Technical Note

Effects of High Volumes of Fly Ash, Blast Furnace Slag, and Bottom Ash on Flow Characteristics, Density, and Compressive Strength of High-Strength Mortar

H. K. Kim\(^1\) and H. K. Lee\(^2\)

Abstract: This paper presents results of an experimental work carried out to evaluate utilization of recycled materials, such as fly ash and bottom ash (by-products of thermoelectric power plants), and blast furnace slag (by-products of ironworks) as binders and aggregates with high volume in high-strength, lightweight mortar. The effects of high volumes of fly ash, blast furnace slag, and bottom ash on flow characteristics, density, and compressive strength of mortar were investigated. In addition, the water capillary absorption characteristics of mortar regarding moisture transport that may affect the durability of the mortar were studied. It was found that the flow characteristics of fresh mortar were neither changed nor decreased with the increase in the replacement ratio of bottom ash, while these were improved by the use of high volumes of fly ash and blast furnace slag as replacements of cement. DOI: 10.1061/(ASCE)MTIT.1943-5533.0000624. © 2013 American Society of Civil Engineers.

CE Database subject headings: Mortars; Fly ash; Bottom ash; Recycling; Mechanical properties; Absorption; Compressive strength.

Author keywords: High-strength lightweight mortar; Fly ash; Blast furnace slag; Bottom ash; Recycled materials; Mechanical properties; Water capillary absorption.

Introduction

Many researchers reported that various recycled materials can be applied to mortar, concrete, and cementitious composites. Fly ash and blast furnace slag are used as replacements of cement due to their pozzolanic nature (Yazici 2007). These particle materials have positive effects on the workability, durability, and long-term strength of concrete (Yazici 2007). Moreover, bottom ash, a by-product of thermoelectric power plants, has been the subject of recent research, focusing on the possibility of its application as lightweight aggregates in mortar and concrete due to low particle densities (Meij and Berg 2001; Kim and Lee 2011; Kim et al. 2012). The mortar and concrete containing fly ash, blast furnace slag, and bottom ash as binders and aggregates have been studied from environmental and economic standpoints. However, those were mostly focused on conventional normal-strength concrete and only a few were on high-strength mortar and concrete. By using high volumes of fly ash, blast furnace slag, and bottom ash as binders and aggregates, the density of high-strength mortar and concrete may be further decreased.

The present study focuses on evaluating utilization of high volumes of fly ash and blast furnace slag incorporating bottom ash aggregates in high-strength, lightweight mortar. All experiments in the present study were carried out at the mortar level. The effects of fly ash, blast furnace slag, and bottom ash on flow characteristics, densities, and compressive strength were investigated. In addition, the water capillary absorption characteristics of mortar regarding moisture transport that may affect the durability of the mortar were studied.

Experimental Program

Materials

Type I portland cement, fly ash, blast furnace slag, and silica fume were used as binders. The quartz sand and bottom ash were used as fine aggregates. They were controlled in terms of the grain size distribution within a range of 0.15–0.60 mm by sieving and were maintained in a saturated surface dry (SSD) condition prior to the experiment. The bottom ash was by-products of the Seocheon thermal power plant located in South Korea. The pulverized coal-firing boiler system was applied in the power plant with a combustion temperature of 1,400–1,550°C. The specific gravities (SSD) of quartz sand and bottom ash were 2.65 and 1.87, respectively, while the water absorptions of quartz sand and bottom ash were 0.08 and 5.45, respectively.

Mixture Proportions

The mix proportion of the control specimen was taken from de Larrard and Sedran (1994) and Richard and Cheyrezy (1995). The mix proportions are shown in Table 1 and are denoted with specific codes. The weight proportions of water, silica fume, and superplasticizer were fixed at 20, 25, and 4.2% by weight of cement in the control specimen. Labels F and S represent the fly ash and blast furnace slag, respectively. In the second level, 20 and 40 refer to volume proportions of substitution for cement. In series B, level B and the numbers 25, 50, 75,
and 100 signify bottom ash and its replacement percentages by volume, respectively.

**Experimental Details**

All specimens were mixed in a 60 L capacity pan mixer. The materials except water and superplastisizer were mixed for 1 min. Water and superplastisizer were added and then mixed for additional 6 min. The flow characteristics of the fresh mortar were tested following the ASTM C1437-07 (ASTM 2007) specifications. Cylinder-type specimens that were 100 × 200 mm were cast for measuring the density and compressive strength of concrete. Fresh mortar was cured for a single day in the laboratory and then demolded. The specimens were cured in a water tank at 20 ± 1°C. The mass and volume of the specimens were then measured at 28-days curing to determine the apparent density. The compressive strength of the specimens was measured following the ASTM C39 (ASTM 2012) test method. The water capillary absorption of the surface of the specimens was measured in accordance with the ASTM C1585 (ASTM 2011) test method using cylindrical specimens 60 mm in length and 150 mm in diameter. The time adopted to calculate the water absorption coefficient \( \kappa [\text{kg/(m}^3\text{h}^{1/2})] \) was fixed at 7 days.

