Compressive Strength, Splitting Tensile Strength, and Chloride Penetration Resistance of Concrete with Supplementary Cementitious Materials

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Abstract. This article presents the outcomes of a study that examined the durability and mechanical characteristics of self-consolidating concrete (SCC) mix in which a percentage of the required ordinary Portland cement (OPC) was substituted with either fly ash or ground granulated blast furnace slag (GGBS). The first part of the study evaluates the chloride penetration resistance and compressive strength of SCC mixes in which OPC in a designed control mix was partially replaced in a series of mixes by fly ash in percentages ranging from 10% to 40%. It noted that replacing OPC with fly ash at each of the four percentages studies improved chloride resistance of concrete compared to the control mix made of 100% OPC as binder. The 40% fly ash mix was the best performer in terms of resistance to chloride migration in contrast with the 100% OPC mix. Samples prepared using the 40% fly ash mix SCC mixes had the lowest compressive strength after 7 days of moist curing. However, the 28-day compressive strength of 40% fly ash mix was a healthy 55.75 MPa, only slightly lower than the 100% OPC mix. Tests also showed that adding 2% or fewer basalt fibres to the SCC mix in which 40% of OPC improves concrete resistance to chloride migration in contrast with the 40% fly ash mix that didn’t contain basalt fibres. This paper also reports the relationship between splitting tensile strength and compressive strength of SCC mixes in which up to 80% of OPC was substituted with GGBS. A total of eight mixes were produced by varying the amounts of GGBS used to replace the OPC content of the control mix. The fresh properties were assessed through the flow test, visual stability index (VSI), and the T50. An empirical relationship was developed to predict the splitting tensile strength based on 28-day compressive strength, and its accuracy was evaluated in comparison to formulas in various design codes.

1. Introduction
In the absence of adequate concrete cover, chlorides in deicing salts, in marine environments, or the soil supporting concrete foundation can penetrate concrete elements and reach the reinforcing bars. Corrosion begins if a sufficient concentration of chloride ions is reached around the reinforcing bars.

ASTM class F fly ash is a popular pozzolan used in producing sustainable SCC by partially replacing Portland cement. SiO2 and Al2O3 are believed to be the primary drivers of fly ash pozzolanic activity as they react with calcium hydroxide produced by hydration of OPC. This reaction leads to the production of more Calcium Silicate Hydrate (CSH) as well as Calcium Aluminate Hydrate (CAH), both of which have the dense matrix that enhances compressive strength as well as resistance chloride penetration. In addition, fly ash is effective in enhancing concrete resistance to alkali-silica reaction.
(ASR) and mitigating damage to freezing and thawing. ASR as well as freezing and thawing were shown to be extremely detrimental to concrete compressive strength in the long-term [1,2].

The resistance of SCC to chloride migration is enhanced when incorporating fly ash [3]. The Rapid Chloride Penetration Test (RCPT) is one of the most commonly used methods for the evaluation of the resistance of concrete to chloride migration. Most published work reports testing conducted on samples at the age of 28 days or more.

The potential downside to using fly ash to replace part of the required cement in a particular concrete mix, is the decrease in concrete compressive strength. In general, fly ash decreases the rate of strength development in comparison to a control mix. It was reported that in a binary mix, the replacement of 15% of OPC by fly ash produces optimum results, i.e., limited or no reduction in compressive strength occurs at the ages of 28 and 56 days, compared to the control mix [4]. Finely ground ASTM class F fly ash having a higher specific surface was reported to decrease water demand and enhance resistance to chloride penetration, more than coarser fly ash [3]. The rate of pozzolanic reaction of finely ground fly ash is generally higher than coarser fly ash [5]. Ultra-fine fly ash (UFFA), which contains 8% special ultra-fine fly ash, was reported to have the additional advantage of providing high early strength, along with decrease in a volume of permeable voids, in compared to the control concrete mix [6].

