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Review Article

A Review on the Application of Circulating Fluidized Bed Fly Ash in Building Materials

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Circulating fluidized bed (CFB)-based coal burning technology is a type of clean coal combustion technology. Owing to its characteristics of low temperature combustion and desulfurization in furnace, the CFB fly ash is quite different from ordinary fly ash. Based on the comprehensive understanding of physical and chemical characteristics of CFB fly ash, this review summarizes the research progress of the application of CFB fly ash in Portland cement, magnesium oxysulfate (MOS) cement, solid-waste–based cementitious material (SWCM), concrete, geopolymer, artificial aggregate, and other building materials. The study shows that CFB fly ash can improve the early physical and mechanical properties and reduce the drying shrinkage properties for cementitious materials. Its unique chemical composition endows it with good application performance in the MOS cement, geopolymer, and SWCM. However, unfavorable characteristics of CFB fly ash, such as loose and porous structure, self-hardening behavior, and expansibility greatly hinder its practical applications in building materials. Therefore, some measures, such as addition of rational water-reducing agent, ultrafine grinding, mixing of ordinary fly ash, controlling the dosage of CFB fly ash, and water-cement ratio, must be taken to improve the negative influence of CFB fly ash on the building materials, in order to expand its application range. This article summarizes the application and research status of CFB fly ash in building materials, aiming at further promoting the research studies on CFB fly ash resource utilization in building materials and improving the efficiency of CFB fly ash resource utilization.

1. Introduction

The global coal consumption has been estimated to increase by more than 50% by 2030, with the developing countries expected to exhibit the increase by more than 97% [1, 2]. The excessive emissions of CO_2, SO_2, and NOx due to extreme coal combustion cause serious harm to human health, animals, and plants as well as hinder the sustainable development of ecological environment [3]. Therefore, the efficient and clean utilization of coal has become an inevitable research development trend in the background of increasingly severe global ecological problems.

Desulfurization in coal burning furnace in circulating fluidized bed (CFB) as a type of clean coal combustion technology, is widely used because of the advantages including low-pollution emission, cost-effectiveness, and wide adaptability of coal burning. However, with the widespread use of CFB boiler, the proportion of CFB fly ash and slag in solid waste has been increasing year by year, in particular, in China. CFB fly ash and slag are the combustion products of sulfur-containing coal and sulfur-fixing agent that are discharged from flue and bottom of CFB boiler. In actual production process, for efficient improvement of sulfur fixation efficiency, the molar ratio of calcium and sulfur content is generally set between 2.0 and 2.5, which leads to the emitted content of CFB fly ash being twice that of ordinary fly ash [4]. In this study, the ordinary fly ash refers to the fly ash discharged from pulverized coal boiler, which is significantly different from the fly ash from CFB boiler in terms of combustion characteristics. Currently, the emissions of CFB fly ash and slag correspond to about 80 million tons annually in China [5]. In order to reduce the negative impact of CFB fly ash on the environment and promote the benign development of CFB coal burning technology, many scholars have carried out related research on the resource utilization of CFB fly ash and slag.

Herein, the research status of resource utilization of CFB fly ash in building materials is introduced and the research results of physical and chemical characteristics of CFB fly ash are summarized. Based on this, the research progress on the applications of CFB fly ash in Portland cement, magnesium oxysulfide (MOS) cement, solid-waste–based cementitious materials (SWCM), concrete, geopolymer, artificial aggregate, and other building materials are systematically reviewed. Finally, problems that urgently require solution and some suggestions in the research of resource utilization of CFB fly ash in the field of building materials are put forward.

2. Characteristics of CFB Fly Ash

2.1. Chemical Composition. The color and properties of CFB fly ash derived from different power plants are different due to the presence of different types of substances in coal. The higher the carbon content in raw coal, the darker the color of CFB fly ash, in general, black purple or black. If the content of internal-free CaO is high, the color of CFB fly ash is relatively light. If the original CFB fly ash contains hematite, the CFB fly ash exhibits different degrees of reddish-brown color according to the content of hematite [5].

Notably, the chemical composition of CFB fly ash is basically the same as that of ordinary fly ash; however, the content of CaO and SO_3 and the loss on ignition (LOI) are higher than those of ordinary fly ash, as presented in Table 1. In order to improve the removal efficiency of SO_2 by using sulfur-fixing agents such as limestone or dolomite, the molar ratio of Ca/S is usually increased to 2.0–2.5, which results in large amount of free CaO, desulfurization product $CaSO_4$, and a small amount of unreacted $CaCO_3$ in CFB fly ash [6]. The combustion temperature of CFB boiler is 850–900°C, which is lower than that of the pulverized coal boiler (1200–1400°C), and the residence time of coal powder in CFB boiler is limited, this results in incomplete burning of a large number of inert carbons in the CFB fly ash. Moreover, still a large number of sulfur-fixing agents and sulfur-fixing products are left in the CFB fly ash, which leads to the LOI of CFB fly ash being much higher than that of ordinary fly ash [5].

2.2. Mineral Composition. CFB fly ash is mainly composed of quartz, anhydrite, calcite, and hematite. However, the crystal phase of ordinary fly ash is mainly composed of quartz, mullite, hematite, and a small amount of silicon disulfide, among which mullite with the highest content is formed from clay minerals in ordinary fly ash at above 1150°C [16]. The most significant difference in mineral composition between ordinary fly ash and CFB fly ash is that the CFB fly ash basically does not contain mullite, which is attributed to the low combustion temperature of CFB boiler that cannot reach the formation temperature of mullite [17].

2.3. Microstructural Characteristics. The microscopic morphology of CFB fly ash is very different from the spherical particles of ordinary fly ash, as shown in Figure 1(a). Almost all the particles of CFB fly ash are block- or rod-shaped irregular particles with loose and porous surface, as shown in Figure 1(b) [18]. This result is attributed to the fact that it is difficult for CFB fly ash to produce enough liquid phase at 850–900°C and after cooling, its surface cannot form smooth spherical glass beads, which result in its low density and loose surface. Moreover, the decomposition of limestone and the release of CO_2 in the reaction process can also lead to its surface loosening [5, 19]. Qian et al. [20] showed that the less the anhydrite and clay minerals content in CFB fly ash, the looser the CFB fly ash.

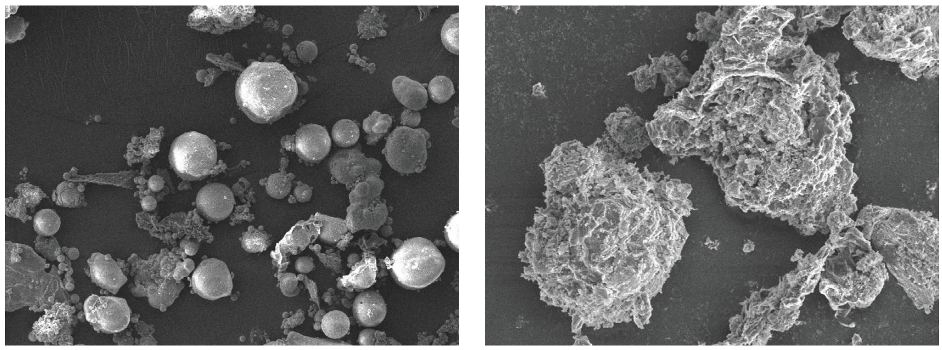
2.4. Particle Size. Song [21] observed a significant difference in particle size distribution between CFB fly ash and ordinary fly ash, which was mainly caused by two reasons. On the one hand, the way of combustion is different in the pulverized coal boiler and CFB boiler. Pulverized coal boiler consists of a pulverized system; however, CFB boiler is without the pulverized system. On the other hand, the friction of fuel coal is different between the pulverized coal boiler and the CFB boiler. In the pulverized coal furnace, the pulverized coal is mixed completely with the air, so as to carry out suspension combustion. In contrast, in CFB boiler, the pulverized coal must get fully fluidized with bed materials, which is followed by crashing, heat exchange, and combustion. Zhao et al. [16] found that the CFB fly ash derived from coal gangue power plant is dominated by fine particles with the particle size distribution between 0.1 and 16 μm, accounting for 52.89%. Nonetheless, the coarse particles in the ordinary fly ash are more, and the fine particles only account for 37.03%. However, Liu et al. [17] compared the particle size of two types of ordinary fly ash and four types of CFB fly ash, and found that the particle size distribution of these two types of fly ash was concentrated, and the particle size of 0–45 μm accounted for about 90%, and there were few fine and coarse particles.

2.5. Expansibility. The expansibility of CFB fly ash is mainly related to the content of CaO and SO_3, and SO_3 mainly exists in the form of II-$CaSO_4$. When CFB fly ash is mixed with water, the anhydrite not only gets hydrated to form gypsum, but also reacts with activated alumina and calcium hydroxide to form ettringite (Aft). The apparent solid volume of gypsum increases by 62% compared with that of anhydrite, while the apparent solid volume of Aft increases by 125% compared with that of anhydrite [22].

