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Durability and Compressive Strength of High Cement Replacement Ratio Self-Consolidating Concrete

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Abstract: This study examines durability and mechanical properties of sustainable self-consolidating concrete (SCC) in which 80% of the cement is replaced with combinations of recycled industrial by-products including fly ash, silica fume, and ground granulated blast furnace slag (GGBS). The water to binder (w/b) ratio of SCC mixes studies was maintained at 0.36. The study proposes empirical relationships to predict 28-day compressive strengths based on the results of three-day and seven-day compressive strengths. In addition, the chloride penetration resistance of the various sustainable SCC mixes was determined after three days, seven days, and 28 days of moist curing of concrete standards. It was concluded that fly ash, silica fume, and GGBS contribute favorably to enhancing strength development, fresh properties, and durability of SCC in comparison to ordinary Portland cement (OPC). The compressive strength of the sustainable SCC mixes falls within ranges suitable for structural engineering applications. Replacing cement with 15% silica fume produced a 28-day average compressive strength of 95.3 MPa, which is 44.2% higher than the control mix. Replacing cement with 15% or 20% silica fume reduced the chloride ion permeability to very low amounts compared to high permeability in a control mix.

Keywords: self-consolidating concrete; fly ash; silica fume; GGBS; compressive strength; sustainability

1. Introduction

The construction industry contributes to environmental pollution including the production of cement used in the concrete industry. Production of cement involves the emission of appreciable amounts of CO_2 into the atmosphere. Therefore, it is imperative that the use of cement in concrete is reduced or eliminated. Industrial byproducts such as fly ash, silica fume, and ground granulated blast furnace slag (GGBS) needs to be recycled appropriately. This study examines the properties of sustainable self-consolidating concrete (SCC) in which up to 80% of the cement is replaced with various combinations of fly ash, silica fume, and GGBS. Therefore, the sustainable SCC mixes examined in this study contribute to both the reduction of the use of cement and the recycling of industrial byproducts. Transferring and handling concrete over large distances from delivery vehicles to the point of placement in the structure can cause segregation of concrete material [1]. However, SCC can be proportioned to flow longer distances while maintaining their stability with limited or no segregation.

SCC is characterized by the high flow-ability and ability to consolidate under its own weight without vibration. SCC mixes contain higher paste and lower coarse aggregate volumes compared to conventional concrete. The use of high-range water reducing (HRWA) admixtures and smaller aggregate size along with high flowability and self-compaction all contribute to denser, higher strength concrete that is also durable.

Studies have shown that replacing cement with 20% fly ash in binary mixes increases the 28-day compressive strength compared to a control mix [2,3]. Both studies indicate that chloride penetration resistance is enhanced by replacing cement with 20% fly ash. Yazıcı [4] indicated that replacement of cement in SCC mixes results in loss of concrete compressive strength during the early stages, but, in many cases, a significant increase in compressive strength develops during later stages.

Adding 3.8% silica fume improves compressive strength, splitting, tensile strength, and durability of SCC mixes Quercia [5]. It was found that replacing 15% of cement by silica fume resulted in a 28-day compressive strength of 95.3 MPa, which was 44% higher than the control SCC mix examined in the study by Mohamed and Najm [6]. Due to their spherical morphology, which reduces inter-particle friction, both silica fume and fly ash enhance workability and is essential for producing high strength concrete.

Partial replacement of cement in SCC with various industrial byproduct wastes such as limestone power, cement kiln dust, and pulverized steel slag improves resistance to chloride penetration [7]. Other studies, however, contend that, under laboratory conditions, the durability of SCC and traditional vibrated concrete may be comparable [8] and that using Rapid Chloride Penetration Test (RCPT) to assess durability of SCC does not produce reliable results. However, the same study acknowledges that the quality of compacting vibrated concrete onsite is unlikely to reach the quality of SCC. As a result, concrete structures built with SCC may still be more durable.

Partial replacement of cement with GGBS in SCC enhances compressive strength and durability. In one study, it was shown that replacing 70% of cement in a particular SCC mix resulted in strength as high as the control SCC mix [9].

Alkali-silica reaction (ASR) may lead to significant long-term damage and degradation of concrete properties [10]. GGBS is known to improve concrete resistance to damage caused by ASR. Splitting tensile strength of SCC containing GGBS may not be predicted by using the same ACI 318 formula originally developed for conventional concrete [11]. Prediction formulas for splitting tensile strength of SCC mixes with high cement replacement ratios were proposed in the literature [12] for cement replacement materials including fly ash, silica fume, and GGBS.

Miura and Iwaki [13] studied strength development of concrete samples cured by using different methods. The percentage of cement that was replaced with GGBS ranged from 50% to 80%. The authors argued that, under severe environments such as marine structures and structures affected by deicing salts, 80% of cement replacement with GGBS may be necessary. The 28-day compressive strength for each replacement ratio from 50% to 80% was lower than the control concrete mix made of 100% ordinary Portland cement. The same trend was observed for compressive strength after 56 days and 91 days of curing.

This paper presents the findings of a study in which mechanical properties and durability of sustainable binary and quaternary SCC mixes are evaluated. The study presents the compressive strength development after three days, seven days, and 28 days of curing and proposes prediction formulas for the average 28-day compressive strength based on three days or seven days of compressive strength. The resistance to chloride penetration of the various SCC mixes is examined after 1, 3, 7, 28, and 40 days of curing.

2. Experimental Program

The material properties and experimental program to evaluate compressive strength development and durability of the SCC mixes is described in this section.

2.1. Material Properties

The cement used in this study is Type 1 conforming with ASTM C150/C150M [14] and complies with the requirements of BSI EN 197-1:2011 [15], which is categorized under the strength class of 42.5 N. The type of fly ash used in this research complies with BSI 3892 Part 1 and BSI EN 450 S [16,17]. The GGBS used in this project complies with BSI 6699:1992 [18]. The specific surface areas of cement, GGBS, fly ash, and silica fume are 348, 440, 410, and 23,000 m^2/kg, respectively. The chemical properties of cement, fly ash, silica fume, and GGBS are listed in Table 1.

Table 1. Chemical Constituents of Cement, Fly Ash, Silica Fume, and GGBS.

Chemical Properties	Cement (%)	GGBS (%)	Fly Ash (%)	Silica Fume (%)
Silicon dioxide, SiO_2	20.62	34.24	37	93.17
Alumina, Al_2O_3	4.87	13.75	9.89	0.14
Iron Oxide, Fe_2O_3	3.35	1.10	4.45	0.04
Calcium oxide, CaO	63.87	42.26	21	0.89
Magnesium oxide, MgO	1.54	5.88	3.5	0.51
Sulphur trioxide, SO_3	2.5	0.24	1.91	0.004
Sodium oxide, Na_2O	–	0.28	0.56	0.58
Potassium oxide, K_2O	–	0.32	–	2.01
Loss on ignition (LOI)	1.5	0.72	3.12	2.43

The sieve analysis results for coarse and fine aggregates are shown in Figure 1 and the fineness modulus for fine aggregates was 3.56 mm. The maximum coarse aggregates size was 10 mm and the maximum fine aggregates size was 5 mm.

