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Compressive strength development and durability of an environmental load-reduction material manufactured using circulating fluidized bed ash and blast-furnace slag

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HIGHLIGHTS

- CFB, BFS and recycled aggregate were utilized for manufacturing zero-cement mortar.
- CFB can react as an alkali activator with BFS.
- The strength of zero-cement mortar could be enhanced by incorporating CS and $Ca(OH)_2$.
- The investigated zero-cement mortar presents excellent sulfuric acid resistance.
- The manufactured product is a potential application as an environmental load-reduction material.

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ABSTRACT

The aim of this study is to investigate the compressive strength and durability of zero-cement mortar fabricated using 100% by-products by incorporating circulating fluidized bed ash (CFB), blast-furnace slag (BFS), and recycled aggregates. CFB can potentially react as an alkali activator with BFS. The compressive strength of zero-cement mortar with an optimal mix proportion of CFB:BFS = 75:25 can reach approximately 28 MPa after 91 days of curing, which is mainly dependent on the curing temperature, water-to-binder ratio, and aggregate type, but not the curing environment. Moreover, for the sake of application to building construction, the strength can be enhanced to 40 MPa after 28 days and 50 MPa after 91 days by maintaining a 40% water-to-binder ratio and incorporating BFS with a fineness of 600 m^2/kg, 2.5% calcium sulfate (CS), and 6% $Ca(OH)_2$. CFB-based zero-cement mortar shows a tendency to improve the chloride diffusion suppression, frost resistance, and carbonation resistance when the water-to-binder ratio is reduced. Furthermore, the investigated zero-cement mortar presents excellent sulfuric acid resistance compared with the cement-based mortar. Although the use of zero-cement mortar is currently limited, the manufactured product is considered to have a potential application as an environmental load-reduction material.

1. Introduction

Cement is ubiquitous in modern life for virtually all skyscrapers, bridges, freeway overpasses, nuclear power plants, and many other buildings and structures. About 3 trillion kilograms of cement are consumed annually around the world and cement manufacturing causes large amounts of carbon dioxide emissions. It is well known that large-scale production of Portland cement consumes a huge amount of energy, and hence has become a major source of CO_2 emission [1,2]. Every 10 units of cement release 9 units of CO_2, thereby cement manufacturing is a major problem of atmospheric pollution and the largest emitter of greenhouse gases.

Coal, the most common fossil fuel energy resource, is widely used to collect heat energy and generate electric power [3–5]. The circulating fluidized bed combustion (CFBC) system is an attractive choice for clean fuel combustion technology for use in coal combustion, because it emphasizes the optimization of coal

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and air interaction in the combustion chamber to maximize combustion efficiency [6–8]. Furthermore, some significant advantages such as flexibility in the fuel types used and the superiority of desulfurization can facilitate utilization of high-sulfur fuels [9] and decrease emissions from burning pollutants in order to maintain sustainable development. Therefore, the amount of circulating fluidized bed ash (CFB) has significantly increased recently, and its disposal has posed challenges to both government and power plants [10–12].

In the past few years, for the suppression of CO_2 emissions to improve the environment, various types of by-products have been used as binder materials in building construction and manufacturing. For example, blast-furnace slag (BFS), a by-product of the steel industry, has been widely used as a binder material for blast-furnace cement, which is specified as a green product favorable to the global environment [13]. Conventional fly ash (FA), a coal ash generated in thermal power plants, has been used successfully as a concrete admixture since its use in dam structures in the 1930s, as it reduces hydration heat in concrete structures. However, the mineral compositions and properties of CFB are different from those of FA because of the differences in the burning process and temperature. CFB is generated by burning e.g. 70% coal, 30% wood, or other fuels at a relatively low temperature of 800–1000 °C and a high pressure of 1 MPa [7,14]. After adding limestone as a sulfur-removal sorbent, the mixture is calcined to obtain CaO, which reacts with SO_2 and O_2 to form $CaSO_4$. It has been verified that excessive addition of FA negatively affects the mechanical properties of hardened BFS-based cement mortar [15].

Utilization options for CFB have received considerable attention. At present, some CFBs have been successfully introduced to several suitable roadbed material and infrastructural constructions, such as the controlled autoclaved brick [16], non-autoclaved aerated concrete [17], controlled low strength materials (CLSM) [6], or geopolymer material [18,19]. CFB and slag was found to be used as the main component of autoclaved load-bearing brick only using 3% cement under the preparation conditions 25 MPa compacting pressure, 24 h precuring time, 6 h autoclaving time and 1.5 MPa autoclaving pressure [16]. In addition, non-autoclaved aerated concrete can also be developed by using the CFB, cement and lime [17]. CFB can also be used as a partial or full replacement for fly ash in CLSM to gain appropriate fluidity and bleeding, which was increased with the CFB content decrease [6]. Geopolymer is a class of synthetic aluminosilicate inorganic cementitious material with a much smaller CO_2 footprint than traditional Portland cement [20]. It has been investigated that CFB can be recycled together with FA for production of environment-load geopolymer composites by a moderate alkali-fusion pretreatment at 350 °C for 0.5 h [19].