He et al. [19] tested the linear expansion rate of different types of CFB fly ash and found that f-CaO and SO_3 in CFB fly ash directly affected the linear expansion rate. Compared with SO_3, f-CaO exhibited a greater effect on the linear expansion rate of CFB fly ash, which increased with the increase of f-CaO. Chen et al. [23] showed that particle size of CFB fly ash directly affected its early expansibility, and further reduction in the particle size of CFB fly ash by grinding could increase its expansion activity and release the expansion at an early stage. Simultaneously, the amount of

Table 1: Chemical composition of CFB fly ash and common fly ash (%) [7–15].

Sample	SiO_2	Fe_2O_3	Al_2O_3	CaO	MgO	SO_3	f-CaO	LOI
CFB fly ash	20.17–52.78	3.54–13.35	13.74–17.76	9.84–43.86	0.86–3.76	3.86–11.61	0.6–13.60	2.75–14.70
Ordinary fly ash	43.71–54.80	5.26–13.41	21.80–35.67	2.93–8.76	0.34–1.80	0.49–2.43	0.43–3.97	2.20–7.62



(a) (b)

Figure 1: SEM images of particles of (a) ordinary fly ash and (b) CFB fly ash.

Aft produced under the condition of 80% relative humidity was much lower than that under the condition of saturated relative humidity.

2.6. Water Requirement. When CFB fly ash is used to prepare cementitious materials, the water requirement of CFB fly ash with normal consistency and that of pulverized CFB slag are usually 2–3 times and 1.5–2 times that of ordinary fly ash, respectively [19]. Figure 1(b) demonstrates that the surface of CFB fly ash is relatively loose and contains a large number of pores connected with the outside, which leads to the increase of water requirement when CFB fly ash is applied to cementitious materials. Furthermore, due to the relatively high content of free CaO and $CaSO_4$ in CFB fly ash, its hydration also requires more water [16, 24]. However, the ordinary fly ash particles with closed smooth surface exhibit a reduction in its water absorption (see Figure 1(a)) [25]. Moreover, the results indicate that the water requirement of CFB fly ash is slightly larger than that of CFB slag due to the slightly longer residence time of CFB slag in CFB boiler than that of CFB fly ash, which improves the sintering degree of CFB slag surface and reduces its water absorption [5].

2.7. Self-Hardening. Compared with ordinary fly ash, another important characteristic of CFB fly ash is self-hardening behavior. The property of CFB fly ash that can form stable compounds in water or humid air is called the self-hardening of CFB fly ash [26]. The self-hardening of CFB fly ash is spontaneous, without the addition of any additive materials. Notably, f-CaO rich in CFB fly ash is a necessary condition for its self-hardening, and $CaSO_4$ is a sufficient condition for its self-hardening [27]. Briefly, f-CaO reacts with SiO_2 and Al_2O_3 in CFB fly ash to generate C-S-H and C-A-H gels, which show certain self-hardening. Dissolved $CaSO_4$ reacts with C-A-H to generate Aft, which further increases its strength [16].

Qian et al. [27] believed that the self-hardening of CFB fly ash was related to its chemical composition to a certain extent. Moreover, the self-hardening strength was directly proportional to the content of CaO and SO_3, and the addition of calcareous sulfur-fixing agent was also significantly related to the self-hardening of CFB fly ash. Ji [28] found that the hardening rate of CFB fly ash was very fast, and the hardening degree of CFB fly ash within one day under standard curing condition was similar to the final setting degree of ordinary Portland cement. In addition, the self-hardening strength of CFB fly ash increased with age, and compressive strength could reach more than 7 MPa at 28 d. Song et al. [29] found that sulfur-fixing agent significantly influenced the early hydraulic properties of CFB fly ash, and the fly ash derived from CFB boiler without adding desulfurizer and the ordinary fly ash did not exhibit obvious hydraulic properties.

2.8. Effect of Type of Fluidization. The technologies of fluidized bed combustion are classified as bubbling fluidized bed (BFB) and CFB according to the combustion method [21]. Significant differences are observed between BFB and CFB, which are mainly shown in the following three aspects: (1) The combustion fraction of BFB is up to 75–95%, while the combustion fraction of CFB is generally 50–60%. (2) However, compared with BFB, temperature of CFB furnace is more uniform and gas–solid contact efficiency is higher, which lead to higher combustion efficiency obtained for CFB [30]. (3) Compared with CFB, BFB fits for various fuels with particle size in a wide range of 0–50 mm and lower calorific value, such as straw, peat, lignite, and coke powder [31]. The combustion efficiency of BFB is less than that of CFB; therefore, BFB fly ash has a higher carbon content [31], which results in significant increase in the carbon content of cementitious materials when BFB is utilized in concrete or cement-based materials. Carbon has an adsorptive effect on the air entraining agent; therefore, BFB fly ash leads to not only the increase in the water consumption, but also the decrease in the frost resistance of concrete. Furthermore, when preparing ceramic materials using BFB, if the carbon in the raw material is not completely burnt, the quality of ceramic green body gets degraded, simultaneously with the introduction of additional colors further affecting the appearance of ceramic materials [32].

According to the different desulfurization methods, the fly ash produced by CFB boilers is generally divided into two categories, i.e., sulfur-fixing fly ash obtained by spraying calcareous sulfur-fixing agent to fix sulfur in furnace, and the wet-desulfurized fly ash obtained via wet desulfurization in the tail of furnace flue [33]. Sulfur-fixing fly ash produced by desulfurization in furnace is characterized by a high SO_3 content with an average of about 9%, and the desulfurization product $CaSO_4$ is about 15% [34], which leads to the higher content of CaO and $CaSO_4$ in the sulfur-fixing fly ash. As mentioned earlier, due to the hydraulicity of CaO and $CaSO_4$, CFB fly ash shows obvious self-hardening. In addition, f-CaO in CFB fly ash continuously generates $Ca(OH)_2$ during long-term hydration; as a result, CFB fly ash as cement-based materials or concrete admixtures seriously affects the stability of engineering materials. Conversely, when the wet desulfurization process is adopted, the sulfur in the flue gas is mainly absorbed by the desulfurization tower located after the furnace, which makes the sulfur content in the wet-desulfurized fly ash similar to that in the fly ash generated from pulverized coal furnace. In the wet desulfurization process, calcareous sulfur-fixing agent is not sprayed into the furnace chamber or separator; thus, f-CaO in the wet-desulfurized fly ash is mostly derived from the calcium element in the coal. Furthermore, the CaO content in coal is generally about 3%, thus, CaO in the wet-desulfurized fly ash is low. Moreover, a part of the CaO enters the slag at the bottom of the furnace after combustion, which further reduces the content of CaO in wet-desulfurized fly ash [34]. Therefore, the wet-desulfurized fly ash does not undergo self-hardening and exhibits better volume stability when used as building materials. In fact, due to the higher calcium and sulfur contents of sulfur-fixing fly ash, it shows different properties from those of ordinary fly ash. The CFB fly ash discussed herein mainly refers to sulfur-fixing fly ash.

The characteristics of fly ash produced by different loads of CFB boilers are also different. For instance, Ma et al. [35] found that although CFB boiler load exhibited little effect on the particle size of CFB fly ash, chemical composition, and phase composition, owing to the large difference in boiler feed and combustion under different boiler loads, the collision, bursting, and flow of fuel particles in the boiler were different, resulting in a large difference in the morphology of CFB fly ash particles. The surface of CFB fly ash produced under load of 170 MW is relatively dense, smooth, and less porous, while that produced under load of 196 MW consists of more pores and cracks, which can directly affect the water demand of CFB fly ash when it is used for cementitious materials.

Further, according to the different pressures in the furnace, the CFB boiler can also be divided into atmospheric pressure CFB and pressurized CFB. Compared with the atmospheric pressure CFB, the pressurized CFB shows favorable characteristics such as fuel saving, reduction in pollution emissions, high combustion efficiency, and high desulfurization efficiency. Therefore, the content of $CaSO_4$ in the pressurized CFB fly ash is higher than that in the atmospheric pressure CFB, and when pressurized CFB fly ash is applied to cement-based materials, the stability of engineering materials is seriously affected. In addition, the grain size of quicklime gradually increases with the increase of combustion temperature, and the combustion temperature in the atmospheric pressure CFB boiler is the low-temperature combustion zone of limestone. The CaO generated at this time is a highly loose and porous substance [21], which directly affects the particle morphology of CFB fly ash. Therefore, the atmospheric pressure CFB fly ash leads to an increase in water demand and the amount of admixture when it is applied in cement-based building materials.

3. Application of CFB Fly Ash in Building Materials

3.1. Application of CFB Fly Ash in Portland Cement. As an excellent mineral admixture, ordinary fly ash has been widely used in Portland cement. Moreover, CFB fly ash as a type of fly ash has also been applied to Portland cement in the form of mineral admixture, and its influence on the physical and mechanical properties of cement-based materials has become the research focus of the resource utilization of CFB fly ash in building materials. Table 2 presents a brief overview on the applications of CFB fly ash in Portland cement.

Figure 2 shows the influence rule of CFB fly ash content and fineness on the compressive strength of Portland cement mortar based on summarizing the main research results. Figure 2 illustrates that although the pure paste formulations adopted by various scholars are different, the 3 days and 28 days compressive strength of CFB fly ash cement paste generally decreases with the increase in the content of CFB fly ash. Further, when the content exceeds 20%, the strength decreases significantly [36]. Despite this, if reasonable formula and mixing process of CFB fly ash are selected, the 28 days compressive strength of CFB fly ash-based Portland cement mortar can still reach more than 100 MPa, which is of great significance for the widespread application of CFB fly ash in Portland cement-based materials.