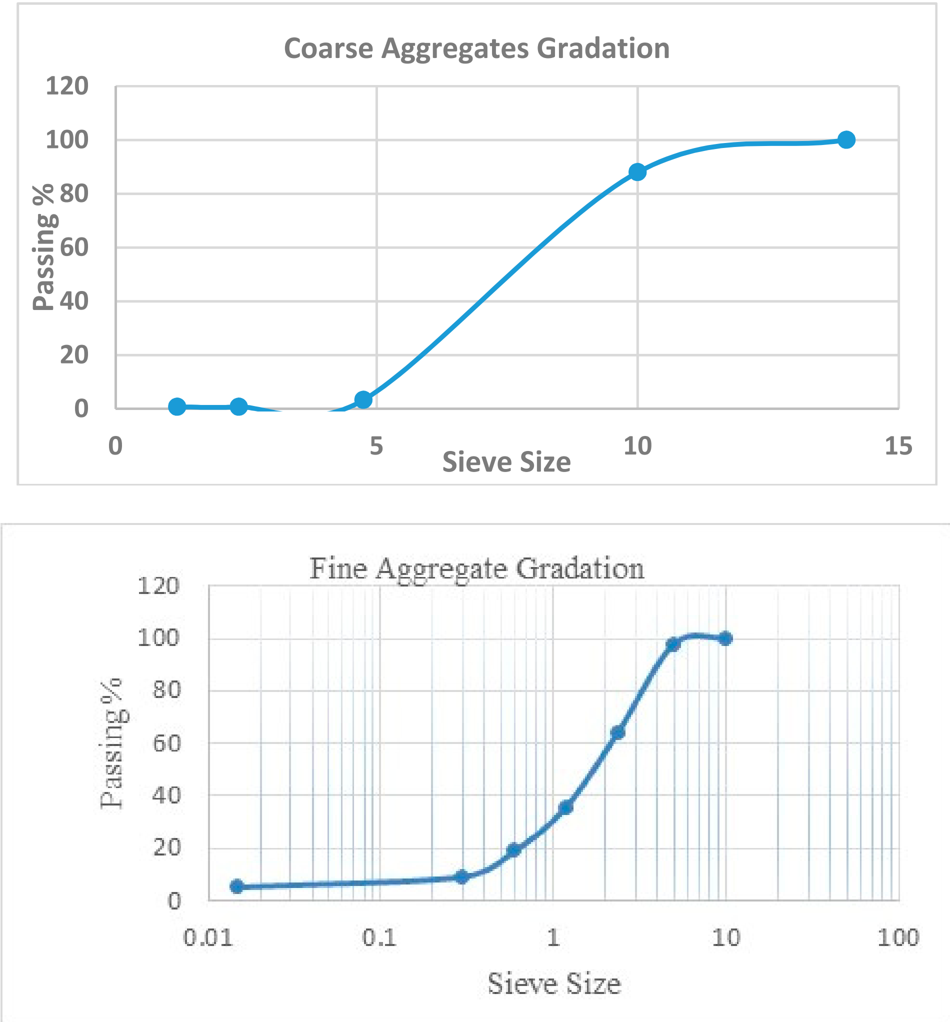

Figure 1. Sieve analysis of coarse and fine aggregates.

2.2. SCC Mix Proportions

A total number of 32 SCC mixes were produced as binary and quaternary mixes with different dosages of supplementary cementitious materials (SCMs). In binary SCC mixes, cement was partially replaced with different percentages of fly ash (FA), silica fume (SF), or GGBS. In quaternary mixes, referred to in this paper as green concrete, 80% of the cement is replaced with various combinations of fly ash, silica fume, and GGBS. The water content was kept at 172.8 kg/m^3 and total binder (cement + SCM) of 480 kg/m^3 resulted in a water-to-binder (w/b) ratio of 0.36 in all mixes. Meddah et al. [19] demonstrated that reducing the w/b ratio below 0.45 not only increases compressive strength but also decreases the chloride coefficient of diffusion, which improves durability. In all mixes, natural coarse aggregate content was 800 kg/m^3 while fine aggregates consisted of 582.5 kg/m^3 sand combined with 313.6 kg/m^3 of dune sand. The dosage of the superplasticizer was maintained at 7.2 kg/m^3.

Three groups of binary mixtures were produced. In the first group, Portland cement was partially replaced with fly ash at percentages of 10%, 15%, 20%, 25%, 30%, and 40%. In the second group, cement was partially replaced with 5%, 10%, 15%, and 20% silica fume. In the third group, the percentage of cement replaced with GGBS was 10%, 25%, 35%, 45%, 50%, 60%, 70%, and 80%. Table 2 summarizes the amounts of cement fly ash, silica fume, and GGBS in the three binary mixes. Similarly, the cement and SCMs constituents of quaternary mixes are summarized in Table 3. Mixes in which 80% of the cement was replaced with combinations of fly ash, silica fume, and GGBS are referred to as Green Mixes (GM) and numbered 1 to 7. In quaternary mixes GM1 to GM7, 80% of the cement was replaced with combinations of fly ash, silica fume, and GGBS and the cement content is maintained at 96 kg/m^3.

Table 2. Cement, fly ash, silica fume, and GGBS amounts in binary mixes.

Binary Mix	Mixture Type	Cement kg/m^3	FA kg/m^3	SF kg/m^3	GGBS kg/m^3
	Control Mix	480	0	0	0
Cement + fly ash	FA10	432	48	0	0
	FA15	408	72	0	0
	FA20	384	96	0	0
	FA25	360	120	0	0
	FA30	336	144	0	0
	FA40	288	192	0	0
Cement + silica fume	SF5	456	0	24	0
	SF10	432	0	48	0
	SF15	408	0	72	0
	SF20	384	0	96	0
Cement + GGBS	GGBS10	432	0	0	48
	GGBS25	360	0	0	120
	GGBS35	312	0	0	168
	GGBS45	264	0	0	216
	GGBS50	240	0	0	240
	GGBS60	192	0	0	288
	GGBS70	144	0	0	336
	GGBS80	96	0	0	384

Table 3. Cement, fly ash, silica fume, and GGBS amounts in green mixes.

Mixture Type	Cement Kg/m^3	FA kg/m^3	SF kg/m^3	GGBS kg/m^3
GM 1	96	96	48	240
GM 2	96	120	72	192
GM 3	96	72	24	288
GM 4	96	72	72	240
GM 5	96	48	72	264
GM 6	96	72	96	216
GM 7	96	48	96	240

3. Results and Discussion

This section describes the results the experimental program to evaluate the compressive strength development and to assess the durability of SCC mixes by using the rapid chloride penetration test.

3.1. Development of Compressive Strength in Sustainable SCC Mixes

The compressive strength was tested after 3-days, 7-days, and 28-days of moist curing of standard 150 × 150 × 150 mm cubes according to BS EN 12390-3:2009 [20]. Table 4 shows the compressive strength results of all binary mixes.

Table 4. 3-day, 7-day, and 28-day compressive strength of binary mixes.

	Compressive Strength (MPa)		
	Curing A		
Mixture Type	3-days	7-days	28-days
Control Mix	51	61.48	66.08
FA 10	46.3	54.3	61.325
FA 15	42	50.3	62.5
FA 20	46.225	50.025	67.96
FA 25	38.6	43	61.7
FA 30	38.6	46.4	56.5
FA 40	31.43	36.7	55.75
SF 5	28.11	56.7	72.3
SF 10	49	58.5	81.11
SF 15	55.65	71.45	95.3
SF 20	37.3	53.41	75.83
GGBS 10	51	58.5	66.75
GGBS 25	52.02	65.3	77.53
GGBS 35	45.93	66.33	81
GGBS 45	51.55	65.54	78.4
GGBS 50	43.5	56.11	74
GGBS 60	59.66	63.95	75.655
GGBS 70	46.7	60.42	62
GGBS 80	41.9	43	50.45

The results show that the control mix achieved a 28-day compressive strength of 66.08 MPa. All fly ash/cement binary mixes had a lower compressive strength after 3 days and 7 days of curing when compared to the control mix. However, replacing the cement with 20% fly ash produced an SCC mix with a 28-day compressive of 67.96 MPa, which slightly exceeded the compressive strength of the control mix. The optimum 20% fly ash replacement ratio is consistent with findings in the literature including the study by Celik et al. [21] where the 28-day compressive strength matched the control mix. Figure 2 shows the compressive strength development of fly ash mixes. Note that replacing cement with as much as 40% fly ash (FA 40) still produces 28-day compressive strength of 55.75 MPa. It will be demonstrated later in this paper that 40% cement replacement with fly ash produces excellent resistance to chloride penetration in the binary SCC mix with 1-day of during. Studies on 19- to 24-year-old concrete in harsh marine environments show that the depth of chloride penetration was significantly reduced when compared to the control mix [22].