Meanwhile, the use of ash binders in low-performance concrete has been promising [21,22], and the concept of "no-cement concretes" was proposed [22,23], which uses a mixture of CFB and FA, where FA acts as the pozzolan that reacts with CaO in the CFB. Since CFB mainly received attention for its utilization in low-strength and low-performance concrete [24,26], limited study is focusing on the methods to increase the mechanical properties of CFB based zero-cement composites. In addition, the relatively high sulfate and lime contents in CFB were found to be detrimental to the shrinkage behavior [25]. However, the shrinkage behavior of CFB in zero-cement composites has not been fully clarified. On the other hand, with the depletion of natural aggregate resources, by-product aggregate materials, such as BFS sand and recycled aggregate, have become an important research topic. Our research group also have reported BFS sand can effectively reduce the drying shrinkage of mortar specimens by approximately 30%; this effect can also be expected in zero-cement composites [26]. With the rising demand for green cement manufacturing with minimal gas emissions, the objective of sustainable development is to utilize 100% waste materials instead of ordinary Portland cement (OPC) in the construction of buildings. However, the focus on durability in this field has been limited [27].

Based on the above discussion, extensive research is required into the mechanical properties and durability of zero-cement composites that incorporate CFB, BFS, and various fine aggregates. This is critical for understanding the properties of zero-cement composites, maintaining their structural performance, investigating the applicability of CFB and various by-products, and conserving natural resources to maintain sustainable development.

2. Experimental program

In this study, CFB, FA, and BFS were used as a replacement for OPC to manufacture zero-cement mortar. For 100% utilization of waste materials, three types of fine aggregates were used in the mortar: recycled aggregate, BFS aggregate, and copper slag aggregate.

2.1. Materials

CFB, FA, and BFS were used as binder materials instead of OPC in hardened materials. OPC (density, 3.16 kg/m^3) was used as a reference material. The chemical compositions of these materials are shown in Table 1. Here, BFS with 400 m^2/kg Blaine fineness was used in the experiment Series 1, Series 2 and Series 3. BFS with higher Blaine fineness 400 m^2/kg was used in Series 4 and Series 5 as a method to improve the compressive strength and expand the application. Fig. 1 shows the particle size distribution of the various fine aggregates used in preparing mortar specimens, as determined by the sieve analysis method. Fineness modulus of fine aggregate is an empirical factor obtained by adding the cumulative percentages of aggregate retained on each of the standard sieves ranging from 80 mm to 150 μm and dividing this sum by 100, which represents mean size of particles in sand. The fineness modulus of fine aggregate used in this experiment was given in Table 2. Larger fineness modulus value indicates that the aggregate is coarser and smaller value of fineness modulus indicates that the aggregate is finer. The physical properties of used fine aggregate materials-copper, BFS and recycled aggregate, are described in Table 2. The aggregate used in this experiment was under the saturated-surface-dry (SSD) condition. It can be revealed from Table 2 that the SSD density for copper aggregate was 3.52 kg/m^3, which is bigger than that of BFS and recycled aggregate. It is clear that the oven-dry density condition of copper aggregate was 3.50 kg/m^3, while that of BFS and recycled aggregate was 2.72 kg/m^3 and 2.39 kg/m^3. While, Table 2 shows that the water absorption ratio of recycled aggregate is 4.26%, which is significantly larger than that of the copper slag aggregate and BFS aggregate, with values 0.58% and 0.74%, respectively.

2.2. Experimental program and mix proportion

The experimental program was designed in the following five series. In Series 1, zero-cement mortar was manufactured and the influence of various by-products used as binder materials on the mechanical property of the zero-cement mortar was examined by varying the dosage of CFB, FA, and BFS. Subsequently, the optimized mix proportions and hydration characteristics of the zero-cement mortar were analyzed. The mix proportions of the mortar and the dosage of mineral admixtures are shown in Table 3. All mortar specimens were casted into ϕ 50 mm × 100 mm plastic molds, with a water-to-binder ratio (W/B) of 60% and a binder-to-sand ratio of 1:2 without any chemical admixture. The