Review on Coal Gangue Aggregate Concrete Incorporating Supplementary Cementitious Materials

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Abstract

This study explores the application potential of coal gangue aggregate concrete in civil engineering by analyzing the characteristics of coal gangue aggregate concrete with different admixtures. It reviews the effects of admixtures such as fly ash, steel fibers, and blast furnace slag on the microstructure and macro properties of coal gangue aggregate concrete. As an industrial solid waste, the large-scale stockpiling of coal gangue causes resource waste and environmental pollution. Converting it into concrete aggregate helps protect natural resources, reduces land occupation, lowers environmental pollution risks, and unifies environmental and economic benefits. The study finds that the physical and chemical properties of coal gangue significantly influence its performance in concrete. Proper admixture selection and optimization can enhance the mechanical properties, workability, and durability of coal gangue aggregate concrete. Different types of coal gangue and replacement rates have significant impacts on concrete properties. High porosity and water absorption pose challenges to workability, but adjusting particle size distribution and optimizing admixtures can improve workability and expand the application scope of coal gangue aggregate concrete in civil engineering. It is feasible to use coal gangue as an aggregate for concrete preparation, with significant resource and environmental benefits, obvious later strength advantages, and suitability for engineering projects with high later strength requirements. Future research should focus on optimizing particle size distribution, selecting appropriate admixture types and proportions, strengthening quality control and testing, and deeply studying application performance to enhance the properties and application scope of coal gangue aggregate concrete.

Keywords

Coal Gangue; Aggregate; Concrete; Admixtures; Engineering Significance.

1. Introduction

In modern civil engineering, the continuous expansion of infrastructure and rapid development of the construction industry have exacerbated the shortage of natural aggregate resources. Simultaneously, the treatment and resource utilization of solid waste have become critical issues in environmental engineering. Coal gangue, as a primary solid waste generated during coal mining and washing, accumulates in large quantities. This not only occupies valuable land resources but also poses environmental risks, including soil contamination, water pollution, and atmospheric dust emissions. Utilizing coal gangue as a concrete aggregate effectively alleviates the scarcity of natural aggregates while achieving waste reduction, detoxification, and resource recovery, offering significant environmental and economic benefits[1].

Research and application of coal gangue aggregate concrete (CGAC) hold substantial theoretical and practical significance in civil engineering. From a civil engineering perspective, a thorough investigation into the performance of CGAC is essential for evaluating its feasibility in practical applications. The physicochemical properties of coal gangue differ markedly from those of conventional natural aggregates, profoundly influencing its performance in concrete. Physically, parameters such as particle gradation, apparent density (typically 2.0–2.5 g/cm^3, lower than natural aggregates like crushed stone at 2.6–2.8 g/cm^3), bulk density (generally 1.0–1.5 g/cm^3), and porosity (high, reaching 30%–50%) exhibit distinct characteristics. The high porosity results in significant water absorption, posing challenges to concrete workability and water-to-binder ratio control. Nevertheless, optimizing the particle gradation of coal gangue to meet concrete aggregate specifications can enhance the workability of fresh concrete mixtures, thereby improving constructability.

Chemically, coal gangue primarily comprises silicon dioxide (SiO_2), aluminum oxide (Al_2O_3), and ferric oxide (Fe_2O_3), along with impurities such as carbon and sulfur. Under certain conditions, SiO_2 and Al_2O_3 can participate in secondary hydration reactions with cement hydration products, forming cementitious compounds like calcium silicate hydrate (C-S-H) and calcium aluminate hydrate (C-A-H), which theoretically enhance long-term strength. However, carbon impurities tend to adsorb chemical admixtures, diminishing their effectiveness and consequently impairing concrete workability and strength development. Furthermore, sulfur may react with cement components to form expansive compounds, potentially causing cracking and reduced durability[2].

To leverage the potential advantages of coal gangue while mitigating its drawbacks, recent research has extensively explored CGAC incorporating various supplementary cementitious materials (SCMs). These include industrial by-products such as fly ash, ground granulated blast-furnace slag (GGBS), and silica fume, as well as fibers and other mineral admixtures. These materials enhance CGAC performance through physical and chemical mechanisms. For instance, fly ash fills internal pores to increase density; GGBS exhibits latent hydraulic activity, reacting with cement hydrates to form additional binding phases; silica fume significantly boosts early strength and durability. Incorporating such SCMs effectively improves the workability, mechanical properties, and durability of CGAC, broadening its application scope in civil engineering[3].

In summary, this paper systematically reviews recent advances in CGAC incorporating various SCMs. It analyzes performance aspects including mechanical properties, workability, and durability, elucidates the influence mechanisms of different SCMs on CGAC performance, and suggests future research directions. By critically evaluating existing findings, this review aims to provide theoretical support and a scientific basis for further research and practical application of CGAC, promoting its efficient and sustainable utilization in civil engineering.

2. Feasibility of Utilizing Coal Gangue as Concrete Aggregate

Coal gangue, as an industrial solid waste, offers significant resource and environmental benefits when used in concrete preparation. It also demonstrates certain economic and later - strength advantages. However, some challenges and issues exist in its practical application.