Figure 3 shows using silica fume as cement replacement improves the 28-day compressive strength compared to a control mix for all replacement percentages between 5% and 20% examined in this study. Replacing 15% of cement with silica fume increased compressive strength significantly after 3 days, 7 days, and 28 days of curing. The SCC binary mix with a 15% cement replacement ratio reached a 28-day average compressive strength of 95.8 MPa with a w/b ratio of 0.36.

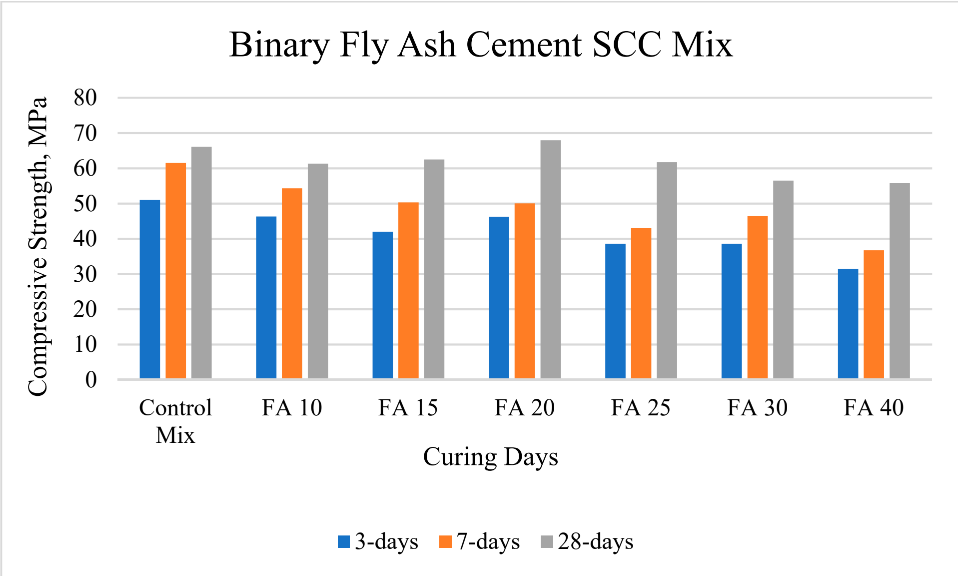

Figure 2. Compressive strength development of fly ash (FA) and cement binary SCC mixes.

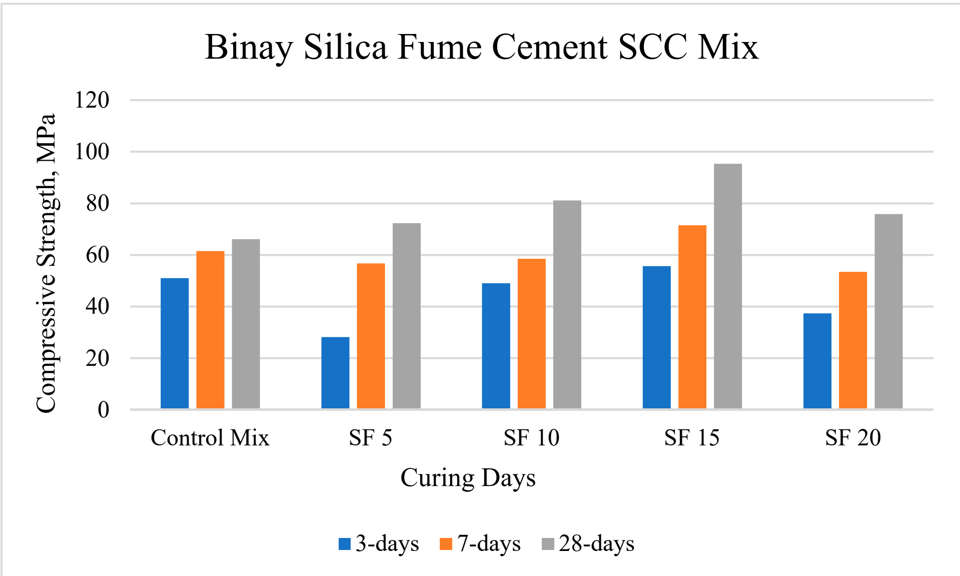

Figure 3. Compressive strength development of silica fume (SF) and cement binary SCC mixes.

Replacing cement with less than 15% silica fume (5% and 10% in this study) produces compressive strength less than the control mix after three and seven days of curing, which is indicated by Figure 3 and Table 4. This is consistent with the findings in the literature [23].

Figure 4 shows the binary SCC mixes in which cement was replaced with 10% to 60% GGBS matched or exceed the 28-day compressive strength of the control mix. In binary cement+GGBS mixes, the maximum 28-day compressive strength of 81 MPa was obtained by replacing the cement with 35% GGBS, which was followed by 78.4 MPa when 45% of the cement is replaced with GGBS. The 45% GGBS replacement percentage is particularly important since it will be demonstrated later in this paper that, at this percentage or higher, the resistance to chloride penetration is very high, which was indicated by the very low passing charge. Furthermore, replacing the cement with 80% of GGBS produced SCC mix with a 28-day compressive strength of 50.45 MPa, which is suitable for many structural engineering applications. Hydrated cement contains about 70% C-S-H and 20% $Ca(OH)_2$ in addition to other compounds [24]. The strength and durability of concrete is affected by the presence of $Ca(OH)_2$, which is water soluble. GGBS binds available $Ca(OH)_2$ and produces more of the stable gel C-S-H and that is responsible for the strength development. Therefore, replacing cement with increasing amounts of GGBS forms more C-S-H until a replacement ratio where the supply of $Ca(OH)_2$ becomes too small to be bound by the available GGBS. In this study, this happens when 35% of the cement is replaced with GGBB.

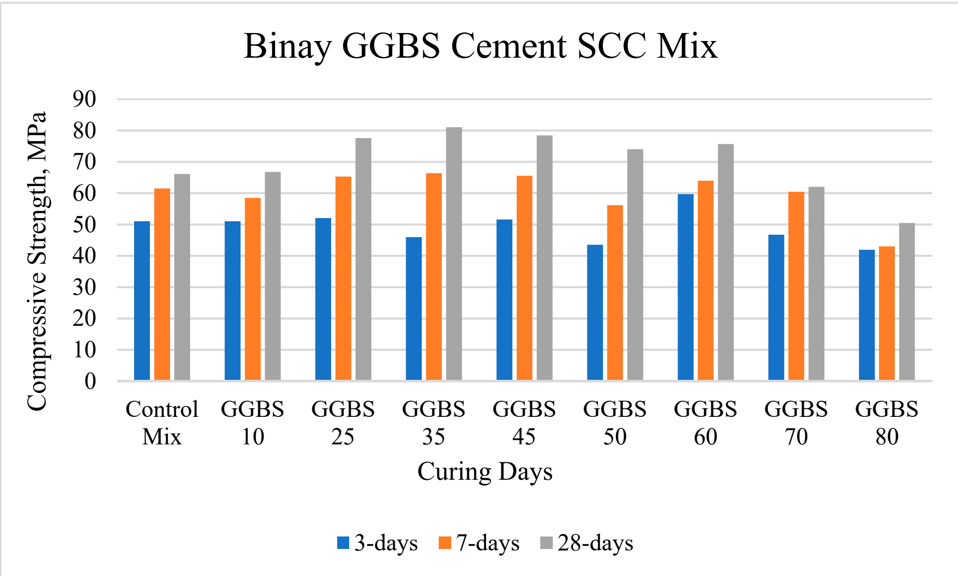

Figure 4. Compressive strength development of binary GGBS and cement SCC mixes.

