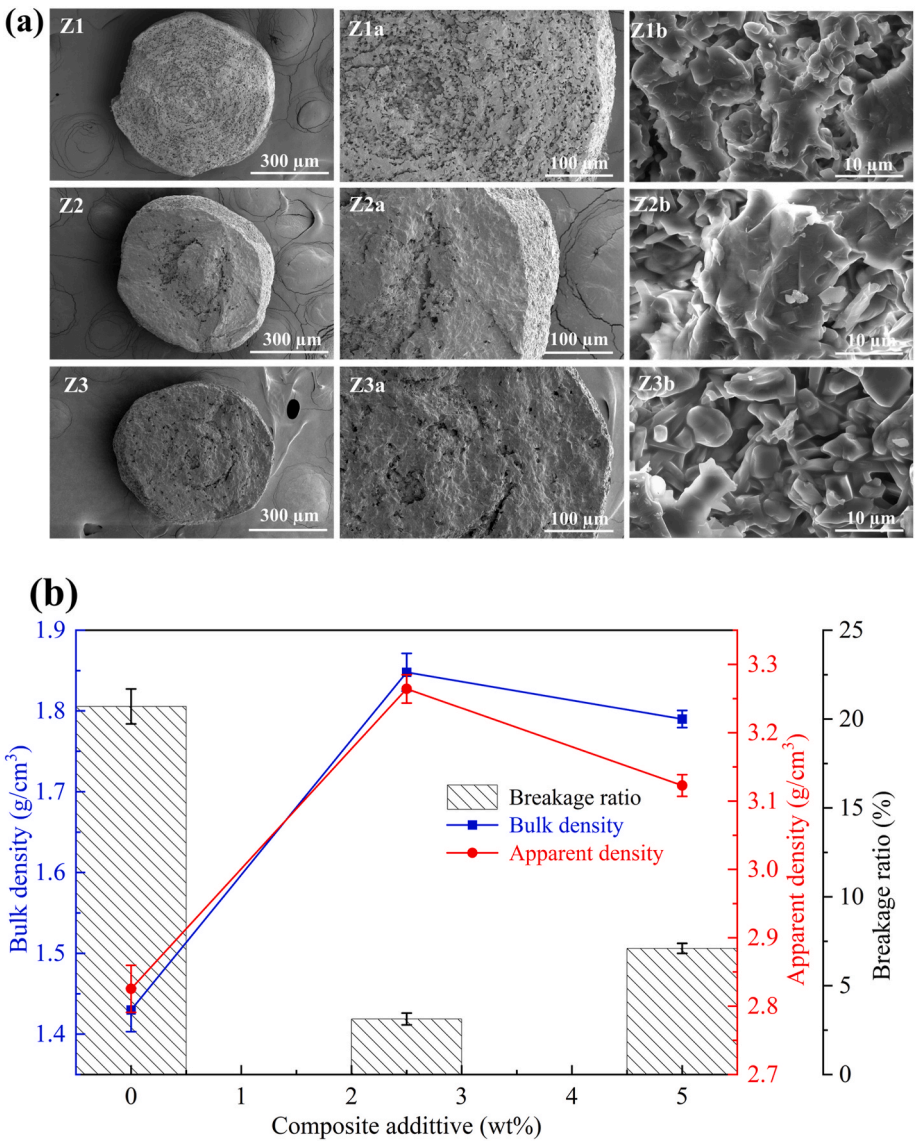

Fig. 5. Microstructural and Performance Characterization of Ceramic Proppants Z1-Z3. (a) Cross-sectional SEM images of ceramic proppants Z1–Z3; (b) Comparison of bulk density, apparent density, and breakage rate of Z1–Z3.

proppant, the number of pores in the outer region increases noticeably. This is possibly attributed to the coarsening of mullite, which leads to an insufficient filling of the pores by the liquid phase, thereby creating more pores [42]. Consequently, both the bulk and apparent densities slightly decrease. Although the interlocking structure of blocky Al_2O_3 particles with rod-shaped mullite is more pronounced in the Z3 proppant, the increased formation of low-strength glass phase and associated pore development caused by the 5 wt% additive leads to a reduction in compressive strength. In summary, at 1450 °C, the ceramic proppant prepared with 2.5 wt% composite additive exhibits the best performance, with a breakage rate of 3.13 ± 0.33 % under 52 MPa, and apparent density and bulk density of 3.26 ± 0.02 g/cm^3 and 1.85 ± 0.02 g/cm^3, respectively.

