The Performance of Slag Containing Engineered Cementitious Composites

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Abstract. Engineered Cementitious Composite (ECC) is a type of fibre reinforced cement-based composite that is used in different construction applications. The use of fly ash in these composites improves tensile strain capacity, multiple cracking behaviour, and durability. However, fly ash is in short supply as many countries are in an effort to phase-out fossil fuels, and are eliminating coal plants. An alternative to fly ash is slag. In contrast to fly ash, the supply of slag is expected to be sustained. Hence, many industries have considered substituting fly ash with slag in the production of ECC. This study was designed to determine the mechanical, and permeability of ECC mixtures containing fly ash and slag. The study contained a total of four mixtures. Two of the mixtures had the ratio of supplementary cementitious materials to cement of 2.2 and two more mixtures had supplementary cementitious materials to cement ratio of 1.2. The water to binder ratio was the same for all mixtures. Test results showed that slag blends improved the mechanical and permeability characteristics.

Keywords: Engineered Cementitious Composites; Slag; Fly Ash; Strength; Durability.

1. Introduction

In recent years, there have been significant advancements in the research and development of high-performance fibre-reinforced cementitious composites (HPFRCC). Superior compressive strength can be achieved with HPFRCC due to its low water-to-cementitious materials ratio (W/CM). In addition,
studies have shown that HPFRC has high bending characteristics, improved durability, and good resistance to weathering conditions (Booya et al. 2020 and Li et al. 2018). Engineered cementitious composite (ECC) is a type of HPFRCC that is designed with micromechanical principles (Li 2003 and Li et al. 2001). These micromechanical principles enable the design of high performing composites with minimal amounts of reinforcing fibres. With a typical fibre amount of less than 2% by volume, it has been determined that tensile strain-hardening behaviour of ECC occurs after first cracking, and that strain capacities of ECC are 300 to 500 times higher than normal concrete. Furthermore, it is characteristic of ECC to exhibit self-controlled crack widths under increased loading. Effective fibre bridging and controlled matrix fracture lead to tight cracks in hardened ECC (less than 60 µm) (Şahmaran and Li 2009 and Zhu 2012).

Typical ECC consists of Type F fly ash as a supplementary cementitious material (SCM). However, various concrete associations around the world have reported a shortage in the supply of Class C and Class F fly ash (National Precast Association 2020). The shortage in fly ash supply is a result of the closure of coal-based plants as countries around the world move towards sustainable and green power sources (Booya et al. 2020).

Alternatively, the supply of slag blends, which is a by-product of the iron-making process, is expected to be sustained. Like fly ash, utilizing slag blends to produce ECC decreases environmental impacts. Slag blends enhances the composites’ performance and has more consistent chemical and physical characteristics compared to fly ash blends (Slag Cement Association). Therefore, concrete suppliers and construction companies often consider slag as a more reliable SCM.

Few studies on ECC containing slag blends have been undertaken. This study aims to expand the literature by investigating the influence of fly ash and slag, as a binary blend, on the durability and mechanical performance of ECC. The effects of replacing higher SCM volume on the durability and mechanical performance of the ECC mixtures were also determined. The strength and permeability of the ECC mixtures were assessed for compressive strength, four-point bending strength, chloride permeability, and immersion absorption.

2. Experimental Program

2.1 Materials

General use type cement (C) was used in all ECC mixtures. Type F Fly ash (FA) and slag (SG), which are commercially available, were utilized as supplementary cementitious materials (SCMs). The chemical and physical characteristics of the cement and SCMs satisfies the requirements and recommendations of CSA A3001, ASTM C989, and ASTM C618 standards. Oven dried sand with maximum particle size of 600 µm was used in all ECC mixtures. A water reducer agent (high range super plasticizer) conforming to ASTM C494, was used to attain workability in the ECC mixtures. Polyvinyl alcohol type fibres (PVA) of 39 µm diameter and 8 mm length were used. The specific gravity and tensile strength of these PVA fibres were 1.3 and 1600 MPa, respectively.