Moreover, Lee et al. [38] also studied the influence of CFB fly ash on the shrinkage and cracking performance of ordinary Portland cement and Portland slag cement. They found that the CFB fly ash exhibited little influence on the compressive strength, fracture strain, and elastic modulus of the two types of cement. Lee et al. [10] also tried to use CFB fly ash as an activator for high-content slag cement, and found that although CFB fly ash neither improved the 3 days initial strength of high-content slag cement, nor caused adverse expansion and strength reduction, it effectively reduced its early self-shrinkage. Nguyen et al. [8] carried out

Table 2: Application of CFB fly ash in Portland cement.

Content of CFB fly ash	Main raw materials	Main mechanical properties	Other properties	Role of CFB fly ash	Pretreatment of CFB fly ash	Reference
0–30%	Ordinary Portland Cement (OPC) P·O 42.5, CFB fly ash	C (3 d): 15.5–27 MPa, C (28 d): 39.2–49.7 MPa, F (3 d): 3.2–5.2 MPa, F (28 d): 6.3–9.0 MPa		The activator promotes the hydration of cement to generate $Ca(OH)_2$, thereby stimulating the potential pozzolanic activity of CFB fly ash to generate C-S-H gel with low silicon-to-aluminum ratio, promoting the hydration of cement in the positive direction and improving the early strength of cement		[36]
0–20%	OPC, ground blast furnace slag, CFB fly ash	C (3 d): 32.2–51.7 MPa, C (28 d): 57.6–63 MPa, T (28 d): 5.8–8.1 MPa	M (28 d): 34.2–52.5 MPa; reduced self-shrinkage and delayed cracking time	When CFB fly ash is mixed with other materials, a large amount of ettringite and silicate are produced due to sulfate ions and f-CaO, which can resist shrinkage and reduce self-shrinkage		[38]
0–7.5%	OPC, Class-F fly ash (FFA), commercial gypsum, CFB fly ash	C (1 d): 15–20 MPa, C (3 d): 15–35 MPa, C (7 d): 30–40 MPa, 28 d C (28 d): 48–60 MPa	DM (3 d): 15.85–16.37 GPa, DM (7 d): 17.76–18.41 GPa, DM (28 d): 18.61–20.13 GPa; DS (3 d): 6.24–6.53 GPa, DS (7 d): 7–7.18 GPa, DS (28 d): 7.05–7.54 GPa	CFB fly ash can accelerate the hydration rate of C_3S and promote the early formation of Aft, thus improving the mechanical properties of cement		[8]
0–40%	Portland cement, limestone filler, CFB fly ash	C (28 d) is similar to grade 52.5 cement, F (7 d): 4.8–6.2 MPa, F (28 d): 6.4–7.1 MPa, F (90 d): 6.5–7.5 MPa, T (28 d): 3.12–4.44 MPa	Water absorption capacity and water penetration depth are improved	When the CFB fly ash is ground into a fineness similar to that of cement, better pozzolanic activity can be obtained, thereby replacing cement clinker	Grinding, after passing 0.045 mm sieve, the cumulative residue rate was 13.6%	[37]
0–80%	P·O42.5, quartz powder, sand, CFB fly ash	C (3 d): 20.2–23.4 MPa, C (7 d): 25.8–28.9 MPa, C (28 d) h: 42.6–45.3 MPa, F (3 d): 4.7–5.4 MPa, F (7 d): 6.2–6.6 MPa, F (28 d): 9.8–11.3 MPa	The shrinkage rate is reduced	The expansion of CFB fly ash reduces the shrinkage of cement mortar	Grinding, $d_{50} = 22.38\,\mu$m, $d_{50} = 12.22\,\mu$m, $d_{50} = 10.19\,\mu$m, $d_{50} = 8.43\,\mu$m	[7]

Table 2: Continued.

Content of CFB fly ash	Main raw materials	Main mechanical properties	Other properties	Role of CFB fly ash	Pretreatment of CFB fly ash	Reference
30–70%	Cement, ordinary PFA, CFB fly ash		Yield stress: 0.57–3.04 Pa; plastic viscosity: 0.11–1.92 Pa·s; the slurry fluidity of cementitious materials is improved	After grinding, the particle surface roughness and porous structure of the CFB fly ash are improved, and the water absorption rate is reduced, thereby improving the fluidity of the slurry	Grinding, $d_{50} = 5–50\,\mu m$	[14]

Note. C (3 d)—3 d compressive strength; F (3 d)—3 d flexural strength; T (28 d)—28 d tensile strength; M (28 d)—28 d modulus of elasticity; DM (3 d)—3 d dynamic young's modulus; DS (3 d)—3 d dynamic shear modulus.

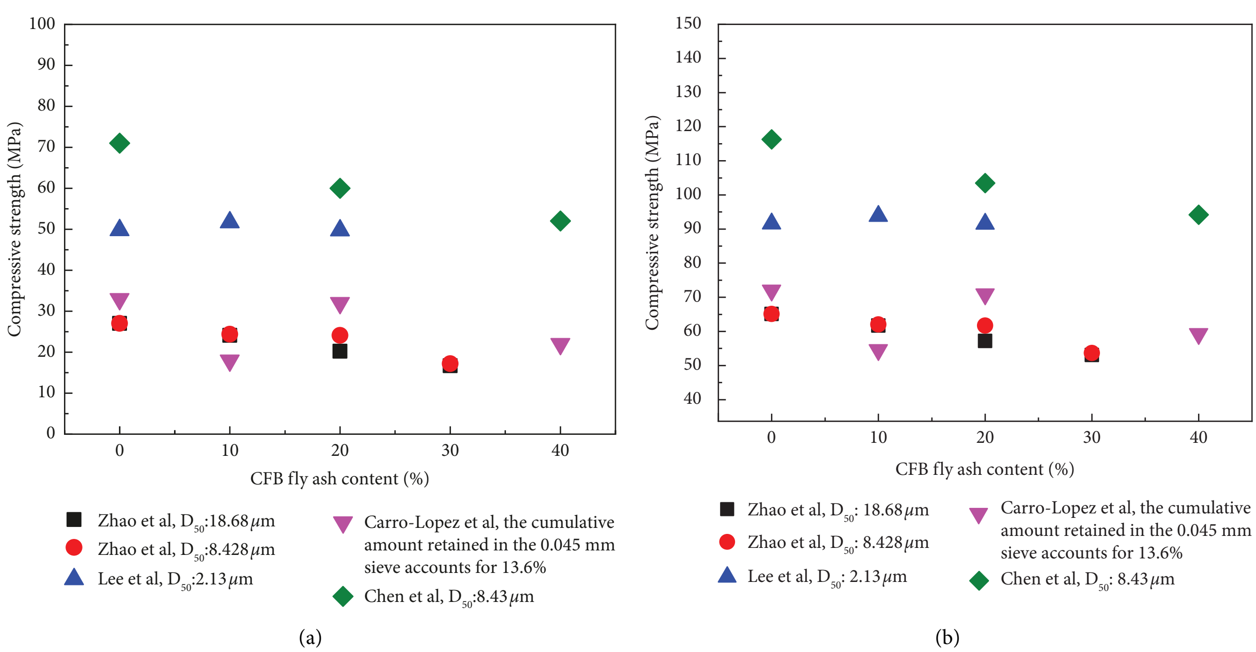


Figure 2: Influence of CFB fly ash content and fineness on compressive strength of Portland cement mortar. ((a) Compressive strength after 3 days and (b) Compressive strength after 28 days) [7, 36–38].

scanning electron microscopy (SEM) and X-ray diffraction (XRD) analysis and found that SO_4^{2-} and OH^- could accelerate the hydration reaction of C_3S and the early precipitation of Aft, and confirmed that addition of CFB fly ash could improve the early mechanical properties of high-content low-calcium fly ash cement paste. When CFB fly ash (2.5–5%) was used to replace class-F ordinary fly ash, the compressive strength after 1, 3, 7, and 28 days of high-content low-calcium fly ash cement increased by 21.3%, 33.95%, 32.4%, and 23.1%, respectively.

The soundness of cement is one of the important indexes that is used to evaluate the cement performance, which mainly describes the volume change of the hardening cement after hydration reaction, such as deformation or cracking. Owing to its expansibility, CFB fly ash directly affects the properties of cement when it is used in cement mixture. Therefore, in order to control the expansion of CFB fly ash, physical grinding can be carried out to further release the expansion source in the CFB fly ash, which sufficiently promotes the hydration reaction of CFB fly ash before the cement hardening [39]. As shown in Figure 2, Carro-López et al. [37] found that when finely ground CFB fly ash was added to the cement at a ratio of 10%, 20%, and 40%, respectively, the composite cement showed high mechanical strength at 28 days, and the compressive strength was similar to that of P·O 52.5 cement. Even though the content of finely ground CFB fly ash was up to 40%, the porosity and permeability of the composite cement did not change obviously. Moreover, similar to that shown in Figure 2, Zhao et al. [36] prepared cement mortar with two types of CFB fly ash with median particle sizes of 8.428 and 18.68 μm, respectively. The results showed that the particle size of CFB fly ash slightly influenced the compressive strength of mortar irrespective of the aging days, i.e., 3 days or 28 days. This result is mainly attributed to the fact that the particle size gradation of the CFB fly ash does not meet the compact packing model, thus, the gradation has little influence on the compressive strength. However, as shown in Figure 2, in general, the finer the CFB fly ash, the larger the compressive strength of Portland cement mortar, and the fineness exhibits a greater influence on the early compressive strength of Portland cement mortar.

