



Resistance of coal bottom ash mortar against the coupled deterioration of carbonation and chloride penetration



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ABSTRACT

This paper investigated the resistance of bottom ash mortar against the coupled deterioration of carbonation and chloride penetration. To evaluate the resistance of the mortar, a comparative study was conducted with variables of ordinary mortar, lightweight mortar using expanded shale, fly ash cement mortar, and slag cement mortar. Test results showed that a combination of carbonation and chloride penetration accelerated the rate of chloride penetration into the mortar regardless of the mortar type. The replacement of sand with bottom ash moderated the penetration depth of chloride under coupled-deterioration environments, while the overall penetrated-chloride contents showed no significant differences. It can be concluded in a coupled-deterioration environment that the chloride resistance of the bottom ash mortar was greater than that of both ordinary mortar and lightweight mortar. The type of cement paste on the surface of a carbonated mortar had a governing impact on the chloride penetration.

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1. Introduction

It has been suggested that power generation by means of coal combustion, which accounts for the highest proportion of power generation overall, maintains its current proportion in South Korea considering that the limits of other means of generating power (e.g., the safety and sustainability of nuclear power generation; the economic viability and efficiency of renewable energy power generation) remain unresolved [1]. For power generation by coal combustion to become sustainable, the recycling and reuse of coal combustion residues such as fly ash and bottom ash are necessary. Among the various means of recycling and reusing coal ash reported thus far, the utilization of coal ash as a construction material is likely the most effective solution operable on a mass scale. Over the past few decades, the utilization of fly ash, which accounts for a relatively high proportion (70%–90%) of coal combustion residue, as a construction material has been studied and implemented [2–4]. Recently, moreover, studies of recycling bottom ash, accounting for a relatively low proportion (10%–30%), as a construction material are actively being conducted [5–9].

Coal bottom ash is a highly porous material with an irregular shape, low abrasion resistance, and a high vitreous content with particle size ranging from 0.075 mm to 50.8 mm [4,8]. Cheriaf et al. investigated the pozzolanic reactivity of bottom ash and revealed that a pozzolanic reaction occurred within cement paste and bottom ash after 28 days,

resulting in calcium consumption [10]. In addition, it was reported that the 28-day compressive strength was 27% higher than a reference material when ground bottom ash was used [10]. Kurama and Kaya studied the replacement ratio of bottom ash and cement, and concluded that a ratio up to 10% resulted in enhanced strength [9]. A study regarding the usability of fine bottom ash as an aggregate material by Kim et al. suggested that bottom ash under a surface-saturated dry condition could enhance the workability of fresh concrete due to the excess water within the aggregates; however, using it may result in lower strength relative to normal concrete [6].

Nevertheless, the effect of using bottom ash as a concrete aggregate material on the long-term durability remains a subject of numerous investigations. As the durability of concrete is an important concern in terms of reducing the social cost of new construction and maintenance of infrastructures, the effect of using bottom ash as an aggregate material on the durability of concrete cannot be neglected. Many studies thus far have treated single-deterioration mechanisms acting on reinforced concrete structures such as chloride attack, carbonation and chemical erosion to some extent. While the durability of bottom ash concrete is not a broad topic of research, a few studies have focused on this issue. With regard to the resistance of bottom ash concrete to chloride penetration and freezing and thawing, Ghafoori and Bucholc reported that mixing with bottom ash enhanced the resistance to freezing and thawing; however, decreased the chloride resistance [11]. A recent study by Kim et al. regarding the chloride resistance of high-strength concrete amended with bottom ash reported that mixing of bottom ash had no impact on the chloride penetration depth but significantly reduced the quantity of penetrated chloride [12].

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However, most cases of the concrete structure were degraded by complex-factors, and studies in this respect remain insufficient. In particular, chloride penetration and carbonation can be considered as the most common coupled-deterioration phenomena affecting the durability of reinforced concrete structures, thus the coupled-deterioration factors should be considered in the material design of concrete [13]. Although a limited number of studies on the coupled action of carbonation and chloride penetration were reported, some of previous studies suggested the potential release of chloride ions bound in Friedel's salt ($3\text{CaO}\cdot\text{Al}_2\text{O}_3\cdot\text{CaCl}_2\cdot 10\text{H}_2\text{O}$) and Kuzel's salt ($3\text{CaO}\cdot\text{Al}_2\text{O}_3\cdot 0.5\text{CaSO}_4\cdot 0.5\text{CaCl}_2\cdot 10\text{--}11\text{H}_2\text{O}$), and that adsorbed on the surface of C–S–H (calcium silicate hydrates) gel due to carbonation. Therefore, a coupled-deterioration environment causes condition vulnerable to chloride penetration [13–16]. Chindaprasirt et al. investigated the effect of carbonation on chloride penetration in a blended cement mortar, and reported that the observation of lower chloride resistance in carbonated mortar in comparison to that of uncarbonated mortar [17]. A further study was carried out to explore the interaction between carbonation and chloride penetration on the concrete by assessing both the effect of chloride penetration on carbonation, and the opposite, the effect of carbonation on chloride penetration [13]. The obtained result was similar to that of Chindaprasirt et al. [17], as the chloride penetration depth of the carbonated concrete was significantly larger than that of uncarbonated concrete [13]. On the other hand, it was found that the chloride penetration led to the low carbonation depths comparing to the concrete without chlorides [13]. This observation was probably attributed to the higher moisture contents and water film inside the pores due to chloride hygroscopy, which may decrease the carbonation rate [13]. Moreover, the pore network could be blocked by the precipitation of chloride-based crystals [13]. In this context, the coupled-deterioration mechanism on concrete is not fully understood to this date. A general agreement, however, resides among the previous studies that the addition of pozzolanic materials including fly ash improved the chloride resistance of concrete in both a single- and coupled-deterioration environment [13,17].