3.3. The effect of sintering temperature on the performance of ceramic proppants

Analysis of Fig. 4 shows that increasing the composite additive content promotes the formation of the corundum phase, which exhibits higher diffraction intensity than the mullite phase. Therefore, to further enhance the compressive strength of the ceramic proppants, the maximum composite additive content in this section is set to 7.5 wt%. In addition, the sintering temperature is also one of the important factors affecting the performance of the ceramic proppants. As shown in Fig. 3 (d), when the sintering temperature is 1450 °C and the composite additive content is 7.5 wt%, the ceramic granules tend to stick together, making it impossible to effectively evaluate and analyze their performance. Hence, in this section, to study the effects of different sintering temperatures on the structure and performance of the ceramic proppants, the sintering temperatures are set to 1250, 1300, 1350, and 1400 °C, and the four proppants are designated as Z5–Z8.

Fig. 6 presents the XRD patterns of the ceramic proppants prepared with a 7.5 wt% additive content under different sintering temperatures, along with the semi-quantitative analysis and FWHM (full width at half maximum) analysis results of the mullite and corundum phases. Analysis of Fig. 6(a) reveals that the main phases in all samples are the corundum phase (PDF#00-046-1212) and the mullite phase (PDF#01-015-0776), with a consistent phase composition. This indicates that variations in sintering temperature between 1250 and 1400 °C do not significantly affect the types of phases present. As the sintering temperature increases from 1250 °C to 1400 °C, the diffraction peak intensities of both the corundum and mullite phases gradually increase, suggesting that the

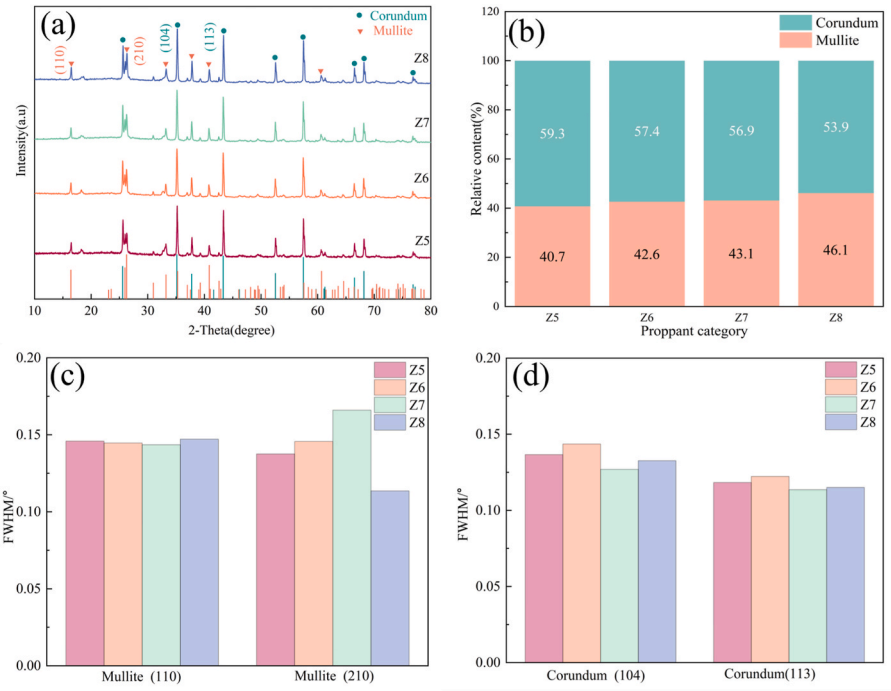

Fig. 6. XRD characterization and phase composition of ceramic proppant samples Z5-Z8. (a) XRD patterns of ceramic proppant Z5-Z8. (b) Semi-quantitative analysis of mullite and corundum phases in Z5-Z8. (c) FWHM of the mullite diffraction peaks in Z5-Z8. (d) FWHM of the corundum diffraction peaks in Z5-Z8.

reaction between quartz and corundum becomes more complete, with a slight increase in mullite formation (see Fig. 6(b)). Combined with the FWHM analysis (Fig. 6(c and d)), it can be seen that at a sintering temperature of 1350 °C, the FWHM of mullite at the (110) plane is smaller than that at the (210) plane, suggesting a faster crystal growth rate along the (110) plane compared to the (210) plane. However, when the sintering temperature is further increased to 1400 °C, the FWHM of mullite at the (210) plane decreases significantly, which indicates that a higher sintering temperature favors the growth of mullite on the (210) plane. The preferentially oriented growth of mullite crystals under different sintering temperatures leads to distinct crystal morphologies [20].