Furthermore, Chen et al. [7] also found that the finely ground CFB fly ash could not only improve the mechanical strength of cement mortar, but also contribute to the cement mortar to rapidly compete the expansion and quickly reach the maximum expansion value. Compared with ordinary cement mortar, the sample mixed with CFB fly ash exhibited higher expansion rate and smaller shrinkage rate. Zheng et al. [14] found that particle size distribution of CFB fly ash cement system was the main factor affecting its rheological properties. When the replacement amount of CFB fly ash ($d_{50} = 56\,\mu$m) to cement was less than 50%, the rheological properties of the cement slurry showed Bingham fluid characteristics. When the replacement amount of CFB fly ash reached 70%, the slurry exhibited the characteristics of modified Bingham fluid model. However, the rheological properties of the cement slurry with ultrafine CFB fly ash ($d_{50} = 5\,\mu$m) followed the Herschel-Bulkey model.

Furthermore, in order to release the expansion source of cement mortar in advance, ordinary fly ash can be mixed to improve the physical properties of cement mortar. Nguyen et al. [40] studied the effects of low-calcium class-F fly ash (FFA) on the compressive strength and hydration products of low energy super-sulfated cement (SSC) mixed with CFB fly ash as activator. They found that the compressive strength of SSC could be significantly increased by replacing blast furnace slag with 10–30% FFA, and increasing the dosage of FFA could significantly increase the yield of Aft, single sulfate, and calcium aluminate silicate hydrate (C-A-S-H).

3.2. Application of CFB Fly Ash in Magnesium Oxysulfide Cement. Magnesium oxysulfide (MOS) cement is a type of nonhydraulic cementitious material, which is a ternary cementitious system of MgO-$MgSO_4$-H_2O prepared with active MgO and a certain concentration of $MgSO_4$ solution. Compared with Portland cement, it offers the advantages such as high early strength, light weight, low density, good air stability, and environmental protection [41]. Reasonable control of the dosage of CFB fly ash can improve the mechanical properties of MOS cement. Table 3 summarizes the application of CFB fly ash in the MOS cement. Xu et al. [42] found that compared with MOS cement without CFB fly ash, the compressive strength of MOS cement increased by 48.37%, 33.33%, and 22.02% in 3, 7, and 28 days, when the content of CFB fly ash reached 20%. Moreover, when the CFB fly ash content is in the range of 4–8%, the water resistance of MOS cement gets significantly improved. In addition, the CFB fly ash can improve the volume stability of MOS cement. The linear expansion rate of MOS cement mixed with CFB fly ash increases rapidly in the early curing stage, and basically remains unchanged in the late curing stage. Also, the linear expansion rate of MOS cement decreases gradually with the increase of the content of CFB fly ash. Xu et al. [43] found through comprehensive analysis of XRD and SEM results that when the content of CFB fly ash was 20%, corresponding to the molar ratio of α-MgO : $MgSO_4 : H_2O$ being 12 : 1 : 16 in MOS cement, the $Mg(OH)_2$ or MgO in the MOS cement was expected to fill the acicular or columnar 5·1·7 phases to form a three-dimensional (3D) continuous network. In this case, MOS cement matrix exhibited higher strength. When the content of CFB fly ash exceeded 40%, the formation of 5 1 7 phase was seriously affected, which resulted in the reduction of the strength of MOS cement.

Next, Xu et al. [44] found that addition of finely ground CFB fly ash into MOS cement could also increase the compressive strength of MOS cement, and when the median particle size of CFB fly ash was 12.94 μm and the dosage was 8%, the maximum compressive strength could reach 80.7 MPa at 28 d.

3.3. Application of CFB Fly Ash in SWCM. SWCM, as an effective supplement and substitute of traditional cementitious material, has always been a research hotspot in the field of solid waste and building materials because of its high utilization rate of solid waste and low carbon emissions in the production process. Many scholars have also made an attempt to use CFB fly ash as raw material to prepare non–cement-based solid waste cementitious materials, as presented in Table 4.

Machowska et al. [45] studied the early hydration process and physical and mechanical properties of CFB fly ash-slag cementitious material system, and found that the higher the CFB fly content, the more intense the hydration reaction process, which resulted in shorter initial setting time and higher early compressive strength. Hlavacek et al. [46] synthesized a ternary cementitious material with CFB fly ash, ordinary fly ash, and calcium hydroxide, and at the same time, investigated the phase volume evolution process of this ternary cementitious material system. The results showed that the compressive strength of the ternary cementitious material was 32 MPa after curing for 28 days. Hermawan et al. [47] studied the physical and mechanical properties of another ternary cementless cementitious materials made of fine-grained blast furnace slag, pulverized FFA, and CFB fly ash at different temperatures. They found that the compressive strength of this ternary cementless cementitious material could be increased to 30 MPa when the content of CFB fly ash was 15% and the pulverized FFA was 10–30%, and this ternary cementless cementitious mortar exhibited good durability and heat resistance at temperature below 400°C.

Kang and Choi [9] prepared nonsintered zero-cement binders using two types of CFB fly ash with different f-CaO contents and other solid wastes such as ordinary fly ash, silica fume, and ground-granulated blast furnace slag. The

Table 3: Application of CFB fly ash in MOS cement.

Content of CFB fly ash	Main raw materials	Main mechanical properties	Other properties	Role of CFB fly ash	Pretreatment of CFB fly ash	Reference
0–20%	$MgSO_4 \cdot 7H_2O$, $MgSO_4$, CFB fly ash, $C_6H_8O_7$	C (3 d): 42.5–63.8 MPa, C (7 d): 54–72 MPa, C (28 d): 58–73.7 MPa	Water resistance improved; volume stability increased; after adding CFB fly ash, the linear expansion rate decreased from 4.527×10^{-3} to 0.444×10^{-3}	The addition of CFB fly ash makes the particle size distribution of the raw material closer to the ideal sieve curve of the optimal bulk density, and significantly reduces the porosity of the gelling system		[42]
0–60%	$MgSO_4 \cdot 7H_2O$, MgO, CFB fly ash, $C_6H_8O_7$	C (7 d): 35–80 MPa, C (28 d): 50–95 MPa; F (7 d): 2–13 MPa, F (28 d): 5–16 MPa	Magnesium oxysulfide cement slurry fluidity decreased	The gypsum and ettringite produced by the hydration reaction of the CFB fly ash increase the strength. In addition, the CFB fly ash and unreacted MgO particles can be filled in the 3D continuous network structure of MOS cement to improve the compressive strength		[43]
0–20%	$MgSO_4 \cdot 7H_2O$, light-burned magnesia powder, CFB fly ash	C (3 d): 57–70 MPa, C (7 d): 65–76 MPa, C (28 d): 65–80.7 MPa		The active SiO_2 in the CFB fly ash can prolong the curing time and reduce the softening coefficient, and f-CaO can shorten the setting time. Active SiO_2, f-CaO and SO_3 can increase the compressive strength	Grinding, $d_{50} = 6.62–22.45\,\mu m$	[44]

Table 4: Application of CFB fly ash in SWCM.

Content of CFB fly ash	Main raw materials	Main mechanical properties	Other properties	Role of CFB fly ash	Reference
30–70%	Ground granulated blast furnace slag (GGBFS), CFB fly ash	C (2 d): 1.21–1.48 MPa	The initial setting time is shortened from 472 to 378 min	CFB fly ash promotes the hydration reaction, so that the cementitious material has a short initial setting time and a high early compressive strength	[45]
15%	GGBFS, FFA, CFB fly ash	Compressive strength can be increased to 30 MPa	The temperature is from 200 to 400°C, the strength loss of SFC mortar is less than 8%, and it has good durability and heat resistance	CFB fly ash particles contain high levels of f-CaO and $CaSO_4$, which induce solidification and hardening processes when in contact with an aqueous solution characterized by self-cementing behavior, while producing hydration products and increasing strength	[47]

Table 4: Continued.