In terms of mechanical properties, Coal gangue has a lower strength than natural aggregates. After partially replacing natural aggregates with coal gangue in the early stage, the compressive, tensile, and flexural strengths of concrete generally decrease. Studies indicate that the relatively weak bond strength in the interfacial transition zone between coal gangue and cement paste, along with its insufficient strength, is the main reason for the early strength reduction. However, with age growth, the active components in coal gangue undergo secondary hydration reactions with cement hydration products, partly compensating for the early strength loss and improving later - age compressive strength. When the coal gangue replacement rate is within a certain range (e.g., 30% - 50%), the 28 - day compressive strength of concrete is lower than that of benchmark concrete, but the 90 - day or 180 - day compressive strength can approach or even

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exceed that of benchmark concrete. The Variation pattern of tensile and flexural strengths are similar to that of compressive strength. They decrease in the early stage due to interface and aggregate strength issues and improve later - stage due to secondary hydration reactions, but with relatively small overall improvement[4]. In terms of workability, To ensure concrete workability, it is necessary to appropriately increase water content or use high - efficiency water -reducers in mix proportioning. Therefore, it is essential to optimize the mix proportion through experiments to find the best solution that meets workability requirements while ensuring concrete strength and durability. Additionally, certain chemical components in coal gangue may affect the cement hydration process, thereby altering concrete setting time. Generally, coal gangue can prolong the initial and final setting times of concrete.

In terms of durability, To enhance the impermeability of coal gangue concrete, measures such as optimizing the mix proportion, adding mineral admixtures (e.g., fly ash, slag powder), and using high - efficiency water -reducers to reduce the water - binder ratio can be taken to improve the internal structure and density of coal gangue concrete. The frost - resistance of coal gangue concrete is closely related to porosity, pore structure, and the bond performance between aggregates and cement paste. Under freeze - thaw cycles, cracks can easily develop in the interfacial transition zone between coal gangue and cement paste, leading to concrete damage. Adding air - entraining agents to introduce a proper amount of tiny air bubbles can alleviate expansive stress during freeze - thaw cycles and improve the frost - resistance of coal gangue concrete. The chemical components of coal gangue can react with harmful chemicals in the environment, affecting the chemical resistance of concrete. For instance, sulfur in coal gangue may react with water and oxygen to form sulfuric acid under certain conditions, which can erode the cement paste in concrete and cause structural damage. Selecting coal gangue raw materials properly, controlling the content of harmful elements like sulfur in coal gangue, and adopting surface treatment measures can enhance the chemical resistance of coal gangue concrete[5].

Overall, it is feasible to prepare concrete with coal gangue as an aggregate. Its resource and environmental benefits are significant. It reduces solid waste stockpiling, saves land resources, and lowers environmental pollution. Economically, coal gangue can partly replace natural aggregates, alleviating the shortage of natural aggregate resources and reducing concrete production costs. Its later - strength advantages are obvious. The active components in coal gangue can participate in secondary hydration reactions to enhance later - age concrete strength, making it suitable for engineering projects with high later - strength requirements[6]. In practical applications, the coal gangue replacement rate should be controlled reasonably according to project characteristics and environmental conditions. The concrete mix proportion should be optimized, and quality inspection and control should be strengthened. Through further research and technological innovation, the application scope of coal gangue in the concrete field is expected to expand, realizing its greater resource utilization value.

3. Coal Gangue Aggregate Concrete with Supplementary Cementitious Materials

3.1. Fly Ash Addition

The incorporation of fly ash in coal gangue aggregate concrete significantly improves the mechanical properties and durability characteristics by optimizing the aggregate structure and enhancing the performance of the interfacial transition zone. Research shows that appropriate addition of fly ash can markedly increase the compressive, flexural and splitting tensile strengths of coal gangue concrete. The splitting tensile strength reaches its peak when fly ash replaces 30% of cement, while the secondary hydration reaction and particle morphology effect of fly ash further densify the internal structure of concrete and prolong the strengthening effect.

Although fly ash addition improves fluidity and impermeability, it negatively affects carbonation resistance at high dosages. These conclusions were confirmed in Zhu Kai's study [7], where when fly ash content did not exceed 30%, the slump of coal gangue lightweight aggregate concrete mixture was greater than that of the reference concrete without fly ash. At 30% fly ash content, the concrete showed optimal impermeability with minimum water penetration depth. With 20% fly ash replacement, the 28-day compressive strength was comparable to the reference concrete, while the 60-day compressive strength exceeded the reference concrete at 10% and 20% fly ash replacement. However, fly ash incorporation reduced the concrete's carbonation resistance, with carbonation depth increasing significantly when the replacement reached 40%. Wang Hai's research [8] found that the splitting tensile strength of non-self-combusting coal gangue concrete first increased and then decreased with increasing fly ash replacement rate. The maximum splitting tensile strength of 4.3MPa was achieved at 15% fly ash replacement for non-self-combusting coal gangue coarse aggregate concrete. The specific mechanical properties of coal gangue aggregate concrete mixed with admixtures are shown in Table 1.