Fig. 7(a and b) shows the cross-sectional microstructures of the ceramic proppants prepared at different sintering temperatures with an additive content of 7.5 wt%, as well as the corresponding curves of bulk density, apparent density, and breakage rate. At a sintering temperature of 1250 °C, the Z5 ceramic proppant exhibits a uniformly distributed porous internal structure, leading to reduced bulk and apparent densities. At this temperature, the reaction forming mullite is incomplete, and a complete rod-like mullite network structure is not established, leading to a relatively high breakage rate; however, the breakage rate still meets the industry standard for oil and gas proppants (<9 %). When the sintering temperature is raised to 1300 °C, the pores inside the Z6 ceramic proppant are significantly reduced (see Fig. 7(Z6a and Z6b)), and the bulk density, apparent density, and compressive strength are all improved. Further increasing the sintering temperature to 1350 °C leads to forming a liquid phase that fills the pores. The Z7 ceramic proppant exhibits a more compact structure, and the internal pore morphology reveals that rod-like mullite continues to grow and interlock with blocky Al_2O_3, forming a tightly interwoven network that significantly enhances the compressive strength of the matrix [43]. When the sintering temperature reaches 1400 °C, the number of pores inside the ceramic proppant increases and their diameters become noticeably larger, with a maximum of 14 μm, as shown in Fig. S9, causing a decline in bulk density. This phenomenon may be attributed to thermal stress, which leads to the migration and reorganization of the internal gas pore positions, forming new, larger pores. In addition, the aspect ratio of the rod-like mullite decreases (see Fig. S10), and it adheres to the glassy phase, resulting in the deformation of the original mullite network structure and an increase in the breakage rate [44]. This study found that the ceramic proppant prepared with 7.5 wt% composite additive at 1350 °C exhibited the best overall performance, with an apparent density of 3.17 ± 0.02 g/cm^3, a bulk density of 1.88 ± 0.01 g/cm^3, and a breakage rate of 2.71 ± 0.32 % under 52 MPa, all by the SY/T5108-2014 standard.

To better observe the internal crystal morphology of the ceramic proppant, the cross-section of the proppant was subjected to acid etching using 3 % HF acid. Fig. 8 shows the SEM micrographs and EDS elemental analysis of the Z7 proppant after HF etching. As seen in Fig. 8(a), the internal crystal morphology of the proppant mainly exhibits blocky, granular, and rod-like forms. In the blocky crystals, only Al and O are detected (see Fig. 8(b)), indicating that the blocky morphology corresponds to corundum. Analysis of Fig. 8(c and d) shows that the rod-like and granular morphologies correspond to mullite. However, the atomic ratios of Al, Si, and O in these two forms deviate significantly from the theoretical atomic ratio of mullite (6:2:13), which is mainly attributed to the low yield and incomplete crystal development of mullite during sintering at 1350 °C [20]. According to relevant literature [45], granular mullite is regarded as secondary mullite, possibly formed through mutual diffusion between the glassy phase and Al_2O_3 particles, resulting in its deposition on their surfaces. Further elemental analysis reveals that the Ti content in both the rod-like mullite and secondary mullite is much higher than the Mn content. This difference is related to the incorporation of Ti^{4+} into two different distorted octahedral sites, leading to a higher Ti^{4+} content in the mullite structure [46]. In contrast, the incorporation behavior of Mn is mainly governed by ionic size [47], and MnO_2 may undergo the following reaction during sintering [48]:

$$MnO_2 \xrightarrow{460-570^\circ C} Mn_2O_3 \xrightarrow{926^\circ C} Mn_3O_4 \xrightarrow{1158^\circ C} MnO \quad (3)$$

