Coal Fly Ash Use in Cement and Concrete

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Nowadays, coal is increasingly being used as an energy source in some countries. This coal-fired generation process, however, has the disadvantage that produces large quantities of coal fly ash. Its characteristics differ depending on the combustion conditions and the coal source. Fineness will influence early compressive strength in cement-based materials. The finer the binding material, the higher the early compressive strength. They can be used to produce high-volume fly ash (HVFA) concrete, self-compacting concrete (SCC), concrete for marine infrastructures, pervious concrete, roller compacted concrete (RCC) and so on.

coal fly ash fineness grate furnace combustion standardization

1. Introduction

Coal fly ash (CFA) is the major combustion residue produced during the burning of pulverized coal in thermo-electric power stations. About of 80–90% of the total ashes are collected by the cleaning equipment of flue emissions, usually are electrostatic precipitators. Spain utilizes imported bituminous coal from South Africa, among other countries, as fossil fuel, for electrical power generation [1].

Coal-fired power generation is not decreasing around the world. Therefore, the up-surge in the coal demand will also increase the production of coal fly ash. After three years of growth, it reached a record of over 10,000 TWh in 2018. Later, it dropped by 3% in 2019. Even though coal-fired power generation decreased in Europe and the United States, it grew up in China and other parts of Asia, where it is the largest source of power generation (36%). Currently, coal supplies 36.7% (2019) of global electricity generation and plays a significant role in iron and steel industry. The share of global power mix in 2019 was slightly lower than in 1973 (38.2%) [2]. In particular, Spain accounts for around 1.9% of the worldwide global coal consumption of 1140 million tons, which is the 29th place. Annually, the Spanish utilities consume 22 million tons (2016) of coal, producing about 310,000 tons of coal bottom ash (CBA) and 2.2 Mt of coal fly ash (CFA) [1].

Recently, some countries currently using coal for electricity generation have agreed for a gradual reduction of its use. This action is aligned with the European milestone of becoming climate-neutral by 2050.

The European Green Deal is focused on climate change mitigation. Furthermore, it covers investment, research, innovation, growth, and related strategies such as climate change adaptation [3].

The target set out in the EU Green Deal for Europe's ambition to become climate neutral by 2050 was written into law in The European Climate Law [4]. In addition, an intermediate target of decreasing net greenhouse gas (GHG) emissions by at least 55% by 2030, compared to 1990 levels was established. This law implies a radical transformation of Europe's economy and society. Therefore, new initiatives, across economic sectors such as energy and fuels and a range of policy areas should be adopted. Finally, The European Circular Economy Action plan describes the actions dealing with resource extraction and waste among other topics [5]. In Europe, the construction sector is responsible for about 35% of the total waste generation. In addition, greenhouse gas (GHG) emissions from material extraction, construction product manufacturing and building construction and renovation are estimated in the range of 5–12% of the national greenhouse gas (GHG) emissions reported by the European countries.

The use of by-products and industrial wastes, such as coal fly ash, as supplementary cementitious materials to manufacture coal-ash cements and concretes is a lever to achieve net zero carbon dioxide emissions in the cement production [6]. Therefore, the cement and concrete sectors play a key role in circularity. The major advantages of using coal fly ash in cements and concretes are the mitigation of the climate change by lowering the clinker to cement ratio and the increase of the concrete durability, which increases the service life of reinforced concrete structures. In addition, carbon dioxide uptake by cement-based materials carbonation can be considered in the carbon dioxide net balance for the cement and cement-based materials, and it is widely acknowledged by scientists that coal-ash cements and concretes carbonate faster than the ones made with common cements without additions [6]. Summing up, coal fly ash added to Portland cements and concretes are an important lever for decarbonization.

The benefits of coal fly ash as a cement constituent derive from its pozzolanic performance. Coal fly ash reacts with calcium hydroxide from cement hydration reactions to form calcium silicate hydrates called C-S-H gel, contributing to the strength gain of the Portland cement [7]. Coal bottom ash also exhibits a pozzolanic reactivity in blended cements when it is finely ground [8]. However, it is normally used as fine aggregate [9], but sometimes is dumped in landfills. Coal fly ash in cements for structural concrete applications typically ranges from 6 to 20 wt%, which are cements CEM II/A-V, and from 21 to 35 wt%, which are cements CEM II/B-V, according to the European standard EN 197-1:2011 [10]. CEM IV/A (V) and CEM IV/B (V) cements could have a coal fly ash content up to 55 wt% and are used for mass concrete in roller compacted concrete pavements and dams, among other applications [11]. Although coal fly-ash typically enhances long term strength of concrete, it also tends to delay early strength development [12]. The European standard EN 450-1 [13] stipulates that the compressive strength of mortars containing 25% coal fly ash must be at least 75% that of coal ash-free mortar after 28 days of curing (activity index). Also, the activity index at 91 days has to be at least 85%. Coal fly ash (CFA) from the combustion of bituminous coal from South Africa was found to meet these requirements at substitutions up to 35 wt% [14]. Also, it was found that its particle size distribution (PSD) can affect positively in the compressive strength development [15]. Long-term mechanical strength and long-lasting durability is improved with coal fly ash more rich in smaller particles [16]. Accordingly, the small hollow spheres with a size ranging from 10 to 1000 μm in diameter, named cenospheres, are very wanted [17], which are the smaller particles (from 1 to 2% of the total) [18]. Most of them present diameters from 5 to 500 μm [19] or from 20 to 300 μm. The shell thickness varies from 1 to 18 μm [20]. Finally, its microstructure contains around 76%, 22% and 2% of glass, mineral matter or char, respectively [17].