Bai Chaoneng et al. [9] discovered that for concrete prepared with coal gangue as coarse aggregate, the density decreased from 2230 kg/m3 to 2140 kg/m3 with increasing coal gangue content after adding fly ash, while the slump remained at about 150 mm. Both splitting tensile strength and compressive strength decreased significantly with increasing coal gangue content, especially when the content exceeded 45%. For every 15% increase in content, the splitting tensile strength decreased by about 12%, and the 28-day compressive strength decreased by about 8%-11.4%. At 100% content, the 28-day compressive strength was only 75.1% of that of concrete without coal gangue. At 56 days, the elastic modulus and shear modulus decreased by 26.7% and 25.6% respectively. Hao Liang et al. [10] found that fly ash significantly improved the strength of coal gangue concrete, confirming Bai Chaoneng's research results. The maximum increases were 17.8% for compressive strength, 13.3% for flexural strength, and the splitting tensile strength reached its maximum value of 52.2 MPa at 30% fly ash replacement of cement. Appropriate fly ash content can optimize the overall mechanical properties of concrete, but excessive amounts may lead to strength reduction, making the selection of proper fly ash dosage crucial.

Guan Hongbo et al. [11] studied the preparation of ceramsite from coal gangue through high-temperature calcination, which resulted in lower density, higher strength and porosity, as well as altered microstructure and mineral composition, significantly improving the physical and mechanical properties of concrete. When changing the water-cement ratio and adding 20% more fly ash, the compressive strength of coal gangue concrete specimens increased by 36.2%, splitting tensile strength by 33%, flexural tensile strength by 19.3%, and elastic modulus by 23.8%. At W/C=0.45, the compressive strength, splitting tensile strength, flexural strength and elastic modulus of calcined coal gangue concrete increased by 37.2%, 32.5%, 19.3% and 23.5% respectively. Wang Shuo's [12] SEM analysis showed that fly ash incorporation could improve the interface properties of cement matrix, reduce $Ca(OH)_2$ content in cement matrix, and decrease the degree of alkali corrosion on basalt fibers. The secondary hydration reaction of fly ash also improved the structure of cement matrix, making the internal structure of SGCC denser, thereby enhancing the later strength and frost resistance of SGCC. When fly ash was combined with basalt fibers, the particle morphology effect of fly ash improved the fluidity of SGCC and prolonged the enhancement effect of basalt fibers on the later mechanical properties of SGCC.

3.2. Addition of Steel/Glass Fibers

Research has demonstrated that incorporating steel fibers and glass fibers into coal gangue concrete can significantly enhance its mechanical properties. Steel fibers effectively improve the concrete's brittleness and increase flexural strength through the "wall effect" and bridging mechanism, while glass fibers exhibit excellent performance in enhancing toughness and crack resistance. Appropriate dosages of steel and glass fibers not only strengthen coal gangue concrete but also optimize pore structure through fiber-matrix synergy, reducing microcrack formation and thereby improving durability and toughness. Zhou Mei et al. [13] found that adding shear-type steel fibers to spontaneous combustion coal gangue concrete significantly enhanced its mechanical properties. The results showed that steel fibers not only improved the concrete's brittleness but also increased flexural strength through the "wall effect." When steel fiber content reached 2%, the flexural strength increased by 72.27% compared to the non-fiber group, reaching its peak value. Yang Qiuning et al. [14] demonstrated that fibers with high tensile strength exhibited notable bridging effects during concrete cracking, with fiber aspect ratio showing more significant improvement on flexural strength than fiber compressive strength. With 2% steel fiber content at 28 days, the flexural strength of coal gangue concrete reached 5.6 MPa. Daming Luo et al. [15] discovered that adding appropriate types and quantities of steel fibers could significantly improve the frost resistance of coal gangue concrete (CGAC) and optimize its air void structure. Among different steel fiber types, U-shaped steel fibers showed the best performance, with only 14.2% and 14.7% compressive strength loss after freeze-thaw cycles at 1% volume content. Furthermore, steel fibers increased the number and surface area of air voids while reducing void spacing and average chord length, thereby further enhancing frost resistance. Cheng Yaohui [16] found in his study on steel fiber reinforced coal gangue concrete that steel fiber addition improved concrete performance. At 25% coal gangue replacement rate and 0.8% steel fiber volume content, the specimens' compressive strength increased by 10.63% compared to conventional concrete. With the same replacement rate, specimens with 1.0% steel fiber content showed 10.63% increase in splitting tensile strength compared to natural aggregate concrete. Meanwhile, specimens with 0.8% steel fiber content exhibited 36.54% reduction in mass loss rate after 100 freeze-thaw cycles. At 50% coal gangue replacement rate, specimens with 0.8% steel fiber volume content showed 41.83% improvement in flexural strength.