In Quaternary mixes, referred to in this article as green mixes, 80% of the cement was replaced with three types of supplementary cementitious materials. Hydration of calcium silicates (C_2S and C_3S) is responsible for most of the strength development in conventional concrete produces primarily calcium hydroxide (CH) that SCM needs to produce calcium silicate hydrates (C-H-S). Therefore, replacement of cement with higher amounts of SCMs should be done carefully to ensure reasonable early and late strength development [25].

The results of the compressive strength indicate that GM4 (15% FA, 15% SF, and 50% GGBS) achieved the highest compressive strength of 63.9 MPa after 28 days of curing, which is lower than the compressive strength of the control mix. However, all quaternary mixes produced compressive strengths that are acceptable for many practical design applications. Table 5 shows the 3-day, 7-day, and 28-day compressive strength of quaternary mixes.

Table 5. Compressive strength development in green SCC mixes.

				Compressive Strength (MPa)		
				Curing Age (Days)		
Mixture Type	**FA kg/m^3**	**SF kg/m^3**	**GGBS kg/m^3**	**3**	**7**	**28**
GM 1	96	48	240	33.49	42	48.95
GM 2	120	72	192	22.26	31.055	40.02
GM 3	72	24	288	35.15	46.3	60.2
GM 4	72	72	240	46	51.7	63.9
GM 5	48	72	264	37.8	44	53.69
GM 6	72	96	216	26.3	33.7	42.455
GM 7	48	96	240	26.4	38.3	46.3

Figure 5 shows the development of the compressive strength of the quaternary mixes.

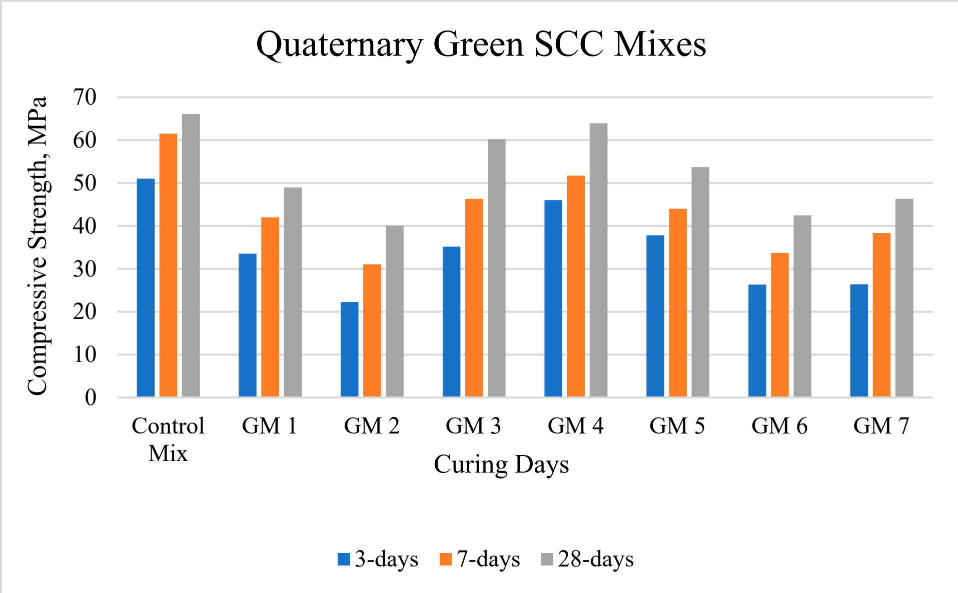

Figure 5. Compressive strength development of green SCC mixes.

3.2. Compressive Strength Prediction

The proposed correlation was carried out based on a regression power analysis that can be described by Equation (1).

$$f_c' = k \times \left(f_c'\right)^n \tag{1}$$

where k is the intercept value and n is the power coefficient obtained from the regression. An integral absolute error (IAE) analysis was also carried out to measure the reliability of the proposed relation by using Equation (2).

$$IAE = \sum \frac{\left[\left(o_i - {p_i}^2\right)\right]^{\frac{1}{2}}}{\sum o_i} \times 100(\%) \tag{2}$$

where o_i is the experimental value and p_i is the predicted value that resulted from regression analysis.

3.2.1. Predicting the 28 Days Compressive Strength from 3 Days Compressive Strength

In this section, regression analysis was conducted to predict the 28-day compressive strength using the 3-day average compressive strength. For each category of SCC mixes, two expressions were developed based on the model described in Equation (1) and the IAE is calculated to assess the ability of the expression to predict the 28-day compressive strength. The parameters "k" and "n" in Equation (1) that produce the lowest IAE (best prediction ability) are shown on the following figures. On each figure, the power n = 0.5 is also derived as the more computationally friendly one along with the corresponding IAE. Figures 6–8 show prediction relationships for binary mixes containing cement and fly ash, silica fume, and GGBS, respectively. For the parameter n = 0.5, k = 9.7 for binary mixes containing fly ash, k = 12.5 for silica fume, and k = 10 for GGBS. These k-values are consistent with expected behavior due to the slow 28-day strength development for fly ash SCC mixes compared to higher strength development for binary SCC mixes containing silica fume.

Figure 9 shows the relationship between the 28-day average compressive strength and the 3-day compressive strength for quaternary or green mixes when n = 0.5 with regression analysis leading to k = 9. Figure 10 shows the relationip between 28-day average compressive strength and 3-day strength for all mixes considered in this study. The slightly lower k = 9 is due to the late development of 28-day strength associated with green mixes and compared to k = 10 for all mixes combined.

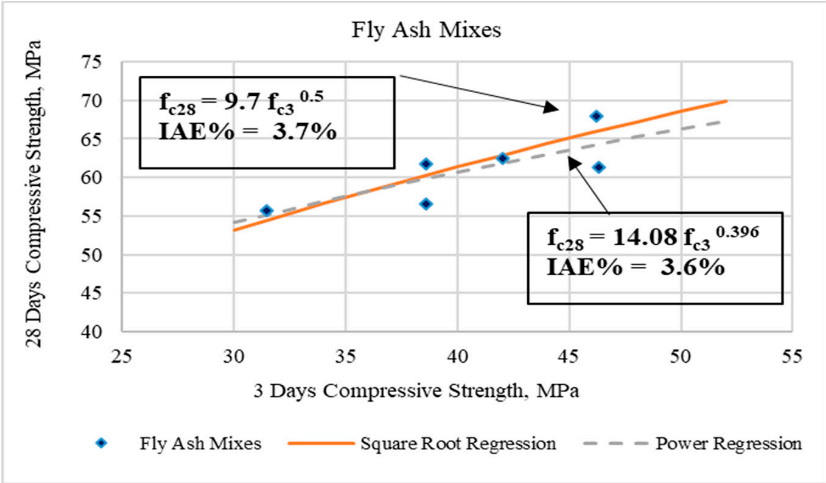

Figure 6. Relationship between 28-day and 3-day average compressive strength for binary cement/fly ash SCC mixes.