It was shown in a 5-year-long study that resistance of concrete to chloride penetration is enhanced significantly when fly ash replacement of OPC is as high as 50%, along with lower water-to-binder (w/b) ratio [7]. At the early age of concrete up to 7 days, tests show that ternary blends with ASTM class F fly ash and silica fume produce superior resistance to chloride migration compared to control mixes prepared using 100% OPC as a sole binder [8].

GGBS, a by-product of steel manufacturing, consists primarily of calcium silicates in addition to another bases. The typical total concentration of the mineral elements in the GGBS is about 95% [9]. These minerals are mostly consisting of silicon, calcium, and aluminum and they are responsible for its cementitious properties [10].

2. Materials and test procedures
2.1 Fly Ash as Supplementary Cementitious Material

The SCC mixes were prepared using ASTM Type I cement and ASTM class F fly ash. All mixes were prepared using a polycarboxylic ether High Range Water Reducing (HRWR) admixture compliant with ASTM C-494. Type F fly ash was used to prepare SCC mixes with the low w/b ratio, as detailed in the upcoming sections of this paper.

Basalt fibres are added to selected SCC mixes to investigate their effect on strength and chloride penetration resistance. Basalt fibres used in this study were 6 mm long x 13 micrometres in diameter, on average. The monofilaments used to produce the fibres were obtained from natural basalt rock, therefore, recyclable and contribute to energy efficiency of the sustainable SCC mix considered in this study. Mineral composition of the basalt fibres used is detailed in the study by Mohamed and Al-Hawat [11].

In order to assess the ability of fly ash to enhance the resistance of concrete to chloride migration, several SCC mixes were designed in which 10%, 20%, 30%, or 40% of the required OPC was substituted with fly ash. The control mix did not contain any fly ash. Samples were cured underwater for 3 days, 7 days, and 28 days, then tested to determine the compressive strength. The SCC mixes are shown in Table 2. Details of the study can be found in Mohamed and Al-Hawat [11]. In all mixes, the total coarse aggregate used was 800 kg/m³, black sand fine aggregate was 582.4 kg/m³, dune sand fine aggregate used was 313.6 kg/m³, superplasticizer used was 7.2 kg/m³, and water content used was 172.8 kg/m³. The cement and fly ash contents were varied as shown in table 1.
The effect of basalt fibers on the chloride penetration resistance and compressive strength was investigated by adding 1.0%, 1.5%, and 2% basalt fibers and producing three variations of the 40% fly ash SCC mixes.

### Table 1. Control SCC mix and 4 other mixes where OPC was replaced with class F fly ash

| Mix type | Control Mix | FA10 | FA20 | FA30 | FA40 |
|----------|-------------|------|------|------|------|
| Cement [kg/m³] | 480 | 432 | 384 | 336 | 288 |
| Fly ash [kg/m³] | 0 | 48 | 96 | 144 | 192 |

#### 2.2 GGBS as Supplementary Cementitious Material

A total of 8 mixes was produced for this study including one control mix containing 100% OPC as the only binder, and 7 sustainable SCC mixes in which a different percentage of OPC in the control mix was replaced with GGBS. The control mix was designed as high strength SCC with acceptable flowability after prescribed period of continuous mixing. Standard 150 mm cubic samples and 100 mm x 200 mm cylindrical samples were cured under water for 3 days, 7 days, and 28 days, then cubes were tested to determine compressive strength. The splitting tensile strength was determined by testing the 100 mm x 200 mm cylinders. Details of the study can be found at Mohamed and Najm [12].

Flowability of SCC mixes was achieved using HRWA that is based on polycarboxylic ether. The initial dosage on all mixes was 1.5% which was slightly adjusted as the percentage of GGBS is increased to control segregation and bleeding. In all SCC mixes investigated in this part of the study, the total content of cementitious materials, which includes OPC and GGBS, was maintained at 480 kg/m³ and the w/b = 0.36, for all SCC mixes. For each SCC mix, the total content of coarse aggregates passing 14 mm sieve size was 800 kg/m³. Fine aggregates were a mixture of two types, black sand in the amount of 582.4 kg/m³ and dune sand in the amount of 313.6 kg/m³ dune sand. Table 2 details the design mixes.