Additionally, Huang Y et al. [17] also found that adding 0.1% PET fibers increased the cube compressive strength and splitting tensile strength of coal gangue concrete by 7.2% and 7.9% respectively compared to CGC-5, representing 13.1% and 32.2% increases over conventional concrete. However, 0.5% PET fiber content led to 9.1% and 26.3% strength reduction compared to CGC-5. At 0.1% PET fiber content, axial compressive strength and elastic modulus increased by 3.2% and 19.2% respectively, while at 0.5%, axial compressive strength decreased by 8.9%. Flexural strength increased by 6.7% at 0.3% PET fiber content but decreased by 8.1% at 0.5%. Thus, 0.1%-0.3% PET fiber content showed optimal performance in enhancing coal gangue concrete properties and toughness. Wang Shuo [12] found that with 0.16% basalt fiber content and 18mm length, the compressive strength of steel fiber reinforced coal gangue concrete (SGCC) increased by 4.80% compared to the reference group without fibers, while splitting tensile strength increased by 14.19% under the same conditions. Basalt fiber incorporation also improved SGCC's durability during increasing freeze-thaw cycles, with fiber length showing more significant effects after 75 cycles. Additionally, randomly distributed basalt fibers effectively enhanced the bond between embedded steel bars and cement matrix, improved aggregate-matrix connection, reduced microcrack formation, increased matrix density, and significantly improved SGCC's long-term strength and frost resistance. Wang Zhenshuang et al. [18] showed that when steel fiber content increased from 0% to 2.0%, the concrete's 28-day compressive strength increased by 16.5%, splitting tensile strength increased from 4.15MPa to 6.91MPa (66.5% increase), and flexural strength increased from 4.76MPa to 8.2MPa (72.27% increase). Steel fiber addition also improved the tensile-compressive ratio from 1/11 to 1/7.7 and flexural-compressive ratio from 1/9.6 to 1/6.5, significantly enhancing concrete toughness and failure characteristics, transforming brittle failure into a more ductile mode. Test results indicated the optimal steel fiber content range as 1.0%-2.0%, where concrete achieves both economic rationality and good mechanical properties. Wang Z et al. [19] demonstrated that compared to non-fiber concrete, concrete with 2% steel fiber volume content showed increased compressive strength from 45.6MPa to 53.1MPa, splitting tensile strength improvement of 10.4%-66.5%, and flexural strength increase from 4.76MPa to 8.20MPa. Steel fiber incorporation enhanced chloride ion penetration resistance, reducing electrical flux from 2680 C to 1240 C, though workability decreased with slump reduction from 38mm to 31mm. Comprehensive consideration suggested 1.5% as the optimal steel fiber content, where the system efficiency coefficient reached its maximum value of 0.87 and concrete performance was optimal.

3.3. Addition of Blast Furnace Slag

Incorporating blast furnace slag into coal gangue concrete can improve both mechanical properties and durability. The pozzolanic activity of slag promotes hydration reactions and enhances concrete density. Research indicates that combined addition of slag and fly ash significantly increases compressive and splitting tensile strengths while optimizing frost and sulfate attack resistance, providing scientific basis for high-performance applications of coal gangue concrete. Yang Qiuning et al. [14] also studied the optimal 1:2 ratio of fly ash to slag powder, where coal gangue concrete achieved maximum 28-day compressive and splitting tensile strengths, with 72.27% and 43% increases respectively in E1 group concrete. Single slag addition showed higher early compressive strength than single fly ash addition, indicating slag's more significant positive effect on early strength development. Reasonable combination of fly ash and slag with ST fibers can substantially improve coal gangue concrete's mechanical properties. Other research showed that at 10% slag and 20% fly ash content, coal gangue concrete achieved 22.59 MPa compressive strength and 2.62 MPa splitting tensile strength, representing 28.5% and 35.7% increases over control groups respectively. Additionally, permeability coefficient decreased to 2.41 mm/s with effective porosity reaching 19.7%, improving both permeability and porosity characteristics for applications like sponge city construction [20]. Y. Zhang et al. [21] found that adding ultra-fine slag powder (UFS) could further increase compressive strength and reduce thermal conductivity. With UFS addition, concrete achieved maximum 7-day and 28-day compressive strengths of 32.5 MPa and 37.7 MPa respectively, with thermal conductivity as low as 0.34 W/(m·k). The study concluded that at 30% coal gangue coarse aggregate replacement rate, 134 kg/m^3 GHB content, and 0.4% NS and 5% UFS dosages (by binder weight), concrete achieved optimal comprehensive performance with 0.41 W/(m·k) thermal conductivity and 37.7 MPa compressive strength.