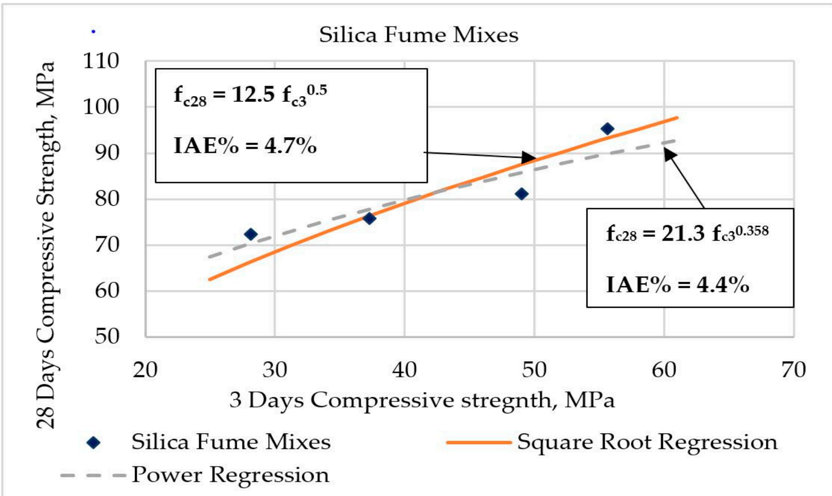

Figure 7. Relationshop between 28-day and 3-day average compressive strength for binary cement/silica fume scc mixes.

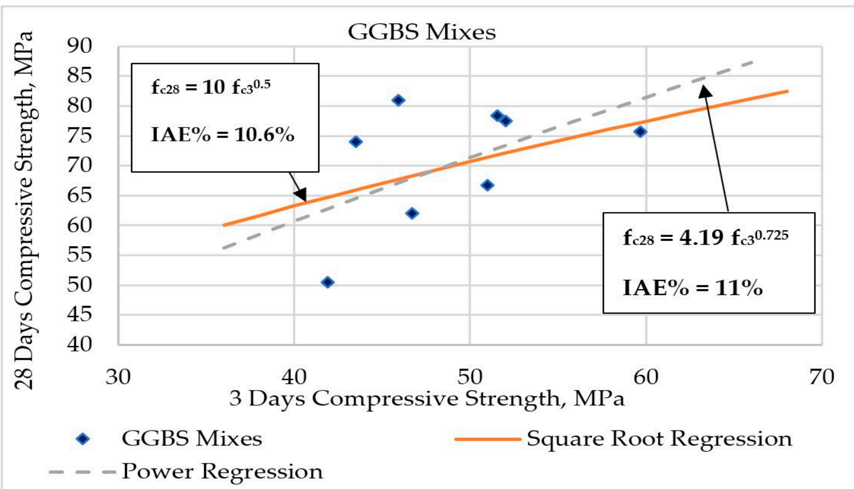

Figure 8. Relationship between 28-day and 3-day average compressive strength for binary cement/GGBS mixes.

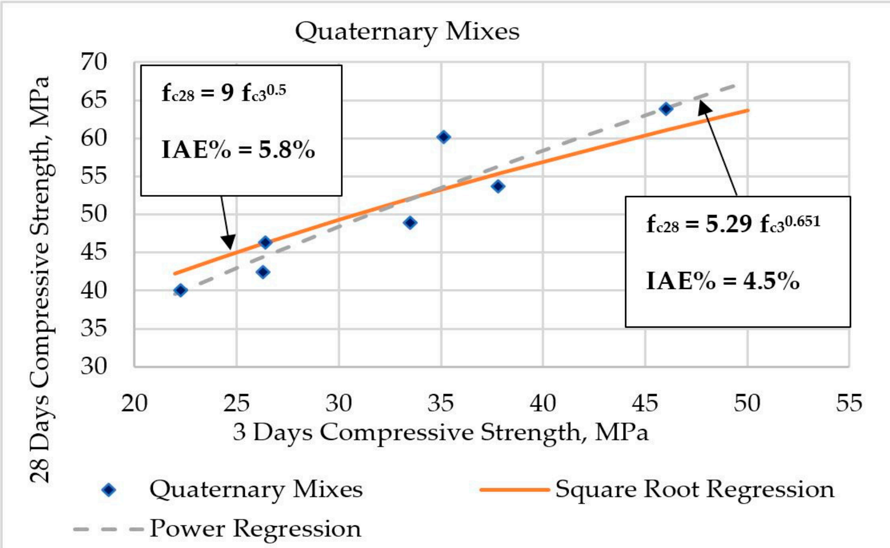

Figure 9. Relationshop between 28-day and 3-day average compressive strength for green SCC mixes.

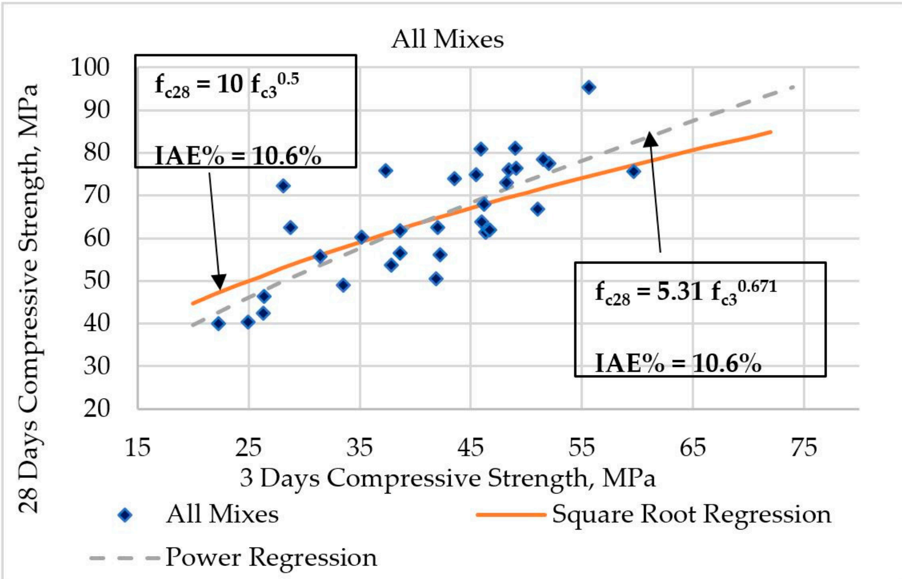

Figure 10. Relationshop between 28-day and 3-day average compressive strength for all SCC mixes.

3.2.2. Predicting the 28 Days Compressive Strength from 7 Days Compressive Strength

This section describes the relationship between the 28-day compressive strength and the 7-day compressive strength for binary, green, and all mixes combined. Figures 11–13 show that, for $n = 0.5$, the parameter $k = 9$ for fly ash binary SCC mixes, $k = 10.5$ for silica fume binary SCC mixes, and $k = 9.5$ for GGBS binary SCC mixes, respectively. As expected, silica fume binary mixes 28-day strength development slows down ($k = 10.5$) after 7-days, which is compared to the relationship between 3-day and 28-day strength ($k = 12.5$).

Figure 14 shows the relationship between the 7-day compressive strength and 28-day compressives strength for quaternary mixes. When the parameter $n = 0.5$, the corresponding value to $k = 7.6$, which shows how the development of strength from 7-days to 28-days is slower, is compared to the development from 3-days to 28-days ($k = 9$).