Content of CFB fly ash	Main raw materials	Main mechanical properties	Other properties	Role of CFB fly ash	Reference
25–100%	GGBFS, OPC, fly ash CFB fly ash	C (28 d): 4–16 MPa, C (91 d): 5–20 MPa	Sulfate resistance, frost resistance, and carbonization resistance were improved	Ca-based minerals, such as CaO, $CaSO_4$, $Ca(OH)_2$, and $CaCO_3$, present in CFB fly ash can act as alkaline activators to promote the reaction with blast furnace slag	[48]
0–35%	GGBFS, OPC, CFB fly ash	W/B = 0.3–0.4, C (7 d): 16.8–72 MPa, C (28 d): 18–86.1 MPa, C (56 d): 17.4–96.8 MPa; T (7 d): 0.865–1.96 MPa, T (28 d): 1.71–4.69 MPa, T (56 d): 2.74–5.34 MPa	Drying shrinkage reduced	The hydration product of CFB fly ash improves the compressive and tensile properties of the cementitious material	[49]
15–25%	GGBFS, CFB fly ash	C (28 d): 45–70 MPa	Drying shrinkage reduced	After adding CFB fly ash, the hydration products of the cementitious material are ettringite, calcium silicate hydrate, and calcium aluminate silicate hydrate, so that the cementitious material has a suitable setting time, and acquires a dense microstructure after hardening	[50]
0–25%	Slag, CFB fly ash	C (28 d): 40–70 MPa	After 143 days of continuous exposure in Na_2SO_4 solution, the highest strength loss rate is about 15%, and the resistance to sulfate attack is good	The self-hardening property of CFB fly ash promotes the rapid growth of the early strength of the cementitious material, and the slow-release pozzolanic activity of CFB fly ash promotes the sustained growth of the later strength of the cementitious material	[51]
20%	Blast-furnace slag, CFB fly ash	C (28 d): 75 MPa		CFB fly ash produces hydration products with good properties and forms a dense structure, which endows the material with sufficient strength	[52]

experimental results showed that when the content of f-CaO in CFB fly ash was 9–17%, the compressive strength and setting characteristics of the zero-cement binders were in a reasonable range.

Zhang et al. [48] prepared zero-cement mortar with CFB fly ash, blast furnace slag, and recycled aggregate. They found that the zero-cement mortar exhibited better sulfate resistance than ordinary cement mortar. When the ratio of CFB fly ash to blast furnace slag was 75 : 25, the compressive strength after 91 days was found to be about 28 MPa. Under the condition that the water–binder ratio was 0.4, the compressive strength of zero-cement mortar mixed with a certain amount of blast furnace slag gypsum and $Ca(OH)_2$ could be increased to 40 MPa at 28 days and 50 MPa at 91 days. When the water–binder ratio was reduced, the freezing resistance and carbonization resistance of zero-cement mortar got improved.

As mentioned above, blast furnace slag-CFB fly ash composite cementitious material (SCFC) as a new green solid-waste cementitious material is prepared mainly with blast furnace slag and CFB fly ash. The results show that the water-cement ratio exhibits a certain influence on the hydration rate and crystal growth rate of CFB fly ash. Increase in the water-cement ratio can increase the dissolution amount of f-CaO and anhydrite, and reduce the possibility of later expansion of the SCFC. However, if the water-cement ratio is too high, the crystallization of hydration products can be accelerated, which easily causes interpenetration and repulsion between crystals, thus increasing the expansion degree of the SCFC. If the water-cement ratio is too low, the hydration reaction remains incomplete, resulting in the generation of a large number of holes in the SCFC [39]. Therefore, a reasonable water-cement ratio can improve the physical properties of materials. Dung et al. [49] found that when CFB fly ash and slag were mixed at the water-cement ratio of 0.3 and CFB fly ash content of 25%, the compressive strength and tensile strength of SCFC could reach more than 80 and 4.6 MPa, respectively, in 28 days. Notably, the hydration products of SCFC are Aft, calcium silicate hydrate (C-S-H), and calcium aluminate silicate hydrate (C-A-S-H), the slurry of this cementitious material system exhibits appropriate setting time and dense microstructure after hardening, which endows it with good mechanical strength [50].

Figure 3 shows the development trend of compressive strength of SCFC with aging corresponding to different CFB fly ash content. Figure 3 demonstrates that when the water-cement ratio W/B = 0.4, the compressive strength growth rate of SCFC increases gradually within 28 days with the addition of CFB fly ash from 15% to 30%; however, the compressive strength decreases significantly with the increase in the dosage of CFB fly ash irrespective of their aging time. Furthermore, when the content of CFB fly ash is less than 30%, the compressive strength of SCFC tends to be gentle after 28 days; in contrast, when the content reaches 30%, the compressive strength still exhibits a significant increase after 28 days. Under the condition of high content of CFB fly ash, the rapid growth of early strength may be related to the self-hardening of CFB fly ash, while the sustained growth of late strength may be related to the slow release of the pozzolanic activity by CFB fly ash. In addition, the expansion ability of SCFC, derived from the mixing of CFB fly ash, compensates for its drying shrinkage, so that it has a low limit shrinkage and a better sulfate erosion resistance. The results show that, when SCFC specimens were continually exposed to Na_2SO_4 solution for 143 days, the strength loss rate of SCFC specimens was the lowest at 5% and the highest at 15% [51]. Owing to the formation of hydration products of SCFC with good performance and dense microstructure, the SCFC acquires sufficient strength, which makes it a potential candidate for a building material for practical civil engineering structures [52].

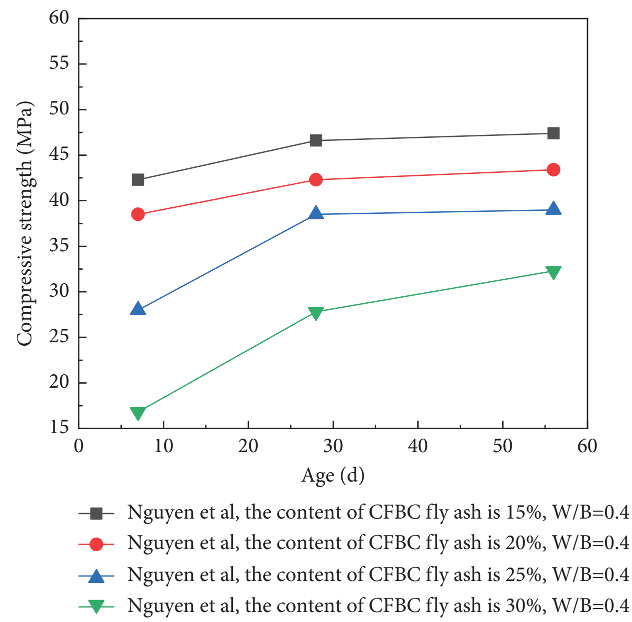


Figure 3: Effect of CFB fly ash content and age on the compressive strength of SCFC [49–52].

3.4. Application of CFB Fly Ash in Concrete Material. In view of the fact that the rational use of CFB fly ash in various types of cement is of beneficial influence on the physical and mechanical properties of cement, and also leads to the improvement in the utilization efficiency of CFB fly ash and significant reduction in the cost of building materials, many scholars have also further attempted to apply CFB fly ash to light-weight concrete materials and normal concrete materials, such as aerated concrete (AC), roller compacted concrete (RCC), and self-compacting concrete (SCC), in order to improve the physical and mechanical properties of these concrete materials, as presented in Tables 5 and 6.

3.4.1. Application of CFB fly Ash in Light-Weight Concrete. Recently, CFB fly ash has been successfully used in the preparation of light-weight concrete. As a building material with excellent performance, light-weight concrete has been extensively used in the building walls or infilled walls of high-rise frame structure because of its light weight, good sound absorption and thermal insulation properties, and good seismic performance. Glinicki and Zielinski [53] used automatic image analysis program to study and conclude that CFB fly ash replacing part of cement could form a good pore structure system in AC. Song et al. [12] found that the maximum dry density, compressive strength, and volume stability of autoclaved aerated concrete (AAC) containing CFB fly ash were higher than those of AAC containing ordinary fly ash, and satisfactory mechanical properties could be obtained when the Ca/Si ratio of CFB fly ash AAC was higher than that of ordinary fly ash AAC. Wu et al. [13] studied the influence of water requirement and water reducing agent on CFB fly ash AAC. They found that higher water consumption was not conducive to the improvement of the compressive strength of AAC, while lower water consumption was not conducive to the C-S-H gel produced by cement hydration. Reasonable water consumption not only prevented the change in the bulk density of AAC, but also improved its strength. The addition of water reducing agent could improve the rheological properties of slurry and optimize the pore structure, thus playing a positive role in improving the physical and mechanical properties of CFB fly ash AAC. Xia et al. [54] prepared AAC with CFB fly ash as the main raw material. Based on the results of the mechanical test, they found that the reasonable dosages of CFB fly ash, cement, and lime in AAC were 65.5%, 22%, and 10%, respectively, and the median particle size of CFB fly ash of 9.6–23.9 μm was the most suitable for the preparation of AAC. Chen et al. [55] found that the self-expansion property of CFB fly ash could compensate for the shrinkage of AAC, and the compressive strength of AAC could be improved by grinding the CFB fly ash and reducing the water-solid ratio of slurry. Figure 4 shows the compressive strength of AAC prepared using CFB fly ash with different fineness obtained by Xia et al. [54, 55] under different water-solid (W/S) ratios.

Table 5: Application of CFB fly ash in light-weight concrete.