At the same time, Zhigang Wang et al. [22] improved workability and strength of coal gangue concrete by adding fly ash and slag. At 30% fly ash content, slump and expansion reached 270 mm and 638 mm respectively, while 30% slag content resulted in 230 mm and 576 mm. Compressive strength decreased with increasing NCCG (coal gangue) coarse aggregate content, dropping to 50.9 MPa (36.69% reduction) at 60% NCCG. After freeze-thaw cycles, 60% NCCG concrete showed 1.41% mass loss and 25.25% relative dynamic elastic modulus loss, demonstrating good frost resistance. For sulfate attack, NCCG content should not exceed 45%, while carbonation depth remained below 3mm after 200 days, showing good carbonation resistance. Zhigang Wang also noted that silica fume addition slightly reduced workability (minor slump and expansion reduction) due to its strong water absorption increasing concrete viscosity. For strength, silica fume coating slightly improved splitting tensile strength, with 0.55 water-silica fume ratio showing 0.13 mm reduced carbonation depth after 200 days compared to uncoated specimens, indicating positive effects on durability. Zhang Chengzhong et al. [23] reported that single slag addition exceeding 25% led to nearly linear increase in carbonation depth with dosage, reaching 1.19 times that of conventional concrete at 40% content. Single coal gangue addition exceeding 30% significantly increased carbonation depth (1.35 times at 30% content). Combined fly ash and slag addition showed dramatic carbonation depth increase when fly ash exceeded 30%, with varying effects when adding 25% slag to fly ash mixtures. Combined fly ash and coal gangue addition showed linear correlation between fly ash content and carbonation depth increase. Combined slag and coal gangue addition changed carbonation depth with slag content variation, showing about 40% increase compared to single slag addition with 20% coal gangue. Daming Luo et al. [15] found that slag powder replacement improved coal gangue concrete's frost resistance, though less effectively than steel fibers. At 40% slag replacement, concrete showed best frost resistance, with changed air void parameters including 30.7% reduced air content and 13.9% reduced air void number compared to conventional coal gangue concrete.

3.4 Addition of Other Admixtures

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Beyond fly ash, fibers and blast furnace slag, other studies have incorporated nano-silica etc. to enhance coal gangue aggregate concrete's strength and durability. Y. Zhang et al. [21] indicated that adding nano-silica (NS) and glazed hollow beads (GHB) increased concrete's compressive strength, with maximum 7-day and 28-day compressive strengths reaching 38.4 MPa and 40.1 MPa respectively with NS addition, while also reducing thermal conductivity to as low as 0.32 W/(m·k). Although GHB reduced water demand, it showed limited effects on mechanical properties and thermal conductivity. Zha Wenhua et al. [20] found that at alkali activator modulus of 1, AFSGPC (alkali-activated fly ash-slag based coal gangue pervious concrete) achieved maximum compressive and splitting tensile strengths of 22.59 MPa and 2.62 MPa respectively, while improving density, permeability and workability with minimum permeability coefficient of 2.41 mm/s for easier construction. Moreover, alkali-activated fly ash-slag cementitious materials enhanced AFSGPC's durability for long-term applications. Hou Xinyue [24] discovered that bentonite addition acted as plasticizer, dividing plastic concrete's setting and hardening into "plasticizing" and "solidifying" stages. Bentonite's strong water absorption reduced concrete strength (plasticizing effect) but decreased material cost by 31.9% compared to conventional plastic concrete by replacing more expensive components.

Table 1 Compressive and Tensile Strength of Coal Gangue Aggregate Concrete with Admixtures.

Company: kg/m^3

Reference	coal gangue (coarse)	stone	coal gangue (fine)	sand	cement	fly ash	slag	fiber/alkali activator	water cement ratio	water reducing agent	splitting tensile strength (MPa)		compressive strength (MPa)			
											7d	28d	3d	7d	28d	90d
[9]	113	965	-	749	383	57%	-	-	0.49	3.8	2.97	4.17	-	25.76	34.68	39.86
	340	738	-	749	383	57%	-	-	0.49	3.8	2.79	3.84	-	24.68	32.88	38.3
	566	512	-	749	383	57%	-	-	0.49	3.8	2.2	3.36	-	21.81	29.35	34.01
	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
[14]	1134	-	-	756	400	-	-	-	0.4	-	1.69	1.93	-	20.6	27.9	-
	1134	-	-	756	280	60	60	-	0.4	-	2.53	3.63	-	33.3	35.13	-
	1134	-	-	756	280	-	120	-	0.4	-	2.5	4.03	-	33.7	38.6	-
[10]	329	913	-	669	320	137	-	-	0.38	-	-	3.48	-	-	44.1	-
[15]	760	-	250	-	500	-	-	-	0.37	0.60%	-	4.89	-	-	53.6	-