### Table 2. SCC binary OPC-GGBS mixes

| Name | OPC [kg/m³] | GGBS | OPC % | GGBS % |
|------|-------------|------|-------|--------|
| Control | 480 | 0 | 100 | 0 |
| GS 10 | 432 | 48 | 90 | 10 |
| GS 35 | 312 | 168 | 65 | 35 |
| GS 45 | 264 | 216 | 55 | 45 |
| GS 50 | 240 | 240 | 50 | 50 |
| GS 60 | 192 | 288 | 40 | 60 |
| GS 70 | 144 | 336 | 30 | 70 |
| GS 80 | 96 | 384 | 20 | 80 |

The flowability and stability of all mixes were assessed in accordance with BS1881:105 [13]. Trial mixes were used to adjust the dosage of superplasticizer to achieve a flow target of 550 mm ± 50mm after mixing for 80 minutes. After mixing is completed the T50, the time it takes concrete flow to reach an average diameter of 50 cm was noted as a measure of concrete flowability. The stability of concrete mixes as indicated by the presence of segregation and/or bleeding was assessed using the visual stability index (VSI).

The compression test was conducted on 150 mm concrete cubes based on the procedure outlined in BS1881:116 [14]. The splitting tensile strength was tested in accordance with BS 1881-117 [15] by
testing 100 mm x 200 cylinders. Cubes and cylinders were cured underwater until the day of mechanical testing. Generally speaking, the mechanical properties of concrete are influenced by the curing method. However, curing by submerging specimens underwater typically produces reliable results in contrast with air curing or chemical curing [16].

It was decided in this study to correlate the splitting tensile strength measured on cylinders to the compressive strength of cylinders. Therefore, the compressive strength of cubic samples determined in this study was converted to an equivalent cylindrical strength using Eqn (1) proposed by Mansur et al [17].

\[
(f_{cu})_{150} = (f'c)_{100x200} + 6.41
\]  

(1)

3. Test results and discussions

3.1 Test Results on Fly Ash as Supplementary Cementitious Material

The effect of fly ash and basalt fibres on resistance of concrete to chloride penetration as well as compressive strength of SCC mixes is discussed in the following sections.

The compressive strength of the 100% OPC mix and the various fly ash mixes was determined after curing samples for 3 days, 7, and 28 days, the results are shown in figure 1. The w/b ratio was 0.37 for each SCC mix. After 3-days and 7-days of curing, the typical slow fly ash pozzolanic reactivity was clear as the 100% OPC mix produced higher compressive strength than mixes that contained fly ash. Specimens tested after 28-days of curing, the compressive strength increased with the amount of fly ash until a fly ash replacement percentage 20%, then dropped when the fly ash amount is increased to 30%.

Figure 1 also shows that the SCC mix in which 40% of OPC was substituted with fly ash exhibited the lowest compressive strength of all other mixes after 3 and 7 days of curing which is due to the slow reactivity of fly ash, especially when such high amount of OPC is replaced. However, samples prepared using the 40% fly ash mix approached the strength of the 30% mixed samples after curing for 28-days.

The results are consistent with published research on the effect of fly ash on compressive strength development of [18]. However, the mix in which 20% of OPC was substituted with fly ash exhibited the highest 28-day compressive strength compared to the 100% OPC mix as well as the mixes in which 10%, 30%, and 40% of OPC was substituted with fly ash.

**Figure 1.** Effect of basalt fibre on compressive strength of self-consolidating concrete mixes with 40% fly ash replacement
In order to understand the influence of basalt fibres on compressive strength of concrete, the self-consolidating concrete mix containing 40% fly ash, which exhibited the least strength after 28 days of curing, was chosen to be supplemented with basalt fibres. Three additional mixes with 40% fly ash were tested, one with the addition of 1% basalt fibres, a second with 1.5% basalt fibres and a third with 2% basalt fibres. Figure 1 shows the results of compressive strength testing of samples cured for 3, 7, and 28 days. In figure 1, FA40 indicates SCC mix in which 40% of the required OPC was substituted with fly ash, while BF stands for Basalt Fibers. The SCC mix which contains 1% basalt fibres offered the highest 28-day compressive strength. Therefore, for this SCC mix, adding 1% basalt fibres permits the replacement of 40% of the required OPC with fly ash while exhibiting a strength very close to replacing only 20% of the OPC with fly ash.