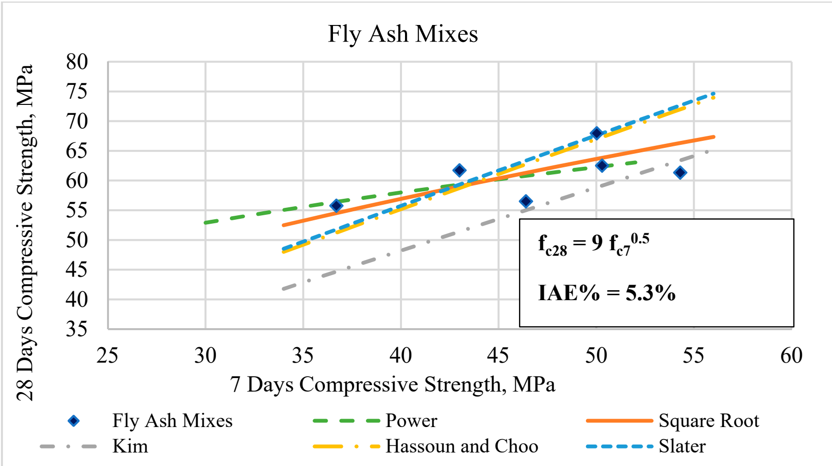

Figure 11. Relationshop between 28-day and 7-day average compressive strength for binary cement/fly ash SCC mixes.

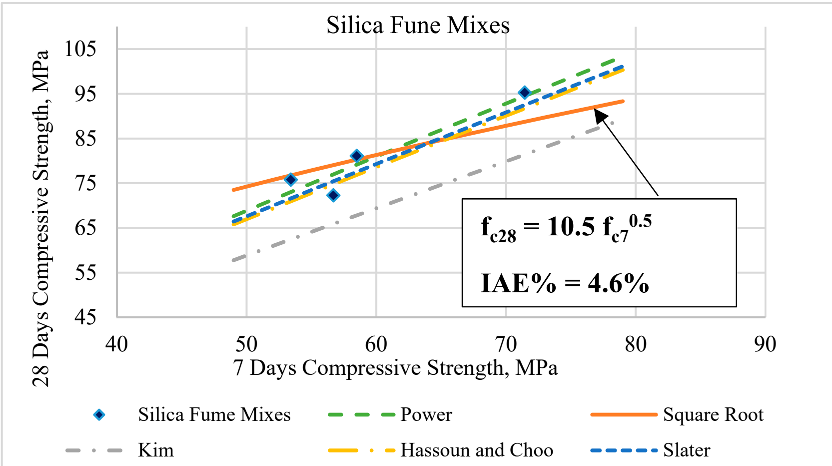

Figure 12. Relationshop between 28-day and 7-day average compressive strength for binary cement/silica fume SCC mixes.

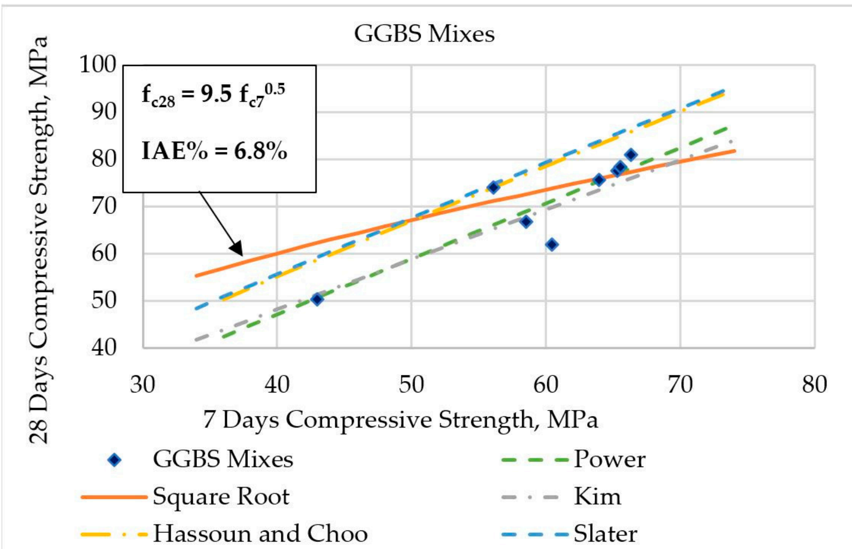

Figure 13. Relationshop between 28-day and 7-day average compressive strength for binary cement/GGBS SCC mixes.

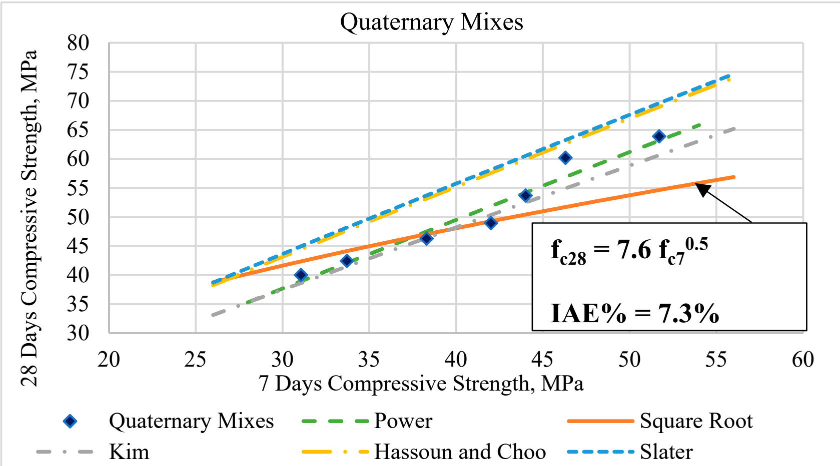

Figure 14. Relationshop between 28-day and 7-day average compressive strength for geen SCC mixes.

Figure 15 shows the relationship between 7-day and 28-day for all SCC mixes in this study. The prediction formula for this study (k = 9.5, n = 0.5) is compared to prediction formulas by various investigators. Table 6 shows the relation between the 7-day and 28-day strength for binary, quaternary, and all mixes combined and is compared to prediction formulas developed by various investigators. Table 6 shows that the prediction formulas developed in this study based on Equation (1) provides, in general, better prediction of 28-day compressive strength from 3-day and 7-day compressive strengths, which is compared to published formulas in the literature.

Table 6. Summary of correlation expressions between 7-day average compressive strength and 28-day average compressive strength, MPa.

Mix Type	Study	Equation	IAE%
Fly Ash Mixes	Current Study (Power)	$f_{c28} = 17.88\ f_{c7}^{0.319}$	4.3%
	Current Study (Square Root)	$f_{c28} = 9\ f_{c7}^{0.5}$	5.3%
	Kim [26]	$f_{c28} = f_{c7} + 2.4 f_{c7}^{1/3}$	10.2%
	Hassoun and Choo [27]	$f_{c28} = f_{c7} + 2.4 f_{c7}^{0.5}$	8.2%
	Slater [28]	$f_{c28} = f_{c7} + 2.49 f_{c7}^{0.5}$	8.3%
Silica Fume Mixes	Current Study (Power)	$f_{c28} = 2.14\ f_{c7}^{0.887}$	3.2%
	Current Study (Square Root)	$f_{c28} = 10.5\ f_{c7}^{0.5}$	4.6%
	Kim [26]	$f_{c28} = f_{c7} + 2.4 f_{c7}^{1/3}$	14.4%
	Hassoun and Choo [27]	$f_{c28} = f_{c7} + 2.4 f_{c7}^{0.5}$	4.7%
	Slater [28]	$f_{c28} = f_{c7} + 2.49 f_{c7}^{0.5}$	4.2%
GGBS Mixes	Current Study (Power)	$f_{c28} = 1.2\ f_{c7}^{0.997}$	4.3%
	Current Study (Square Root)	$f_{c28} = 9.5\ f_{c7}^{0.5}$	6.8%
	Kim [26]	$f_{c28} = f_{c7} + 2.4 f_{c7}^{1/3}$	5.5%
	Hassoun and Choo [27]	$f_{c28} = f_{c7} + 2.4 f_{c7}^{0.5}$	10.9%
	Slater [28]	$f_{c28} = f_{c7} + 2.49 f_{c7}^{0.5}$	11.9%
Quaternary Mixes	Current Study (Power)	$f_{c28} = 5.3\ f_{c7}^{0.651}$	4.5%
	Current Study (Square Root)	$f_{c28} = 7.6\ f_{c7}^{0.5}$	7.3%
	Kim [26]	$f_{c28} = f_{c7} + 2.4 f_{c7}^{1/3}$	3.8%
	Hassoun and Choo [27]	$f_{c28} = f_{c7} + 2.4 f_{c7}^{0.5}$	10.9%
	Slater [28]	$f_{c28} = f_{c7} + 2.49 f_{c7}^{0.5}$	12.0%
All Mixes	Current Study (Power)	$f_{c28} = 1.95\ f_{c7}^{0.887}$	6.2%
	Current Study (Square Root)	$f_{c28} = 9.5\ f_{c7}^{0.5}$	9.4%
	Kim [26]	$f_{c28} = f_{c7} + 2.4 f_{c7}^{1/3}$	11.5%
	Hassoun and Choo [27]	$f_{c28} = f_{c7} + 2.4 f_{c7}^{0.5}$	14.1%
	Slater [28]	$f_{c28} = f_{c7} + 2.49 f_{c7}^{0.5}$	15.1%