	739.4	-	269.7	-	500	-	-	1%	0.37	0.60%	-	7.23	-	-	59.3	-
	739.4	-	269.7	-	350	-	30%	-	0.37	0.60%	-	4.25	-	-	47.3	-
[11]	770	-	-	770	300	30	-	-	0.55	6	-	2.24	17.81	23.05	31.82	-
	770	-	-	770	360	36	-	-	0.45	7.2	-	2.98	24.92	35.34	43.33	-
	770	-	-	770	475	48	-	-	0.3	9.5	-	3.65	29.33	41.43	48.82	-
[22]	271.96	634.58	-	536.44	560	240	-	-	0.25	7.75	-	5.2	-	-	60.3	76
	271.96	634.58	-	536.44	560	-	240	-	0.25	7.75	-	5.7	-	-	68.3	71.7
	271.96	634.58	-	536.44	560	80	160	-	0.25	7.75	-	6.3	-	-	68.5	79.8
[17]	-	1151.3	297.8	619.9	379.6	-	-	0.10%	0.54	1.63	-	4.18	-	35.4	47.6	-
	-	1151.3	297.8	619.9	379.6	-	-	0.50%	0.54	1.63	-	2.83	-	31.2	40.5	-
[20]	1452.91	-	-	-	-	59.23	236.91	AA-98.48	0.22	-	-	0.7	-	-	4.15	-
	1089.68	363.23	-	-	-	89.34	357.34	AA-148.55	0.16	-	-	1.55	-	-	17.03	-
[8]	323.61	755.09	206.9	482.72	250.7	70.1	-	-	0.52	6.08	-	-	21.5	22.8	27.7	31.2
	323.61	755.09	344.8	344.8	250.7	70.1	-	-	0.52	6.08	-	-	17.5	18.9	23.6	27.5
[21]	812	348	-	580	354	50	35	-	0.45	0.03%	-	-	-	19.4	27.2	-
[7]	1106.3	-	-	737.5	312	78	-	-	0.41	0.50%	-	-	-	23.6	40.9	57.2
	1106.3	-	-	737.5	273	117	-	-	0.41	0.50%	-	-	-	22.6	38.8	55.4
[16]	451	451	-	800	355	-	-	62	0.47	7.1	1.96	2.88	-	23.6	36.4	-
	676	226	-	800	355	-	-	94	0.43	7.1	1.63	2.74	-	20.3	32.3	-
[12]	750	-	-	878	328	82	-	0.16%	0.34	10	2.22	3.1	-	29.5	40.7	-
	750	-	-	878	328	82	-	0.40%	0.34	10	1.93	2.84	-	25.6	38.1	-
[19]	800	-	-	730	410	-	-	0.50%	0.46	2	-	4.55	-	36.2	47.1	-
	800	-	-	730	410	-	-	1.50%	0.39	4.1	-	6.21	-	42.6	50.4	-

Note: AA - alkaline activator (e.g. AA-98.48, alkaline activator dosage of 98.48 kg/m^3);

4. Significance of Utilizing Coal Gangue as Concrete Aggregate

From the perspective of resource utilization, coal gangue, as solid waste generated during coal mining and washing processes, represents significant resource wastage due to its massive production. Its conversion into concrete aggregate provides a new approach for recycling solid waste, reduces dependence on natural aggregates, and helps protect natural resources. Environmentally, the accumulation of coal gangue occupies large areas of land and may trigger chain reactions of ecological pollution, including soil, water, and atmospheric contamination. When used as aggregate in concrete production, it not only reduces land occupation but also lowers environmental pollution risks, demonstrating significant environmental benefits and achieving a balance between economic and environmental advantages.

In terms of engineering potential and performance, the civil engineering field faces continuously growing demand for concrete while natural aggregate resources become increasingly scarce. Coal gangue aggregate concrete offers a new solution to alleviate this contradiction. Although coal gangue's physicochemical properties differ from conventional aggregates and may affect concrete workability, strength, and durability, it also possesses unique advantages [1]. For instance, while its high porosity and water absorption present challenges to workability, proper adjustment of particle gradation can improve mixture workability. Furthermore, incorporating different admixtures such as fly ash, slag powder, and silica fume - industrial byproducts and mineral admixtures - can effectively enhance the workability, mechanical properties, and durability of coal gangue aggregate concrete [25], expanding its application scope in civil engineering.

5. Conclusion

Based on previous research analysis, this paper thoroughly investigates the characteristics of coal gangue aggregate and the mechanism of its interaction with admixtures on the microstructure and macroscopic performance of concrete. Through scanning electron microscopy (SEM) observation of the microstructure of coal gangue coarse aggregate concrete, significant effects of different coal gangue types and replacement rates on concrete performance were discovered.

SEM analysis of coal gangue concrete microstructure revealed that as the replacement rate of S-type coarse aggregate (self-combusted coal gangue) increases, the interfacial transition zone (ITZ) between it and the cement matrix becomes thinner and denser [26]. This phenomenon is attributed to two factors: first, the porous nature of S-type aggregate absorbs moisture from the cement matrix, reducing the water-cement ratio in the ITZ; second, the reactive surface of S-type aggregate interacts with cement hydration products, generating new compounds that fill pores and strengthen bonding, stabilizing the ITZ structure. As shown in Fig. 1, for R-type coarse aggregate (rock-type coal gangue) concrete, increasing replacement rates lead to thicker ITZ, looser structure, and more pores. The powdery material on the surface of R-type aggregate weakens its bond with the cement matrix, making the ITZ a vulnerable area. The microstructural characteristics correspond well with macroscopic failure patterns, demonstrating the significant influence of coal gangue coarse aggregate type and replacement rate on concrete mechanical properties. The reactivity and porosity of S-type aggregate can optimize interface structure, while R-type aggregate may reduce overall performance due to surface powdering [27].