2.2 Mixture Design and Proportioning

All ECC mixtures had a water to binder (W/B) ratio of 0.25. Two mixtures had SCM/C ratio of 1.2 and sand to binder (S/B) ratio of 0.34. Another two mixtures were prepared with SCM/C ratio of 2.2 and sand to binder ratio of 0.36. Table 1 lists the mixture proportions of all ECC mixtures. From this table, the mixture IDs were selected to reflect the SCM type and the SCM/C ratio used in the ECC mixtures. For example, mixture FA2.2C refers to an ECC mixture that has zero slag content (only fly ash as SCM) and SCM/C ratio of 2.2, while SG1.2C refers to an ECC mixture that has slag (no fly ash) and SCM/C ratio of 1.2.
### Table 1: ECC Mixture Proportioning

| Mixture ID | SCM/C | S/B  | W/B  | Cement Content (Kg/m³) |
|------------|-------|------|------|------------------------|
| FA2.2C     | 2.2   | 0.36 | 0.25 | 380                    |
| SG2.2C     | 2.2   | 0.36 | 0.25 | 420                    |
| FA1.2C     | 1.2   | 0.34 | 0.25 | 600                    |
| SG1.2C     | 1.2   | 0.34 | 0.25 | 600                    |

#### 2.3 Testing Method

ASTM C109 was followed to determine the compressive strength of the produced ECC mixtures. Five cube specimens of 50 mm were tested, and the average value was reported at each testing age of 28, and 90 days.

Four-point bending test was performed on 355 mm x 75 mm x 75 mm prisms. ASTM C1609 recommendations were followed to conduct the testing. The prism deflection was obtained via a 25 mm linear variable displacement transducer (LVDT) that was positioned at the mid-span. The average flexural strength of three specimens was reported for the testing age of 28 and 90 days. Figure 1 shows the test setup for the four-point bending test.

The resistance chloride ion penetration of the ECC mixtures was assessed in accordance with ASTM C1202, and the charge passed through the disk specimen was monitored and calculated. For each ECC mixture, two 50 mm thick disks (cut from the mid-portion of a Ø100 mm diameter by 200 mm high cylinder) were prepared for testing ages of 28 and 90 days. After following the conditioning procedure specified in ASTM C1202, the disk specimens were attached to the testing cell with one face in contact with 3% NaCl solution and the other face in contact with 0.3N sodium hydroxide (NaOH) solution. A data acquisition system (DAQ) was employed to log the current (DC) of 60 ± 0.1 volts, and time over a period of six hours. The passed charge through the specimen was then calculated. The chloride permeability rating of concrete was then determined (ranging from “negligible” to “high”) per ASTM C1202.

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**Figure 1 – Flexural Strength Setup**
ASTM C642 recommendations were followed to determine the water absorption percentages. Two 50 mm thick cylindrical specimens were cut from Ø100 × 200 mm cylinder specimens. The specimens were conditioned, and oven dried for 24 hours, and then cooled to room temperature. The disk specimens were then immersed in 20°C water for a period of two days. The change in specimen mass was calculated. The two-day immersion water absorption was selected for each testing age of 28, and 90 days.

3. Results and Discussions

3.1 Compressive Strength

The compressive strength values of all ECC mixtures are shown in Figure 2. From this figure, it is obvious that mixtures with fly ash blends had the lowest compressive strength (FA1.2C and FA2.2C), regardless of the testing age. Among all mixtures, FA2.2C had the lowest compressive strength. ECC mixture SG1.2C had the highest compressive strength of 97.9 MPa, at 90 days. This is a 23% increase in strength when compared to ECC mixture FA1.2C. Slag has pozzolanic properties that are known to be advantageous for early age strength gain (Zhu et al. 2012). Therefore, it was expected that ECC mixtures with slag would exhibit higher strength gain at 3 and 7 days compared to ECC mixtures with fly ash only. Increasing the SCM/C ratio from 1.2 to 2.2 led to compressive strength reduction, as shown in Figure 2. This can be attributed to the lower cement content per cubic meter. Nonetheless, all ECC mixtures had compressive strengths higher than 51.1 MPa, at 28 days. Such value may satisfy the requirement of most construction and engineering applications.