Although Mn^{4+} (0.052 nm) has an ionic radius very close to that of Al^{3+} (0.057 nm), it is nearly impossible for Mn^{4+} to overcome the grain boundary energy barrier at temperatures below 570 °C. As a result, Mn^{4+} is unlikely to directly enter the lattice or substitute for Al^{3+}. On the other hand, Mn^{2+} (0.091 nm) has an absolute ionic radius difference |Δ|

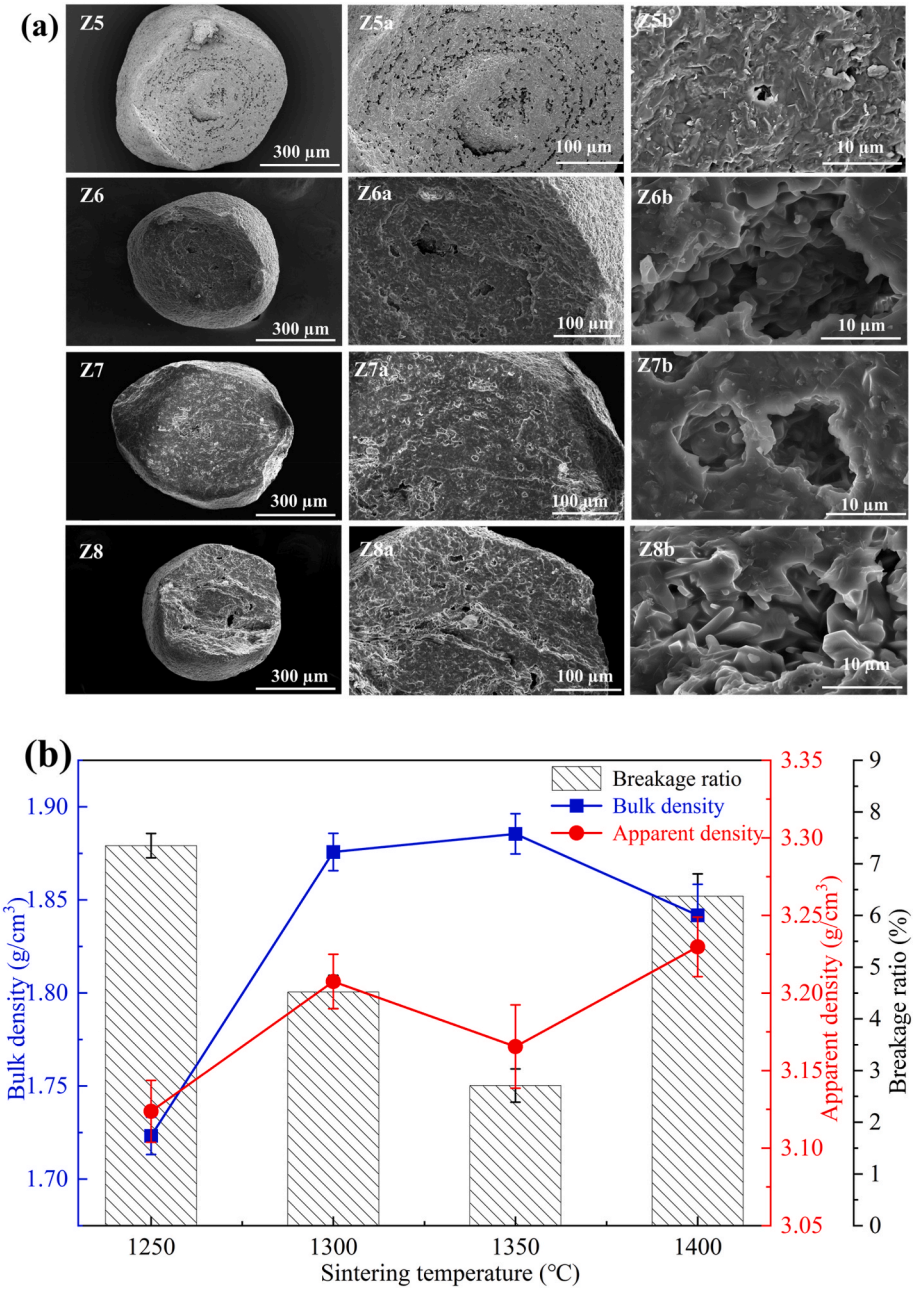

Fig. 7. Microstructural and Performance Characterization of Ceramic Proppants Z5–Z8. (a) Cross-sectional SEM images of ceramic proppants Z5–Z8; (b) Comparison of bulk density, apparent density, and breakage rate of Z5–Z8.