This study investigates the resistance of mortar amended with coal bottom ash against the coupled deterioration of carbonation and chloride penetration. The chloride resistance of bottom ash mortar exposed to the coupled-deterioration environment was compared with those of ordinary mortar, lightweight mortar using expanded shale, fly-ash cement mortar, and slag cement mortar. An exposure test under a single-deterioration environment of chloride penetration was conducted simultaneously as a reference to investigate the effect of a coupled-deterioration environment on the chloride penetration characteristics of mortar amended with coal bottom ash.

2. Experimental procedure

2.1. Materials and specimen preparation

Type-I Portland cement, blast furnace slag, and fly ash were used as binder materials. The blast furnace slag cement (SC) was produced by substituting slag for 40 vol.% of cement, and the fly ash cement (FC) was produced by substituting fly ash for 20 vol.% of cement. The chemical compositions and physical properties of the Portland cement, blast furnace slag, and fly ash are listed in Table 1. Three types of aggregate were used. River sands were used as a normal aggregate, and coal bottom ash (BA) and expanded shale (ES) were used as lightweight aggregates. The bottom ash originated from the Seocheon coal-fired thermal power plant in South Korea, and the expanded shale was produced by Hanya Raw Material, Ltd. in China. The particle sizes of all of the aggregate materials used in this study were below 2 mm. All aggregate materials were immersed in water for a few weeks and then washed to remove washable chlorides, after which they were dried to ensure a saturated-surface-dry state. The chemical compositions and physical properties of the bottom ash, expanded shale and river sand are listed

Table 1

Chemical compositions and physical properties of the Portland cement, blast furnace slag, and fly ash.

Compositions (wt.%)	Portland cement	Blast furnace slag	Fly ash
CaO	65.9	50.5	2.9
SiO ₂	10.6	22.6	50.4
Al ₂ O ₃	3.8	12.0	27.6
Fe ₂ O ₃	3.9	0.6	8.0
MgO	1.0	2.7	2.0
SO ₃	2.3	2.3	0.9
Cl	1.8	–	0.0
K ₂ O	1.4	0.5	1.6
TiO ₂	0.2	1.0	2.1
MnO	0.2	0.4	0.1
P ₂ O ₅	–	–	0.3
Specific gravity	3.15	2.86	2.12

in Table 2. In addition, all ingredients used to fabricate mortar specimens are shown in Fig. 1.

Seven types of specimens were designed in this study. The mix designs of the mortar specimens are provided in Table 3. The water-to-cement ratio and the aggregate-to-cement ratio of the reference specimen (REF in Table 3) were 0.5 and 2.5 by mass, respectively. To investigate the effects of the aggregate type and the substitution rate on the chloride penetration rate, specimens with the same paste type, BA25, BA50, ES25 and ES50, where the number represents the volume of BA or ES that replaced sand, were prepared. Furthermore, FC and SC were prepared to compare the resistance of coal bottom ash mortar against the coupled deterioration of carbonation and chloride penetration to that of blended cements, which are known to have high chloride resistance [14,18]. Each mortar specimen was mixed using a 10-liter mortar mixer, cast into a 50 mm × 50 mm × 50 mm mold, and then covered with plastic wrap. After three days of curing, the mold was removed and all specimens were cured at 20 °C under a sealed condition for 28 days.

2.2. Test procedures

Compressive strength test was conducted to investigate the mechanical performances of all specimens. The test was conducted using a 3000 kN universal testing machine in accordance with ASTM C109 [19] at 3 days, 28 days, and 91 days. The collected strengths were the average of three separate tests.

For the penetration of carbon dioxide and chloride in a one-dimensionally expanded state into mortar, five faces, except for one exposed face, of the specimens were covered with a silicon sealant after they were cured for 28 days. The exposure conditions were set for the accelerated chloride-penetrating environment using a 10% NaCl solution; the accelerated carbonation environment was set with a temperature of 20 °C, a relative humidity of 60% and a CO₂ concentration of 5%, to accelerate the deterioration tests. One face of each test specimen in contact to a coupled environment was exposed to an accelerated chloride-penetrating environment for four weeks,

Table 2

Chemical compositions and physical properties of the bottom ash, expanded shale and river sand.

Compositions (wt.%)	Bottom ash	Expanded shale	River sand
CaO	2.0	14.1	–
SiO ₂	44.2	42.0	–
Al ₂ O ₃	31.5	20.0	–
Fe ₂ O ₃	8.9	18.0	–
MgO	2.6	0.2	–
TiO ₂	2.4	1.6	–
Specific gravity	1.91	1.92	2.57

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