Concrete type	Content of CFB fly ash	Main raw materials	Main mechanical properties	Other properties	Role of CFB fly ash	Pretreatment of CFB fly ash	Reference
AC	20–40%	OPC CEM I 32.5 R, crushed basalt aggregates, sand, CFB fly ash	C (7 d): 44.9–47.5 MPa, C (28 d): 49.7–56.4 MPa		The unburned carbon in CFB fly ash significantly increases the adsorption capacity of the concrete, resulting in a larger pore spacing coefficient, the concrete forms a satisfactory void system		[53]
ACC	17–25%	CFB fly ash, fly ash, cement	Compressive strength: 5.25–10.25 MPa	Higher volume stability	CFB fly ash enables ACC to have a higher calcium-silicon ratio, thereby improving pore structure		[12]
ACC	65.5–70.5%	CFB fly ash, PCC fly ash, cement, phosphogypsum	C (7 d): 2.4–13.5 MPa, C (28 d): 12.2–18.7 MPa	Yield stress and bonding strength reduced	CFB fly ash is solidified and hardened with water, thereby increasing the strength of the concrete	Grinding, $d_{50} = 9.6–23.9\ \mu m$	[54]
ACC	30–80%	Aluminate cement, Portland cement, CFB fly ash	Compressive strength: 2.2–3.3 MPa	Drying shrinkage reduced	The self-expansion of CFB fly ash can compensate for the shrinkage of ACC	Grinding, $d_{50} = 8.43–22.38\ \mu m$	[55]

Table 6: Application of CFB fly ash in normal concrete.

Concrete type	Content of CFB fly ash	Main raw materials	Main mechanical properties	Other properties	Role of CFB fly ash	Pretreatment of CFB fly ash	Reference
RCC	0–15%	Cement, CFB fly ash, river sand	C (3 d): 13–19 MPa, C (7 d): 21–26 MPa, C (28 d): 26.2–34.9 MPa		CFB fly ash has good self-gelling properties, and can improve the splitting tensile strength and sulfate corrosion resistance of concrete		[56]
RCC	0–30%	CFB fly ash, OPC, coarse aggregates, gravel, river sand	C (3 d): 24–30 MPa, C (7 d): 28–41 MPa, C (28 d): 33–48 MPa; F (28 d): 3.49–6.89 MPa	The initial setting time is shortened by 30–60%, and the final setting time is shortened by 16–20%. Sulfate resistance enhanced	CFB fly ash contributes to the strength development of concrete in later period		[57]
Slag-fly ash-CFB fly ash SCC	0–50%	Slag, FFA, CFB fly ash	C (28 d): 32.3–42.6 MPa; tensile strength: 3–5.4 MPa; bonding strength: 18–22.8 MPa		CFB fly ash has good fluidity and filling ability, and increases the mechanical properties and bonding properties of concrete		[58]

Table 6: Continued.

Concrete type	Content of CFB fly ash	Main raw materials	Main mechanical properties	Other properties	Role of CFB fly ash	Pretreatment of CFB fly ash	Reference
Slag-fly ash-CFB fly ash SCC	15–25%	GGBFS, FFA, CFB fly ash	C (7 d): 34–62 MPa, C (28 d): 41.8–65.6 MPa, C (150 d): 52–82 MPa	DM (7 d): 31.8–37 GPa, DM (28 d): 33.4–38.8 GPa, DM (150 d): 34.2–40.4 GPa; DS (7 d): 12.2–14.3 GPa, DS (28 d): 12.6–15.1 GPa, DS (150 d): 12.6–15.6 GPa	CFB fly ash stimulates the hydration properties of concrete, resulting in better durability and mechanical strength		[59]
Cement-based SCC	0–7.5%	OPC, FFA, CFB fly ash	C (3 d): 25.6–34.9 MPa, C (7 d): 30.3–40.0 MPa, C (28 d): 49.3–60.7 MPa	The bond strength between concrete and steel bars increased by nearly 10%, the durability improved	The f-CaO contained in the CFB fly ash promotes the hydration of OPC and FFA particles		[60]
Non–cement-based SCC	15%	GGBFS, FFA, CFB fly ash	C (28 d): 40.22 MPa	The lowest water absorption rate being 3.66%. The volume of permeable voids being 8.54%. Good durability	The paigeite in the CFB fly ash can react with SiO_2 or Al_2O_3 in blast furnace slag to form C-(A)-S-H gel, which stimulates the hydration of blast furnace slag and improves the strength		[61]
RPC	10%	OPC P·O52.5R, silica fume, CFB fly ash		The carbonization depth of 28 d being almost 0, and with better carbonization resistance. The mass loss being almost zero after freeze-thaw cycles of 350 times, and with better frost resistance. Better sulfate resistance	CFB fly ash improves the compactness of concrete, thereby improving the carbonization resistance. CFB fly ash also reduces the alkalinity of the liquid phase in the gel system and the harmful expansion, and enhances the sulfate resistance	Grinding, $d_{50} = 12.75–23\ \mu m$	[62]
RPC	0–15%	P·O42.5R, CFB fly ash, silica fume, quartz sand	C (7 d): 47.9–109.9 MPa, C (28 d): 71.3–132.2 MPa; F (7 d): 8.9–19.2 MPa, F (28 d): 10.3–22.7 MPa	Drying shrinkage reduced	CFB fly ash enhances the bonding ability of ettringite and other hydration products, thereby improving the strength of concrete. Anhydrite and free calcium oxide in CFB fly ash can also improve the self-shrinkage of concrete		[63]

Figure 4 demonstrates that the fineness (or median particle size) of CFB fly ash and W/S exhibits a significant influence on the compressive strength of CFB fly ash AAC. With the increase of W/S ratios, the compressive strength of CFB fly ash AAC decreases significantly. However, with the decrease of median particle size D50, the compressive strength of CFB fly ash AAC increases gradually, and the compressive strength of CFB fly ash AAC can reach more than 7 MPa.

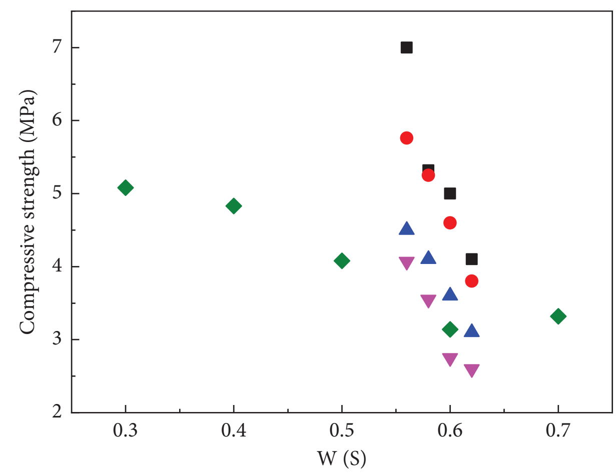


Figure 4: Influence of fineness of CFB fly ash and W/S ratio on compressive strength of CFB fly ash AAC [54, 55].

3.4.2. Application of CFB fly Ash in Normal Concrete. Some scholars have also tried to apply CFB fly ash to the preparation of RCC, which is a type of dry-hard concrete with no collapse degree. RCC was initially used in the construction of dam on water resources, and then in the construction of low-speed road pavement and parking lots. With the improvement of technology, RCC has been used to pave higher level of highway. Chi and Huang [56] showed that CFB fly ash contains high CaO and SO_3 contents and has a high LOI, which not only endows the RCC with high water absorption rate, but also effectively reduces the initial surface adsorption rate, which represents the permeability of RCC. Finally, CFB fly ash shows a positive effect on the compressive strength, splitting tensile strength, and sulfate resistance of RCC. Chi and Huang [56] suggested that fine aggregate could be replaced with 5% CFB fly ash in RCC, and the optimal rolling pressure could be 75 $g{\cdot}cm^{-2}$. Furthermore, based on SEM and XRD test results, Lin et al. [57] confirmed that the density of C-S-H gel improved and the content of $Ca(OH)_2$ gradually increased with the increase of the amount of CFB fly ash replacing fine aggregate. They also believed that the performance of RCC was the best when CFB fly ash was used instead of 10% fine aggregate and the rolling pressure was 100 $g{\cdot}cm^{-2}$. Figure 5 shows the relationship between compressive strength and age of RCC obtained by Chi and Huang [56] under different contents of CFB fly ash. Figure 5 illustrates that the compressive strength of RCC decreases with the increase of CFB fly ash content. The compressive strength of RCC mixed with CFB fly ash increases rapidly before 7 days, the strength increases slowly after 7 days; nonetheless, the compressive strength still increases gradually with age.

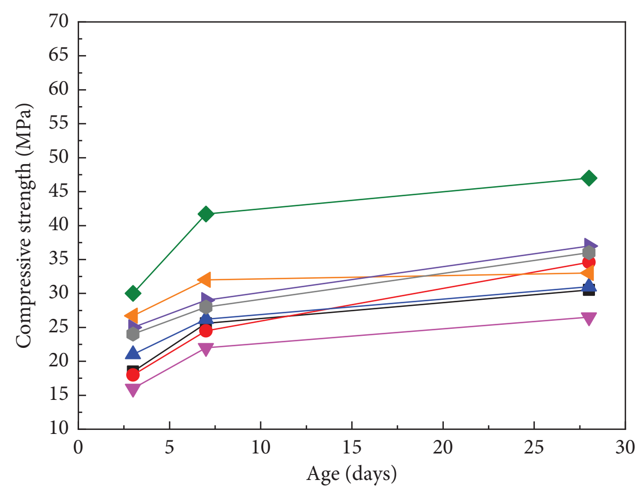


Figure 5: Influence of age on compressive strength of RCC with different contents of CFB fly ash (rolling pressure = 50 $g{\cdot}cm^{-2}$) [56, 57].