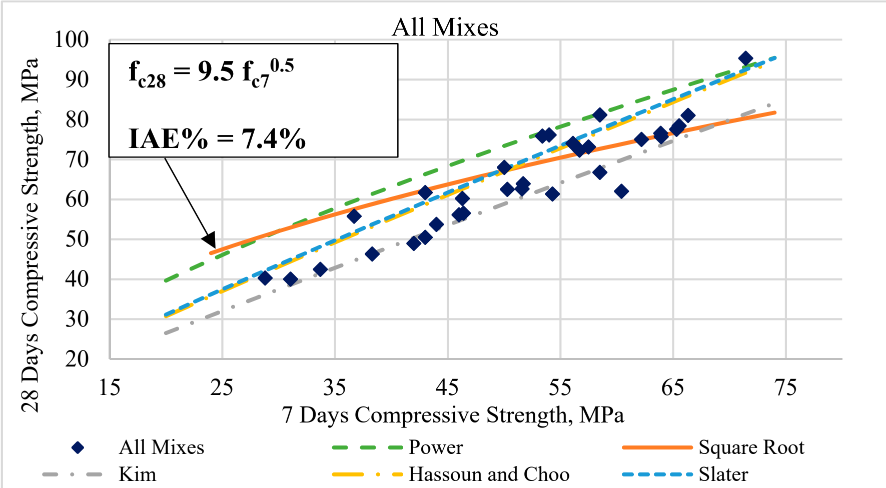

Figure 15. Relationship between 28-day and 7-day average compressive strength for geen SCC mixes.

3.3. Chloride Penetration Resistance of SCC Mixes

3.3.1. Binary Mixes

The durability of SCC mixes was tested by examining the concrete resistance to chloride penetration. The rapid chloride penetration test (RCPT) was performed after 1-day, 3-days, 7-days, 14-days, 28-days, and 40-days of curing. RCPT measures the electrical conductivity of the concrete. ASTM C1202 [29] provides a reasonable relationship between these two parameters, electrical conductivity, and chloride permeability. Table 7 relates the passing charge measured in coulombs with chloride ion permeability.

Table 7. Rating of chloride ion penetrability based on the charge passed.

Charge Passed (Coulombs)	Chloride Ion Penetrability
>4000	High
2000–4000	Moderate
1000–2000	Low
100–1000	Very Low
<100	Negligible

The results show that replacing the cement with fly ash produced SCC mixes with higher resistance to chloride penetration compared to the control mix since the measured passing charge was lower at all curing days. The reason behind the increase in concrete resistance is the fine particles of fly ash, which can fill the existing voids in concrete.

Figure 16 shows the effect of increasing the fly ash dosages on the SCC resistance to chloride penetration. As shown in Figure 16, the FA 40 SCC mix achieved the highest resistance to chloride penetration at all curing days from 1 day to 40 days. The measured passing charge at 1 day of curing was 2224.02 coulombs, which indicates a moderate permeability, while the measured charge at 40 days of curing was 567.18 coulombs, which indicates a very low permeability.

Replacing the cement with silica fume enhances concrete resistance to chloride penetration significantly.

The results of the RCPT for the binary cement/silica fume mixes show that all dosages of silica fume produced a very low penetration after 28 days of curing. Replacing cement with 15% and 20% of silica fume produced a very low penetration after one day of curing since the measured passing charges in coulombs were 509.41 and 341.31, respectively. This is attributed to the high density of the

SCC mix, which is consistent with findings in the literature [30]. Figure 17 shows the effect of silica fume on the SCC resistance to chloride penetration.

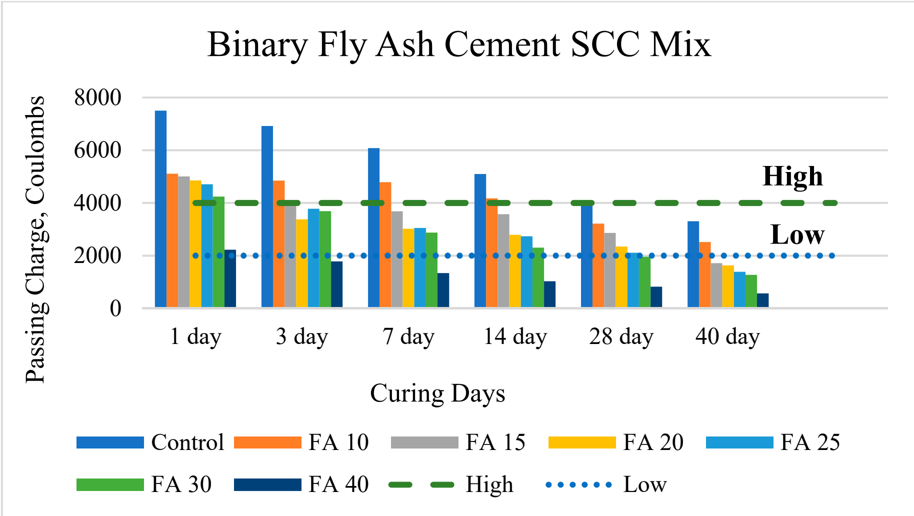

Figure 16. Passing charge measured after curing for binary cement/fly ash mixes compared to the control mix.

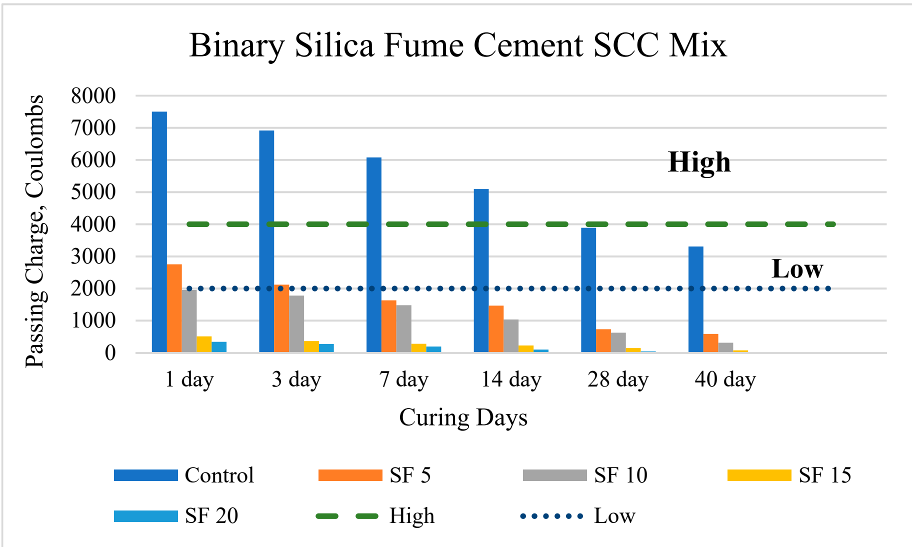

Figure 17. Passing charge measured after curing for binary cement/silica fume mixes when compared to the control mix.