Coal gangue coarse aggregate concrete (CGAC) with and without steel fibers shows distinct characteristics in void distribution and cross-sectional morphology (Fig. 2). Ordinary CGAC resembles conventional concrete, with relatively high proportions of low-frequency, large visible voids in total pore volume, while fine pores show the opposite trend. Most air voids have chord lengths of 0.02-0.1 mm, with larger voids (>0.5 mm) accounting for significant volume fractions. After adding steel fibers, void sizes decrease, and more isolated, closed voids appear in cross-sections. In steel fiber-reinforced CGAC, the proportion of small voids is relatively low, which relates to the smooth surface and flat shape of crimped steel fibers (CPSF) that facilitate better mixing with concrete and reduce air entrainment, thereby improving various concrete properties. Cross-sectional analysis shows that while porous coal gangue aggregate as lightweight aggregate can densify the ITZ, it compromises mechanical performance. Ordinary coal gangue aggregate contains numerous large voids, and water freezing in these voids exerts pressure on pore walls, negatively affecting frost resistance. Steel fibers can reduce microcrack and large void formation, increase the number of isolated closed voids, and alleviate expansion pressure from freezing water, thereby enhancing frost resistance. Figure 3 illustrates the influence of different fly ash replacement rates on void distribution and cross-sectional morphology of CGAC. After adding fly ash, the frequency and content of 0.02-0.03 mm voids decrease, while those of 0.03-0.04 mm and 0.06-0.08 mm voids increase. Cross-sections show reduced numbers of large voids and formation of small, isolated closed voids due to fly ash filling effect. Although this benefits frost resistance improvement, the effect is limited because of slow early hydration of fly ash. Overall, considering the heterogeneity of CGAC, fly ash has difficulty effectively optimizing void structure, and its contribution to frost resistance improvement is limited [15].

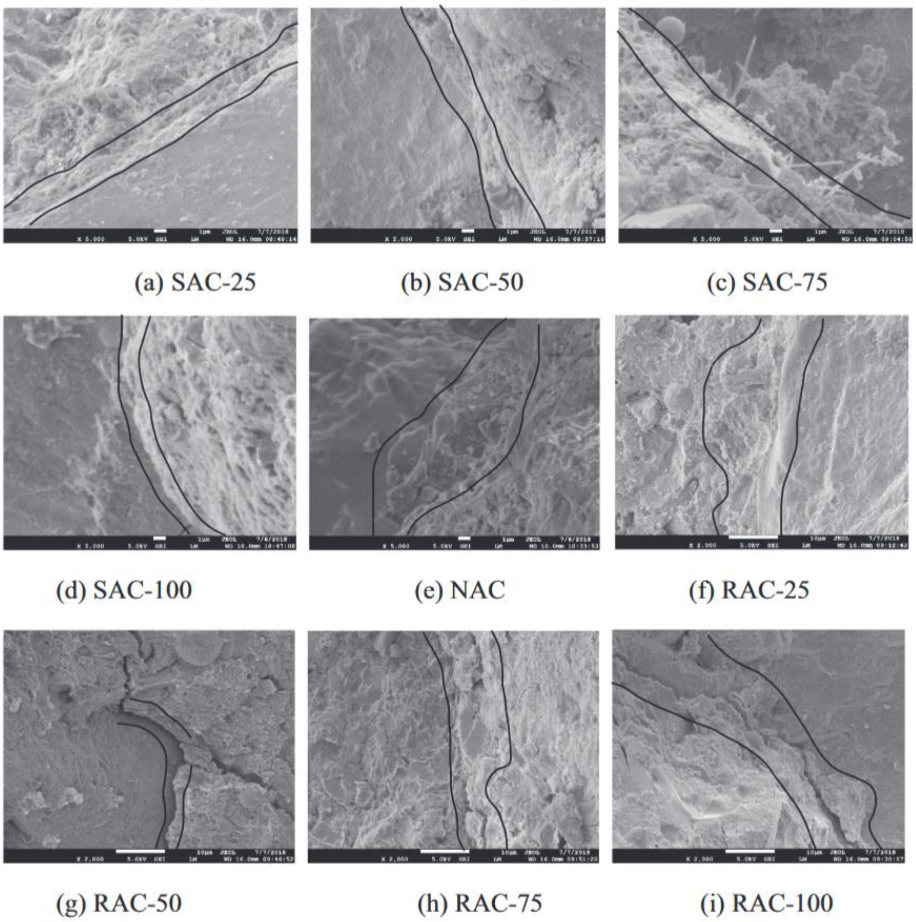

Fig. 1 SEM photos of concrete with different coal gangue types and different replacement percentages.[27]