of approximately 59.64 % compared to Al^{3+} (0.057 nm), which makes direct substitution infeasible. However, Mn^{3+} (0.066 nm) has an absolute ionic radius difference $|\Delta|$ of approximately 15.79 %, allowing Mn^{3+} to partially replace Al^{3+} and form a limited solid solution. Therefore, only a small amount of Mn^{2+} exists in the mullite structure.

3.4. Evaluation and comparison of coal gangue incorporation systems

The accumulated amount of coal gangue in China has exceeded 7 billion tons, making it the largest industrial solid waste with the most extensive land occupation. With the increasing demand for coal, the annual production of coal gangue is also growing rapidly, reaching 330 million to 550 million tons [49], leading to a low market price of 200–300 RMB per ton. However, coal gangue contains various heavy metal elements, which, under external conditions such as weathering, erosion, and rainwater leaching, are prone to migration, causing serious environmental pollution [50]. Thermal treatment, as an economical and environmentally friendly solidification and stabilization technology, can effectively convert hazardous solid waste into harmless products [51]. Under high-temperature conditions, heavy metals can be fixed by physical encapsulation in the glass phase or by forming new chemical bonds [52]. Luo et al. [53] investigated the effect of using lead-zinc tailings and coal gangue to produce ceramic proppants. The results showed that after sintering at 1150–1250 °C, the leaching concentrations of Pb and Zn did not exceed the standard. At a sintering temperature of 1250 °C, after adding 3.0 % Pb and Zn, the leaching concentrations of all samples did not exceed 0.213 mg/L, well below the Chinese standards (Pb < 5 mg/L, Zn < 100 mg/L). Peng et al. [54] prepared ceramic proppants using coal gangue and dyeing sludge and conducted heavy metal leaching tests on the ceramic before and after sintering using sulfuric and nitric acid methods. The results showed significant reductions in Cd, Cr, Cu, Ni, and Zn levels. Despite the

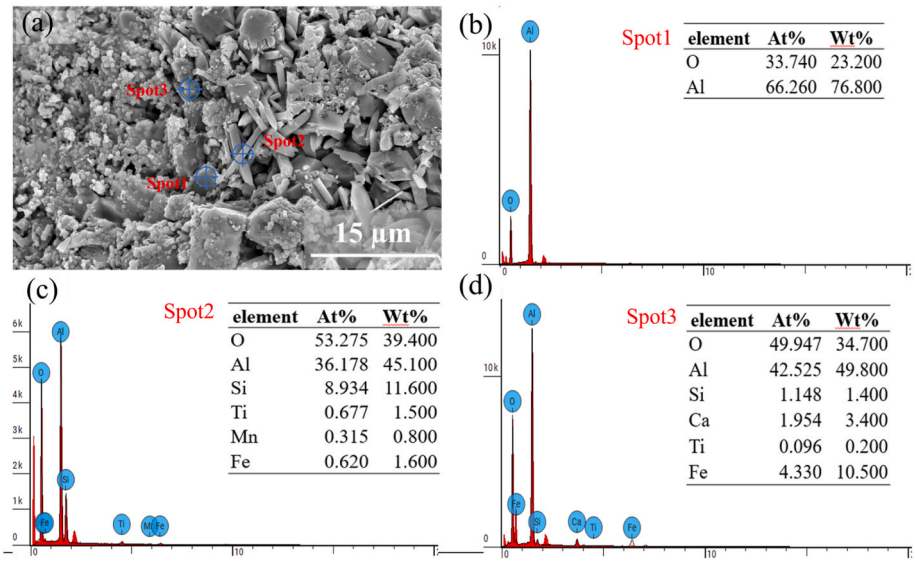

Fig. 8. SEM and EDS spectra of Z7 ceramic proppant after 3 % HF treatment.

Table 2
Comparison of coal gangue-based ceramic proppants prepared with composite additives and those reported in literature.