RCPT was done in accordance with ASTM C1202 on SCC mix samples. RCPT determines the electrical conductance of concrete as an indicator of concrete resistance to the penetration of chloride ions. An electrical current is sent across 100 mm x 50 mm concrete cylinders. From the results of RCPT test, the following observations were made:

- The coulomb charge of the control mix measured after 7 days of curing is higher than the fly ash mixes, indicating that mixes containing fly ash have resistance to chloride penetration in comparison to 100% OPC concrete mixes.
- In all mixes, the coulomb charge decreases with curing time. The mixes with 30% and 40% fly ash produced similar resistance to chloride penetration at 7 days.
- After 14 days of curing, the mix with 40% fly ash demonstrated the best resistance to chloride migration in comparison to all other mixes.

Figure 2 shows the measured charge (in coulombs) for control and fly ash SCC mixes. The highest resistance to chloride migration of all the tested mixes was exhibited by the SCC mix containing 40% fly ash. The effect of basalt fibres on resistance of SCC to chloride penetration is assessed by creating three variations of the 40% fly ash mix, one mix contains 1% basalt fibres, the second contains 1.5% basalt fibres, and the third contains 2% basalt fibres.

Figure 2. Variation of coulomb charge based RCPT and concrete curing days

Figure 3 shows the chloride penetration test results of samples after 7-days of curing. It is evident that increasing the content of fly ash enhances the resistance to chloride migration as indicated by the decreasing charge passed. The 40% fly ash mix that contains basalt fibres exhibited higher resistance to chloride migration in contrast to the 40% fly ash mix in which no basalt fibres were added.
Figure 3. Variation of coulomb charge obtained in RCPT and concrete during days for basalt fibers fly ash mixes

3.2 Test results on GGBS as a supplementary cementitious material
All mixes containing GGBS exhibited flow diameter ranging from 45 to 58 cm indicating acceptable flowability for all GGBS replacement percentages. However, the viscosity of concrete mixes containing GGBS decreased with an increase in replacement percentage. The stability of the mix was measured through the VSI test and showed that the increase of GGBS replacement beyond 35% increases the tendency to segregation and/or bleeding. These findings are consistent with those reported by Boukendakdi et al [19]. Nonetheless, the VSI value in this study didn’t exceed 1.0, which indicates acceptably low level of segregation and/or bleeding, and may be controlled by adjusting the HRWR admixture dosage and/or viscosity modifying admixture.

The 28 days strength of 10, 35, 45, 50, 60, 70, and 80% replacement was 66.75, 81, 74, 75.66, 62, and 50.45 MPa, respectively. Figure 4 demonstrates the strength development of the GGBS mixes after the designated curing periods. The strength development of GGBS mixes at early ages was very close to that of the 100% OPC mix. Meanwhile, the 28 days strength results showed that even with high replacement percentage of OPC with GGBS, the strength of concrete is still considered to be high and it can be used for many structural applications. GS45, where 45% of OPC was replaced with GGBS exhibited the highest splitting tensile strength. Figures 4 and 5 show GS35, in which 35% of OPC was replaced with GGBS had the highest maximum compressive strength.

Figure 4. Compressive strength of control and GGBS SCC mixes after 3-, 7-, and 28-days of curing
In general, splitting tensile strength increases with 28-day compressive strength as indicated by the pattern in figure 5.