To both achieve climate change mitigation targets and as well as for the use of coal fly ash, high-volume coal fly ash (HVFA) concrete has been developed in which more than 50% of coal fly ash is utilized in the binder mixture in concrete [21]. High-volume fly ash (HVFA) concrete, which has normally 50–60% coal fly ash as the total content of cementitious materials, is widely used.

2. Advantages of Coal Fly Ash

Coal fly ash in concrete has several advantages, such as increasing the resistance to chloride penetration, sulphate attack, and alkali-silica reaction, lowering cracking due to drying and thermal shrinkage, improving the workability and reducing the water demand [22]. By contrast, most of the studies reported that coal fly ash provides early age compressive strength to the concrete [23][24], but at the later ages its contribution to compressive strength becomes larger. Furthermore, wet-curing periods result in lower compressive strength, and more porous and permeable concretes [25][26].

High-volume coal fly ash concrete presents good mechanical strength utilizing 50–60% of coal fly ash replacement. However, at replacement levels beyond this the mechanical strength decreases, particularly at early ages, due to the slow pozzolanic reaction [27][28][29]. It has been reported compressive strength of 66.55 MPa [29] when 50% of cement was replaced (HVFA-50 concrete) at 28 days this value was reduced to 30.55 MPa for HVFA-70 concrete. In addition, compressive strengths at 28 days equivalent to 78% and 73% of the reference compressive strength (concrete without coal fly ash) for HVFA-40 and HVFA-60 concretes, respectively, have been reported [27][28][29][30].

According to Ankur, et al. [31], the application of high-volume coal fly ash (HVFA) based self-compacting concrete (SCC) is feasible for civil engineering works where early mechanical strength is not the deciding design factor. In addition, coal fly ash levels higher than 30% normally hinders the compressive strength of the self-compacting concrete Therefore, the use of HVFA based SCC should not exceed 40–50% of coal fly ash percentage. By contrast, the use of coal fly ash in high volume in self-compacting concrete may contribute to promotion of SCC in developing countries.

Coal fly ash blended cements enhance the durability of concrete by its particle packing effects and pozzolanic reaction [32]. Nevertheless, its effectiveness level depends on the concrete mix design, curing conditions and type of coal fly ash. Accordingly, this material provides enhanced durability in the marine environment [33], i.e., a good resistance to chloride penetration into the concrete for marine infrastructure [34].

High strength concrete is widely utilized in civil engineering due to its better mechanical and durability characteristics than conventional concrete. Coal fly ash high strength concrete is more crack resistant due to the lower cement content and mixing water [35]. In addition, the uniaxial tensile strength of hardening coal fly ash high strength concrete at early age is generally lower than splitting tensile strength at the same age [36].

Pervious concrete, i.e., no-fines concrete, is a pavement concrete with high porosity and, therefore, high water permeability. Vázquez-Rivera et al. [37] reported compressive strength and density values of pervious concrete ranging from 2.5 MPa to 13.5 MPa and 2120–2360 kg/m^3, respectively, while the increase in coal fly ash/binder ratio results in the decrease of the concrete compressive strength. Coal fly ash in concrete (10–30%) provides a more workable mix and a good abrasion resistance because of the pozzolanic reaction and filler effect. Nevertheless, compressive strength are about 0.85 times that of control mix [38]. Although, 20% coal fly ash decreases the porosity and increases the density, the compressive strength is lower compared to that of 10% coal fly ash [39]. Finally, it is suggested to utilize pervious concrete made with high levels of coal fly ash as base layer in rigid pavements. By contrast, Saboo et al. [40] suggest an optimum range of coal fly ash replacement in pervious concrete between 5 and 15%.

The use of large amounts of coal fly ash in roller compacted concrete (RCC) reduces the hydration temperature and enhances durability [41]. Then, it is suitable for use in dams and pavements [42]. The increase in coal fly ash content in roller compacted concrete (RCC) adversely affects its compressive strength. In addition, the increase in coal fly ash replacement promotes the formation of interlayer cold joints [43]. Furthermore, with the increase of the delay of placement time of the roller compacted concrete (RCC) upper layer, it shows lower splitting-tensile strength and higher permeability [44].

Sahmaran et al. [45] studied the effect of self-healing on self-consolidating concrete made with high volume of coal fly ash (HVFA) when submitted to permanent water exposure. The self-healing effect was attributed to the pozzolanic reaction of un-hydrated coal fly ash particles available in the pore system, which hydrates on the crack surfaces filling the crack by newly formed C–S–H gels.

Jing et al. [46] reported the use of coal fly ash cenospheres to produce ultra high-performanceconcrete (UHPC). They show an improvement of the hydration process of ultra high-performance at early age and a filler effect at 28 days.

Ultrafine coal fly ash may refine the pore diameter and improve the workability of ultra high-performance concrete pastes compared with the ones containing high-volume of ordinary coal fly ash [47]. The high specific surface area and filler effect of fine coal fly ash leads to higher compressive strength [47][48]. However, workability is a key factor for the development of ultra-high mechanical properties and good durability of ultra high-performance concrete [49].

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