Furthermore, Nguyen et al. [58] tried to prepare SCC using three industrial by-products including slag, class-F ordinary fly ash, and CFB fly ash. They found that the hydration reaction of slag-fly ash-CFB fly ash SCC could be effectively triggered when the content of CFB fly ash was 15% of the mass of class-F ordinary fly ash and pulverized blast furnace slag mixture. At this time, the 28 days compressive strength of slag-fly ash-CFB fly ash SCC could reach 41.8–65.6 MPa. Moreover, when the content of class-F fly ash reached 30%, the slag-fly ash-CFB fly ash SCC exhibited better fluidity and durability [59]. In addition, Nguyen et al. [60] also found that addition of CFB fly ash could significantly improve the compressive strength, bond performance, and durability of cement-based SCC with high volume of low-calcium fly ash. Compared with the performance of cement-based SCC modified with FFA, the compressive strength of 1, 3, 7, and 28 days of self-compacting concrete could be increased by 43.8%, 30.2%, 22.3%, and 17.8% by adding 3.63% CFB fly ash, respectively. Furthermore, the bonding strength of cement-based SCC and steel bar increased by about 10% after the addition of a small amount of CFB fly ash. Further, Djayaprabha et al. [61] found that the paigeite in CFB fly ash could react with SiO_2 or Al_2O_3 in blast furnace slag to generate C-A-S-H gel, which stimulated the hydration of blast furnace slag and improved the strength of non–cement-based SCC.

Notably, CFB fly ash can also be used in the preparation of reactive powder concrete (RPC). RPC is a type of cementitious material with high strength and durability, it was developed in 1990s. Zhang et al. [62] studied in detail the long-term performance and durability of RPC mixed with CFB fly ash. The study showed that due to the pozzolanic effect of CFB fly ash, the density of RPC improved, which made CO_2 difficult to enter inside RPC and resulted in the carbonization depth of RPC at 28 days being almost zero, thus proving that RPC mixed with CFB fly ash showed good carbonization resistance. Next, the freeze-thaw cycles test results showed that when the freeze-thaw cycles reached 350 times, the mass of RPC was equal to that at the beginning of the freeze-thaw cycles, and RPC showed good frost resistance. In addition, the RPC added with CFB fly ash was soaked in 5% Na_2SO_4 solution for 28 days, and showed good sulfate resistance. Gao et al. [63] found that the early strength of RPC containing added CFB fly ash under humid and heat curing condition was about 30 MPa, which was higher than that of standard curing. Under humid and heat curing condition, the early shrinkage of RPC was promoted and the drying shrinkage was reduced in later period, which further proved that the expansion property of CFB fly ash could effectively improve the self-shrinkage of RPC.

In other types of concrete, CFB fly ash also exhibits a significant effect on their performance. Horszczaruk and Brzozowski [64] applied CFB fly ash to prepare underwater concrete, and found that with the increase of CFB fly ash content, the 28 days compressive strength of underwater concrete decreased. However, after 56 days of aging, the compressive strength of underwater concrete with 30% CFB fly ash content was close to that of underwater concrete without CFB fly ash.

3.5. Application of CFB Fly Ash in Geopolymer. Geopolymers were first proposed by a French scientist Joseph Davidovits [65]. After more than 40 years of development, the preparation technology of geopolymer has become mature. Geopolymers are made from raw materials rich in silica (Si^{4+}) and alumina (Al^{3+}) (such as kaolin and fly ash.) through geological polymerization process. In this process, aluminosilicates (such as fly ash) react with alkaline polysilicates to form a type of hardened material with $[Si\text{-}O\text{-}Al\text{-}O]_n$ present in 3D polymerization chain and ring structure [66, 67]. Geopolymers are widely used because of the following advantages: (1) High-temperature stability: Compared with ordinary Portland cement, the 3D network structure of geopolymer endows it with better fire resistance and heat resistance properties. (2) Green and environmentally friendly: The preparation process of geopolymer produces less harmful gas and consumes less energy. (3) Good mechanical properties: The $[Si\text{-}O\text{-}Al\text{-}O]_n$ skeleton of geopolymer endows it with hardness similar to that of ceramics. (4) Good corrosion resistance to acid: Owing to the presence of Si-O and Al-O in internal structure of geopolymer, it is difficult for it to undergo reaction with acid at room temperature. (5) Geopolymer can effectively absorb metal ions and other toxic substances [68]. Therefore, many scholars have explored the application of CFB fly ash in geopolymers, and studied the effect of CFB fly ash on geopolymers, as presented in Table 7.

Although CFB fly ash undergoes certain self-hardening, it is difficult to be widely used in the preparation of building materials. Therefore, appropriate activators must be added to improve the properties of CFB fly ash building materials. In the alkali-activated mechanism, the bridge oxygen bond of Al_2O_3 and SiO_2 network structure is broken by alkali metal or alkali metal ion, thus the silicon oxygen tetrahedron is released and the hydration reaction gets accelerated [39]. In terms of preparation of CFB fly ash geopolymer, Chen et al. [69] used sodium silicate and NaOH as a compound alkaline activator, and found that the main characteristic peak strength of Si-O-Al or Si-O-Si for geopolymer was the highest when the molar mass ratio of NaOH to CFB fly ash was in the range of 2.5–3.1 $mol{\cdot}kg^{-1}$, and the strength of CFB fly ash geopolymer reached the maximum. When the molar mass ratio of NaOH to CFB fly ash was greater than 3.1 $mol{\cdot}kg^{-1}$, the main characteristic peak position of Si-O-Al or Si-O-Si changed to low wave number, and the strength of geopolymer decreased gradually with the increase of alkali content. This is mainly attributed to the fact that when the ratio of NaOH to CFB fly ash is higher, the high alkalinity in the cementitious system of geopolymer, on the one hand leads to the polycondensation of the silica-aluminum groups being prohibited, and on the other hand leads to the precipitation of silica-aluminum gel before reaction [70]. Xu et al. [71] attempted the alkali fusion method to enhance the reactivity of CFB fly ash, and to maintain the Na/Al balance in geopolymer by adding aluminosilicate, which made the CFB fly ash with low reactivity a potential raw material to prepare geopolymer. Huo et al. [72] found that when the modulus of sodium silicate was 1.5, the dosage was 25%, the alkali content was 30%, and the curing temperature was 90°C, the 7 days compressive strength of CFB fly ash geopolymer could fetch up to 58.9 MPa. It was also proven that the low temperature curing could ensure the medium water that dissolved the structure elements to smoothly migrate during the formation of geopolymer, which also endowed the CFB fly ash geopolymer with better high-temperature resistance. Chindaprasirt et al. [73] used high concentrations of NaOH and $Al(OH)_3$ to control the formation of Aft in CFB fly ash geopolymer. They found that addition of NaOH (15 mol) could promote the formation of $Ca(OH)_2$, which could stimulate the pozzolanic active reaction of CFB fly ash, and ultimately enhanced the strength of geopolymer. The addition of 2.5% $Al(OH)_3$ could promote the reaction to form a dense aluminum silicate compound; however, when the amount of $Al(OH)_3$ was 5%, the mechanical properties of the CFB fly ash geopolymer got weakened.

Furthermore, research studies were also carried out on the solidification of heavy metals using geopolymers. For instance, Xu et al. [74] studied the performance and mechanism of CFB fly ash geopolymer for solidifying chromium sludge. The results showed that the chromium in the sludge was possibly solidified in the form of physical encapsulation in the CFB fly ash geopolymer. Moreover, the amount of maximum solidification for heavy metals of

Table 7: Application of CFB fly ash in geopolymer.

Content of CFB fly ash	Main raw materials	Main mechanical properties	Role of CFB fly ash	Processing technology of CFB fly ash	Reference
73–81%	NaOH, sodium silicate, CFB fly ash	C (1 d): 2.5–5.5 MPa, C (7 d): 4–6 MPa	Si and Al in the CFB fly ash promote the geologic polymerization reaction, which increases the strength		[69]
30–70%	CFB fly ash, metakaolin	C (7 d): 13.1–49.5 MPa	The SiO_2 in the CFB fly ash reacts with sodium hydroxide, and is converted into aluminosilicate after being treated by the alkali fusion method, which leads to the enhanced dissolution of Si and Al in CFB fly ash aqueous solution, and effectively improves the geopolymerization activity of CFB fly ash		[71]
50%	CFB fly ash, metakaolin	C (7 d): 17.2–58.9 MPa	CFB fly ash and metakaolin react under the action of strong alkali to form a flocculated structure, which binds the small particles in the system to each other to generate strength	Grinding	[72]
38–40%	CFB fly ash, $Al(OH)_3$, Na_2SiO_3	C (7 d): 6–29 MPa, C (30 d): 9–33 MPa, C (90 d): 14–36 MPa	The calcium content of CFB fly ash is high, and calcium silicate hydrate (C-S-H) is formed in the composite material, which is an important factor to improve the strength of CFB fly ash geopolymer		[73]
26–79%	CFB fly ash, chromium sludge, metakaolin, sodium silicate, NaOH	C (28 d): 6.5 MPa	CFB fly ash is suitable as a raw material for geopolymers because of its silicon and aluminum content and its pozzolanic reactivity		[74]