**Experimental Results**

**Effect of Bottom Ash on Flow Characteristics of Fresh Mortar**

The flow characteristics of fresh mortar were constant or decreased with the increase of the replacement ratio of bottom ash. As shown in Fig. 1, the flow values of fresh mortar with less than 20% replacement of fly ash or blast furnace slag were slightly increased or unchanged. However, the flow values of fresh mortar with high replacement (40%) of fly ash or blast furnace slag were increased by 40–50 mm (20–25%). Further studies are needed to attain a better understanding of this phenomenon.

**Effect of Bottom Ash on the Density of Mortar**

The density of mortar was decreased roughly from 2,100 to 1,800 kg/m³ with replacement of 100% of bottom ash, as shown in Fig. 2. It was further decreased to 1,700 kg/m³ when 20–40% of fly ash and blast furnace slag with 100% of bottom ash aggregates were used.

**Effect of Bottom Ash on the Compressive Strength of Mortar**

Fig. 3 shows the effect of bottom ash on the compressive strength of mortar. As shown in Fig. 3(a), the compressive strength of the control and F20 specimens at 3 days was decreased by 29 and 22 MPa, respectively, when 100% fine aggregate was replaced with bottom ash. At 28 days, the relative value of compressive strength of bottom ash mortar was approximately 70–80%. At 91 days, the control specimen with 100% bottom ash (B100) showed a lower strength value (64 MPa) than any other specimens, as presented in Fig. 3(c). However, higher values of compressive strength were obtained when a high volume proportion (40 vol.%) of fly ash and blast furnace slag were employed to replace cement, compared with the control specimen with 100% bottom ash (B100).

In the case of high-strength concrete with a low W/B, the less space for products from latent hydraulic reaction was formed and the filler effect of mineral binder materials on compressive strength became dominant (Poon et al. 2000). Particles of mineral binder materials played the role of space filler or microaggregates in high-strength cement pastes (Poon et al. 2000). Thus, at a...
lower W/B ratio, the difference in compressive strength between mortar without mineral binder materials and mortar with high volumes of fly ash and blast furnace slag is small (Poon et al. 2000).

**Effect of Bottom Ash on the Water Absorption Properties of Mortar**

As shown in Fig. 4, all specimens may be classified as waterproof materials because the values of the water absorption coefficient \( k \) are smaller than 0.5 kg/(m\(^2\)h\(^{1/2}\)) (Lee and Lee 2001). The effect of replacement of bottom ash on the water absorption coefficient \( k \) was more significant than in the cases of using fly ash and blast furnace slag as a binder. This indicates that the capillary absorption of water in this study dominantly takes place through the internal pores of bottom ash.

**Conclusions**

This paper focuses on evaluating utilization of high volumes of fly ash and blast furnace slag incorporating bottom ash aggregates in high-strength, lightweight mortar. The effects of fly ash, blast furnace slag, and bottom ash on flow characteristics, density, and compressive strength were investigated. In addition, the water capillary absorption characteristics of mortar regarding moisture transport that may affect the durability of the mortar were studied. The following conclusions have been drawn:

- The flow characteristics of fresh concrete were constant or decreased with the increase of the replacement ratio of bottom ash fine aggregates. Also, the flow values of fresh concrete with a high replacement (40%) of fly ash or blast furnace slag were increased by 40–50 mm (20–25%).
- The density of mortar with 100% of bottom ash was further decreased below 1,700 kg/m\(^3\) when high volumes of fly ash and blast furnace slag was used.
- The compressive strength of the control specimens with 100% of bottom ash at 91 days was constant or slightly enhanced by use of 20–40% of fly ash and blast furnace slag.
- All specimens in this study may be classified as waterproof materials because the values of the water absorption coefficient \( k \) are smaller than 0.5 kg/(m\(^2\)h\(^{1/2}\)).

The results of this study can possibly be used to establish guidelines for practical applications of high volumes of fly ash and blast furnace slag as binders and bottom ash as fine aggregates in high-strength, lightweight mortar, which has slightly different characteristics than conventional normal-strength mortar.

**Acknowledgments**

This research was sponsored by a grant from System Integration for Hybrid Cable Stayed Bridge Program, Korea Institute of construction technology (KICT), and the National Research Foundation of Korea (NRF) grant funded by the Korean government (MEST 2012008855). The authors would like to thank to Mr. C.K. Lee, B.J. Yang, and Sam Na at KAIST for helping the experiment.

**References**