Raw materials	Sintering temperature (°C)	Additives/wt%	Apparent density(g/cm^3)	Bulk density(g/cm^3)	Breakage ratio(%)	Refs.
Bauxite coal gangue	1350	$CaCO_3$	3.10	1.42	8.41(52 MPa)	[24]
Bauxite coal gangue	1250	Magnesia slag/3	–	–	7.64(52 MPa)	[55]
Bauxite coal gangue	1400	Feldspar, dolomite TiO_2/12	–	1.36	2.19(52 MPa)	[28]
Bauxite coal gangue	1450	–	2.85	1.54	6.8(35 MPa)	[13]
Calcined firestone clay coal gangue	1400	–	2.79	1.27	8.36(52 MPa)	[56]
Bauxite coal gangue	1350	MnO_2, TiO_2/7.5	3.17	1.88	2.71(52 MPa)	This work
	1250		3.12	1.72	7.35(52 MPa)	

reduction in heavy metal leaching due to thermal treatment, the issue of heavy metal leaching from coal gangue-bauxite-based ceramic proppants in underground environments still requires further attention, especially its potential impact on groundwater. Compared with coal gangue, the market price of bauxite has risen to 2850 RMB per ton. Additionally, economic analysis shows that substituting 30 % coal gangue for bauxite reduces the cost to 2070 RMB per ton, saving 27.4 % on raw material costs. According to industry data, raw materials account for 30 %–60 % of the total cost of ceramic proppants. This substitution would lower the total cost of ceramic proppants by 8.2 %–16.4 %, while simultaneously alleviating the pressure of solid waste disposal. This approach offers both economic and environmental benefits for large-scale industrial applications. Therefore, this study not only enables the large-scale utilization of coal gangue but also promotes its high-value application while lowering the cost of ceramic proppants. Table 2 presents data from existing literature on the proportion of coal gangue used, sintering temperature, density, and breakage rate in ceramic proppant production using coal gangue and bauxite as raw materials. A comparative analysis shows that while the apparent density and bulk density of the ceramic proppants prepared in this study are slightly higher, their breakage rate or sintering temperature is lower than those of similar ceramic proppants. This study successfully achieves the goal of producing high-strength proppants with high coal gangue content and low energy consumption.

4. Conclusion

Ceramic proppants with a breakage rate below 9 % were successfully produced using bauxite and calcined coal gangue as raw materials, along with 2.5–7.5 wt% composite additives of MnO_2 and TiO_2 (with a ratio of MnO_2 to TiO_2 of 3:1), within a sintering temperature range of 1250–1400 °C. Increasing the content of the composite additive promoted the development of corundum phases, the dissolution of mullite, and the formation of micropores. As the sintering temperature increased, the diffraction peak intensities of mullite and corundum gradually became more pronounced. The ceramic proppant prepared at 1350 °C with 7.5 wt% of composite additives exhibited the best performance, presenting an apparent density of 3.17 ± 0.02 g/cm^3, a bulk density of 1.88 ± 0.01 g/cm^3, and a breakage rate of 2.71 ± 0.32 % under 52 MPa. This study provides experimental evidence and data for the preparation of ceramic proppants utilizing composite additives.

CRediT authorship contribution statement

Heng Zhang: Writing – review & editing, Writing – original draft, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Tian Yuan:** Writing – original draft, Investigation, Formal analysis, Data curation. **Liehui Zhang:** Formal analysis, Data curation. **Zhaozhong Yang:** Writing – review & editing, Supervision, Resources, Project administration, Investigation. **Xiaogang Li:** Writing – review & editing, Supervision, Resources, Project administration, Methodology, Investigation. **Fatereh Dorosti:** Writing – review & editing, Investigation. **Jingyi Zhu:** Writing – original draft, Methodology, Investigation, Formal analysis. **Jin Zhang:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Data curation, Conceptualization. **Hongcheng Yang:** Writing – original draft, Formal analysis, Data curation. **Hao Wang:** Writing – original draft, Validation, Supervision, Resources, Project administration, Funding acquisition. **Lei Ge:** Writing – review & editing,

Writing – original draft, Supervision, Resources, Project administration, Methodology, Funding acquisition, Formal analysis, Data curation, Conceptualization.

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.

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Appendix B. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ceramint.2025.06.353.

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