![Figure 2 – Compressive strength of the mixtures at 28 and 90 days](image)

3.2 Flexural Strength

Figure 3 lists the ultimate flexural values for the ECC mixtures. From this table, the lowest flexural strength of 7.1 MPa was recorded for mixture SG2.2C, at 28 days. However, mixture SG1.2C had the highest flexural strength of 11.5 MPa and 12.2 MPa at 28 and 90 days, respectively. As can be seen in Figure 3, increasing SCM/C from 1.2 to 2.2 did not contribute to the increase in flexural strength for mixtures FA2.2C and SG2.2C, at 28 days, as compared to mixtures FA1.2C and SG1.2C. For mixtures containing fly ash, FA1.2C, and FA2.2C had a maximum flexural strength of 9.2 MPa and 8.5 MPa, respectively. The flexural strength of mixtures containing fly ash improved at the age of 90 days with FA1.2C and FA2.2C reaching flexural strengths of 10.5 MPa and 9.1 MPa, respectively. It is worth mentioning that at both testing ages, and in all ECC mixtures, very tiny and multiple cracking behaviour was observed.
3.3 Rapid Chloride Penetration

Chloride transfer through cementitious materials often led to major defects, particularly when chloride ions reach embedded steel reinforcements. The penetration of chloride ions causes the formation of rust products, resulting in reduced durability and service life of cement-based structures (Booya et al. 2018 and Booya et al. 2019). The rapid chloride ion permeability test (RCPT) is a way of assessing and evaluating the long-term durability of concrete (Booya et al. 2020). Table 2 lists the chloride penetration charges in coulombs that passed through the specimen after a period of 6 hours. ECC mixtures containing fly ash minerals had higher charges compared to mixtures with slag only blends, regardless of the SCM/C replacement ratios. However, the extended curing periods showed a reduction in the charges passed for all mixtures. At 90 days, all mixtures had less than 1000 Coulombs which can be categorized as “very low”, per ASTM C1202.

**Table 2: RCPT Charges and ratings as per ASTM C1202**

| Mixture ID  | SG2.2C | FA2.2C | SG1.2C | FA1.2C |
|------------|--------|--------|--------|--------|
| 28 day     | <1000  | <1500  | <800   | <1000  |
| Rating     | Very Low | Low    | Very Low | Very Low |
| 90 day     | <700   | <800   | <500   | <400   |
| Rating     | Very Low | Very Low | Very Low | Very Low |

3.4 Immersion Absorption

The immersion water absorption test is a way of assessing and estimating the total interconnected pores that water can reach in cementitious composites. The two-day absorption test results are shown in Figure 4. Mixture FA1.2C had the largest absorption of 1.92% and 1.73% at 28 and 90 days, respectively. It is evident from this table that higher slag volumes reduce water absorption. Hence, SG2.2C had the highest reduction in water absorption among all ECC mixtures, at both testing ages. The reported absorption value for mixture SG1.2C is 1.75% and 1.62% at 28 and 90 days, respectively. Furthermore, the absorption percent value for mixture SG2.2C was reduced by 37.1% and 41.4% at 28 and 90 days, respectively, when compared to mixture SG1.2C.
4. Conclusions

Below are the main conclusions that can be drawn based on the experimental results presented in this paper. The conclusions made herein are limited to the specimens, and conditions used in the study.

- Mixtures incorporating slag had increased compressive strength values in comparison to the fly ash only mixtures, at 28 and 90 days. Slag improved early age strength. Increasing the SCM/C amount from 1.2 to 2.2 led to lower compressive strengths. Nonetheless, all ECC mixtures had compressive strength value of at least 51.1 MPa at 28 days. Extended the curing period (up to 90 days) was effective in increasing the compressive strength.

- Slag addition improved the flexural strength. However, higher fly ash amount (i.e., SCM/C = 2.2) replacement in mixture FA2.2C provided better flexural characteristics.

- The RCPT results indicated that slag blends are more effective in reducing chloride ion transfer compared to fly ash blends, at 28 days. However, prolonged curing period resulted in low chloride ions penetration rating for all ECC mixtures.

- The immersion absorption percent values revealed that slag blends are more effective than fly ash blends in reducing the water absorption. Therefore, incorporating higher slag amount resulted in greater reductions. Increased SCM/C amount from 1.2 to 2.2 reduced the water absorption.

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