chromium sludge in CFB fly ash geopolymer was 52%, and the leaching amounts of total chromium and hexavalent chromium were $0.37\,mg{\cdot}L^{-1}$ and $5.93\times10^{-3}\,mg{\cdot}L^{-1}$, respectively, which were far lower than the standard limit of Identification standards for hazardous wastes—Identification for extraction toxicity (GB5085.3-2007). Liu et al. [75] synthesized calcite using steel slag and CFB fly ash as raw materials through hydrothermal method and geopolymerization to adsorb heavy metal ions Pb^{2+} and Cu^{2+}. The results showed that the maximum adsorption capacity of calcite for Pb^{2+} and Cu^{2+} was $75.76\,mg{\cdot}g^{-1}$ and $21.83\,mg{\cdot}g^{-1}$, respectively. Liu et al. [76] prepared geopolymer with ultrafine CFB fly ash as raw material to solidify Pb^{2+}. The results showed that the geopolymer-based solidification of Pb^{2+} was mainly physical solidification, and the ultrafine CFB fly ash geopolymer and Pb^{2+} exhibited good compatibility, so that the large dosage of Pb^{2+} could be well solidified and the solidified rate was more than 90%. In addition, Liu et al. [77] found that the CFB fly ash geopolymer showed good compatibility with Zn^{2+}, which made it solidify Zn^{2+} with a high dosage and the solidified rate was more than 99%.

3.6. Application of CFB Fly Ash in Artificial Aggregate. The CFB fly ash contains a large amount of substances with the characteristic of high-temperature foaming agent, such as $CaCO_3$, $CaSO_4$, and incomplete combustion residual carbon, which produce gas during high-temperature calcination. Therefore, the development of sintered porous materials with CFB fly ash offers inherent advantages, and can simultaneously realize efficient and large dosage utilization of CFB fly ash [78]. Table 8 summarizes the applications of CFB fly ash in the artificial aggregates.

Zhang et al. [78] prepared sintered CFB fly ash ceramisite containing 70% CFB fly ash with bulk density of $624\,kg{\cdot}m^{-3}$ and cylinder pressure strength of 5.3 MPa. They also found that the source and chemical composition of CFB fly ash showed a significant influence on the properties of CFB fly ash ceramisite. For example, the content of $CaSO_4$ in the CFB fly ash that mainly plays the role of foaming and melting agent would obviously affect the water absorption and apparent density of the CFB fly ash ceramisite. However, $(CaO + Fe_2O_3 + MgO + Na_2O + K_2O)/(SiO_2 + Al_2O_3)$ in the raw material of the CFB fly ash ceramisite mainly affects the production of liquid phase on/in the surface and inner part of the ceramisite in the sintering process, thus affecting the sintering temperature and the ultimate physical and mechanical properties of CFB fly ash ceramisite. Zhang et al. [78] also designed the production process of CFB fly ash ceramisite and corresponding automatic control system of tail gas desulfurization, which could achieve accurate removal of SO_2 in the sintering process of CFB fly ash ceramsite.

Furthermore, some scholars also used CFB fly ash to prepare nonsintered light aggregate. For instance, Luo et al. [79] found that addition of 5–10% CFB fly ash to the high-titanium slag nonsintered ceramsite prolonged the setting and hardening time of the matrix, thus effectively improving

Table 8: Application of CFB fly ash in artificial aggregate.

Content of CFB fly ash	Main raw materials	Main mechanical properties	Other properties	Role of CFB fly ash	Reference
50–70%	CFB fly ash, bentonite, perlite tailing powder, glass powder, calcium carbonate	Cylinder strength: 5.3 MPa	1 h water absorption rate: 0.49–23.72%; apparent density: 1190–1770 kg·m^{-3}; softening coefficient: 0.94	The $CaSO_4$ in CFB fly ash has foaming and fluxing effects during high-temperature calcination, which makes the interior of the ceramsite porous and the surface vitrified sealing structure, which significantly reduces the apparent density and water absorption of the ceramsite	[78]
5–10%	Blast furnace high-titanium slag powder, fly ash, CFB fly ash, sodium silicate, aluminum powder	Cylinder strength: 5.58–6.27 MPa	Bulk density: 790–942 kg·m^{-3}; 1 h water absorption: 11.97–12.73%	After adding an appropriate amount of CFB fly ash, the coagulation and hardening of the matrix is prolonged, the viscosity of the slurry is increased, and the gas-holding ability of the ceramsite is increased	[79]
40%	Oil-contaminated drill cuttings, CFB fly ash, quicklime	Cylinder strength: 14.87 MPa	Apparent density: 1500.6–1622.7 kg·m^{-3}; bulk density: 800–870 kg·m^{-3}; water absorption: 6.28%	The pozzolanic reactivity of CFB fly ash is beneficial to the development of the strength of nonsintered light-weight aggregates	[80]

the viscosity of slurry, improving the problem of insufficient gas retention of ceramsite, and aiding in the preparation of nonsintered ceramsite with lower density. Also, Chen et al. [80] prepared the nonsintered CFB fly ash light aggregate with oil-polluted drilling cuttings, CFB fly ash, and lime as raw material by mechanical-chemical treatment method. The nonsintered CFB fly ash light aggregate showed cylinder compressive strength of 14.87 MPa and water absorption rate of 6.28%. At the same time, XRD and FTIR spectroscopy analysis results showed that the mechanical-chemical treatment method could improve the pozzolanic activity of the CFB fly ash, which would be beneficial to improve the mechanical strength of the CFB fly ash–based light aggregate.

4. Conclusion and Prospect

Significant differences between the properties of CFB fly ash and ordinary fly ash prevent the application of CFB fly ash in building materials. Recently, based on numerous studies on the characteristics of CFB fly ash, many scholars have tried to apply CFB fly ash to cement-based or noncement cementitious materials, concrete, geopolymer, artificial aggregate, and other building materials, in order to break through the bottleneck of resource utilization of CFB fly ash. The main research results include the following aspects:

(1) The loose porous structure and large loss on ignition of CFB fly ash lead to the reduction in the efficiency of water reducing agent and increase in the water requirement when it is used for cement-based cementitious materials, thus affecting the physical and mechanical properties of CFB fly ash cement-based materials. Therefore, it is necessary to select reasonably optimized dosage of CFB fly ash and add appropriate water reducing agent.

(2) The rich calcium-containing components such as f-CaO and $CaSO_4$ in the CFB fly ash endow it with certain self-hardening behavior and expansibility. Moreover, attributed to this result, using CFB fly ash to prepare cementitious materials not only improves the physical and mechanical properties in the early stage and reduces the drying shrinkage property, but also leads to the risk of expansion and cracking in the later stage. Taking the measures of releasing or suppressing the expansion source of CFB fly ash in advance, such as ultrafine grinding, addition of ordinary fly ash, and controlling the dosage of CFB fly ash and water-cement ratio, CFB fly ash cementitious materials can be prevented from deformation or cracking.

(3) Owing to the special chemical composition, CFB fly ash presents good application performance in MOS cement, geopolymer, and SWCM. New green solid-waste–based building materials with compressive strength of 80 MPa have been prepared by rational use of CFB fly ash. It has been proven that CFB fly ash plays a certain role in improving the durability of SWCM, such as sulfate resistance, carbonization resistance, and frost resistance.

(4) CFB fly ash possesses a certain high-temperature foaming function because of the presence of large amount of $CaCO_3$, $CaSO_4$, and unburnt residual carbon. Therefore, it offers a congenital advantage of

using CFB fly ash to prepare the sintered porous materials, which is also one of the main directions of resource utilization for CFB fly ash.

However, due to the differences in raw coal, desulfurization process, and operating environment of boiler, the performance of CFB fly ash produced in different regions is significantly different, which makes the conclusions from different researchers lack universality. Undeniably, a lot more systematic explorations are further demanded to promote the extensive and large-scale use of CFB fly ash in building materials:

(1) Comprehensive studies on the composition, structure, morphology, and performance of CFB fly ash are essentially required, and the differences in composition and performance of CFB fly ash should be summarized. Moreover, the universal standard requirements for the applications of CFB fly ash in cement-based materials should be put forward, which can lay a foundation for the resource utilization of CFB fly ash in traditional cement-based materials.

(2) Based on the research on the influence of CFB fly ash on the physical and mechanical performances of cement-based materials, geopolymer, and SWCM, the influence of CFB fly ash on the hydration reaction mechanism and on the long-term and durability performances for these cementitious materials should be further studied, so as to provide a theoretical basis for the extensive use of CFB fly ash in building materials.

(3) The influence of the ultrafine process of CFB fly ash and the ultrafine CFB fly ash on the working performance and physical and mechanical properties of various cementitious materials should be further studied.

(4) The preparation of artificial aggregate with high dosage of CFB fly ash is one of the effective ways of resource utilization of CFB fly ash. The beneficial effects of special chemical composition of CFB fly ash on the preparation of artificial light-weight aggregate, such as high-temperature foaming agent function, self-hardening, and expansibility at room temperature, still need to be further investigated, which will be pursued in the future studies.

Conflicts of 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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