![Figure 5. Tensile strength versus 28-day compressive strength of SCC mixes with up to 80% GGBS [10]](image)

Figure 5. Tensile strength versus 28-day compressive strength of SCC mixes with up to 80% GGBS [10]

It is common to use a form of Eqn. 2 to relate tensile strength of concrete to compressive strength. Therefore, it is used in this study to evaluate the ability of formulas proposed by selected building codes to predict the tensile strength using data generated in this study.

\[ f_{sp} = k \times (f'_{c})^n \]  

(2)

Table 3 shows the recommended values of “k” and “n” in selected design codes where lack of consensus is clear. In addition, code-based splitting tensile strength prediction models are adopted for normal concrete without reference to replacement of cement by a cementitious material such as fly ash or slag.

| Source         | k    | n  |
|----------------|------|----|
| ACI318-11      | 0.56 | 0.5|
| JCI            | 0.13 | 0.85|
| JSCE,2007      | 0.23 | 2/3|
| CEB-FIB        | 0.3  | 2/3|

Regression analysis was conducted in the current study, to calculate the coefficients “k” and “n” and their values are compared to those reported by selected code/standards as shown in Table III. The integral absolute error (IAE) given by Eqn. 3, was used to evaluate the coefficients “k” and “n”.

\[ IAE = \left( \frac{\sum (O_i - P_i)^2}{\sum O_i} \right)^{1/2} \times 100 \]  

(3)

Oi is the value measured experimentally, and Pi is the predicted quantity from the regression model that is being evaluated.

The lower the value of IAE, the higher the prediction accuracy. IAE value as high as 10% is considered acceptable for this type of regression analysis related to concrete strength [20]. Table 4 shows that ACI 318-11, JCI, CEB-FIB underestimate the splitting tensile as indicated by the high value of IAE. JSCE-2007 offered the closest prediction of the splitting tensile strength as indicated by the IAE value of 5%, which is the same finding reported by Mohamed et.al [21].
Table 4. IAE% analysis for different codes

| Source                                           | IAE% |
|--------------------------------------------------|------|
| American Concrete Institute (ACI318-11)          | 25%  |
| Japanese Concrete Institute (JCI)                | 24%  |
| Japanese Society of Civil Engineers (JSCE 2007)  | 5%   |
| CEB-FIB                                          | 34%  |

JSCE-2007 does not address the applicability of its splitting tensile strength formula when high volume GGBS or other supplementary cementitious materials are used. However, figure 6 shows that this code predicted the test data of this study with the highest accuracy.

Using regression analysis of the data produced in this study, an expression is developed to predict the splitting tensile strength based on the 28-day compressive strength of SCC mixes where up to 80% of OPC is replaced with GGBS. Eqn (4) is proposed with IAE value of 2.4% reflecting reliably high accuracy (Figure 7).

\[ f_{spt} = 0.8 \times (f'_c)^{0.36} \] (4)

Figure 6. Predicting splitting tensile strength based on selected codes

Figure 7. Regression analysis for GGBS data sets
4. Conclusions

- Sustainable SCC mix where fly ash was used to replace 40% of the required OPC content, offers a significant improvement in resistance to chloride migration in contrast with the control mix preparing using 100% OPC. The SCC mix in which 40% of OPC was replaced fly ash mix reached a healthy 28-day compressive strength of the 55.75 Mpa.
- Resistance of the self-consolidating concrete to chloride migration improved by adding basalt fibres in the amounts of 1%, 1.5%, and 2% to the mix with 40% fly ash in contrast with the same mix without basalt fibers. The SCC mix with 40% fly offered the best resistance to chloride migration in contrast to mixes with lower percentages of fly ash.
- Self-consolidating concrete with 20% fly ash replacement of Portland cement offered improved resistance to chloride migration in comparison with the control SCC mix, as well as the highest 28-day compressive strength in contrast with the control mix and as well as all mixes with fly ash replacement ratios higher or lower than 20%.
- Seven SCC mixes were prepared where GGBS was used to 10% to 80% of OPC. Tensile strength prediction models provided by selected building codes were evaluated against test data in this study. Four codes underestimated the splitting tensile strength of concrete. JSCE07 offered the highest ability to predict splitting tensile strength. A high accuracy prediction formula using regression analysis of the test data was proposed and evaluated.
- SCC mix in which 35% of OPC was substituted with GGBS exhibited the highest compressive strength after 28-days of moist curing, in contrast with the 100% OPC mix and compared to all other GGBS replacement percentages.

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