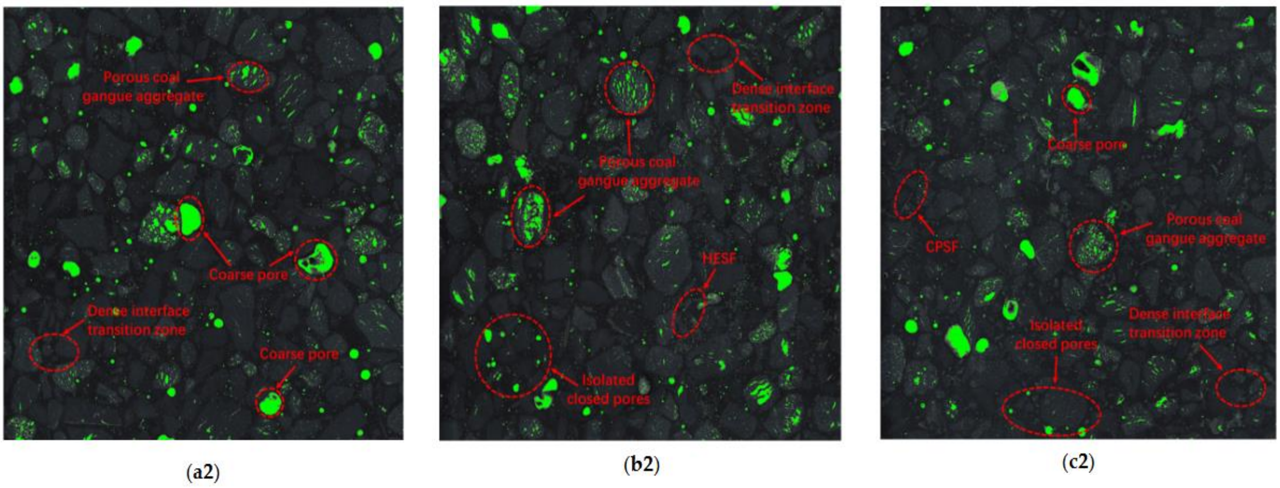

Fig. 2 Air-void distribution and cross-sectional morphology of CGAC (a) without steel fiber;(b) with 1% HESF; (c) with 1% CPSF (1: Air-void distribution; 2: Cross-sectional morphology).[15]

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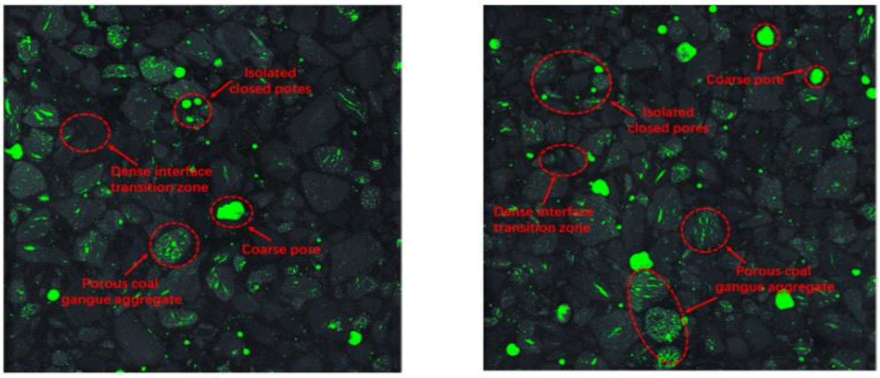

(b2) (a2)

Fig. 3 Air-void distribution and cross-sectional morphology of CGAC with (a) 10% cement substitution rate; b) 40% cement substitution rate (1: Air-void distribution; 2: Cross-sectional morphology).[15]

6. Summary and Outlook

As an industrial solid waste, the application of coal gangue in concrete production not only alleviates the shortage of natural aggregate resources but also demonstrates unique advantages in environmental protection and economic benefits. Research has confirmed that although coal gangue aggregate differs from traditional natural aggregates in physicochemical properties, its comprehensive performance in concrete can be effectively improved through proper control of replacement rates and mix optimization. Specifically:

The physical properties of coal gangue aggregate concrete can be optimized: Adjusting particle gradation improves workability and enhances construction performance.

The compressive strength of coal gangue aggregate concrete decreases with increasing replacement rates, showing lower early-age strength. However, SiO_2 and Al_2O_3 in coal gangue can participate in secondary hydration reactions to improve long-term strength. Carbon impurities may reduce workability and strength development, while sulfur elements may cause expansion cracking.

Fly ash incorporation improves microstructure, enhancing long-term strength and durability, but high dosages may reduce carbonation resistance. Steel and glass fibers significantly improve mechanical properties and durability by optimizing pore structure and reducing microcracks. Blast furnace slag enhances both mechanical properties and durability, with combined use of fly ash further optimizing frost and sulfate attack resistance.

Coal gangue aggregate concrete demonstrates significant resource and environmental benefits by reducing solid waste accumulation, conserving land resources, and decreasing environmental pollution. Economically, it serves as an alternative to natural aggregates, alleviating resource shortages and reducing costs. Its notable advantage in later-age strength makes it particularly suitable for projects requiring high long-term strength performance.

Although research on coal gangue aggregate concrete has achieved significant results, many issues remain to be addressed. Future studies should focus on developing pretreatment technologies such as high-temperature calcination and chemical cleaning to precisely regulate the performance of coal gangue aggregate, remove harmful impurities, and improve its quality. Meanwhile, through multiscale simulation and experimental verification, in-depth research should be conducted on the optimal combination of supplementary materials to establish synergistic effect models and develop intelligent design systems that enable automated and precise mix design to meet customized requirements for different engineering applications [28]. Furthermore, application research should be expanded to complex environments such as marine and desert conditions, with the development of intelligent coal gangue aggregate concrete featuring self-sensing and self-healing capabilities to adapt to smart city construction. Finally, a comprehensive life cycle assessment system should be established to quantify resource consumption and environmental emissions throughout the entire process from extraction to disposal, providing a basis for formulating sustainable development policies and promoting green and low-carbon industrial transformation. Through these efforts, the widespread application of coal gangue aggregate concrete in civil engineering can be anticipated, contributing to the sustainable development of the construction industry.

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