Using GGBS as partial replacement of cement SCC mixes improved the concrete resistance to chloride penetration. Figure 18 show that replacing cement with 45% to 80% GGBS decreases the passing charge (coulombs) in RCPT to less than 500, which is classified as *very low* after one-day of curing. Therefore, a high cement replacement percentage with GGBS enhances resistance to chloride penetration significantly. It was noted earlier in this paper that replacing cement with 35% GGBS (GGBS35) produced the highest 28-day compressive of 81 MPa in binary GGBS + cement mixes, which is followed by 78.4 MPa when the replacement ratio is 45%. GGBS35 produced the highest 28-day compressive strength in its category and exhibited a very low passing charge after 14-days of moist curing.

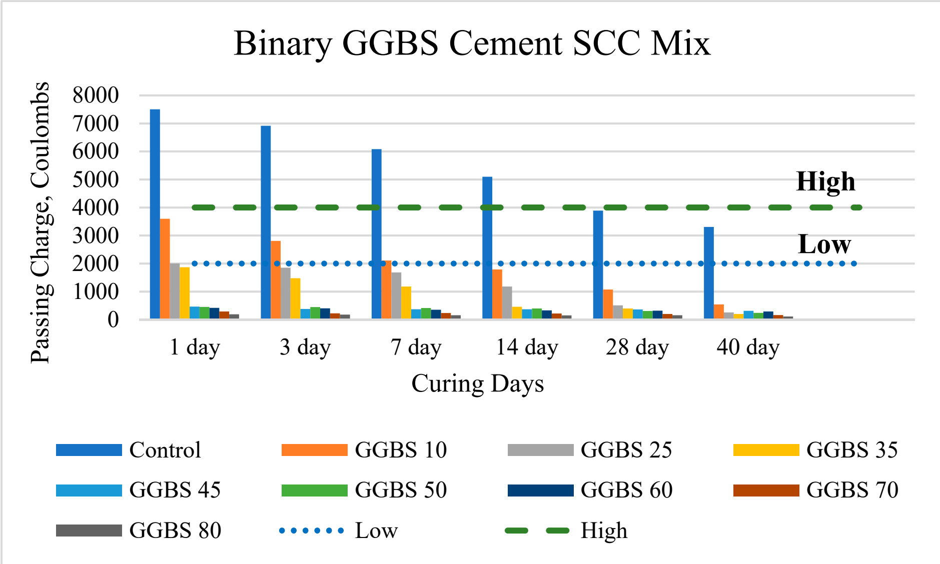

Figure 18. Passing charge measured after curing for binary cement/GGBS compared to the control mix.

3.3.2. Quaternary Mixes

This section describes the results of the sustainable green mixes in which 80% of the cement was replaced with three supplementary cementitious materials. Figure 19 show that all quaternary SCC mixes produced very low penetration after one day of curing. The chloride penetration is almost negligible after 28 days of curing for all the green mixes. After seven days of curing, both GM6 and GM7 show a negligible passing charge. GM7 is unique in that the passing charge is nearly negligible after one day of curing. This is not surprising since, in GM7, 20% of the cement was replaced by silica fume and 50% of the cement was replaced by GGBS. Both silica fume and GGBS replacements exhibited superior resistance to chloride penetration, which is discussed earlier in this paper.

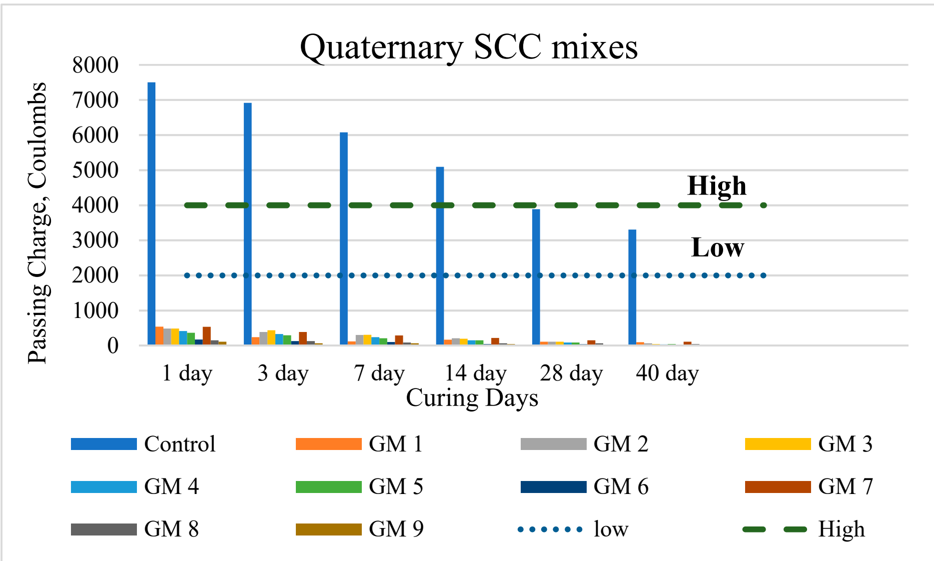

Figure 19. Passing charge measured after curing for green SCC mixes compared to the control mix.

4. Summary and Conclusions

Durability and mechanical properties of sustainable self-consolidating concrete are studied. In all mixes studied, up to 80% of Type 1 cement of a control is replaced with various combinations of recycled industrial byproducts such as silica fume, fly ash, and ground granulated blast furnace slag.

- Replacing 20% of Portland cement with fly ash produced a 28-day compressive strength of 67.96 MPa, which slightly exceeds the control mix. However, the 20% replacement ratio of cement with fly ash brings a passing charge in RCPT to *low* after 40-days of curing.
- In binary fly ash + cement SCC mixes, it is necessary to replace up to 40% of the cement with fly ash to bring a decrease for the passing charge to *low* after one-day of curing and, thereby, enhance resistance to chloride penetration.
- In binary silica fume + cement SCC mixes, replacing cement with 15% silica fume increased the compressive strength and exceeded the control mixes after 3-days, 7-days, and 28-days of curing. The 28-day compressive strength of binary SCC mix with 15% silica fume replacing cement reached 95.8 MPa. Replacing 15% of cement with silica fume also increased to resistance to chloride penetration significantly such that the passing charge in RCTP was *very low* after 1-day of curing.
- In binary GGBS + cement SCC mixes replacing cement with 35% GGBS produced the highest 28-day compressive strength of its category along with excellent chloride penetration resistance, which is indicated by a *very low* passing charge after 14-days of curing using RCPT. Replacing 45% of cement with GGBS produced a high 28-day compressive strength of 78.4 MPa along with superior resistance to chloride penetration after 1-day of curing. This superior resistance to chloride penetration after 1-day of curing is the same for all GGBS replacement ratios between 45% and 80%.
- The most sustainable self-consolidating concrete mixes (GM1 to GM9) in which 80% of the cement is replaced with combinations of supplementary cementitious composites exhibited excellent resistance to chloride penetration, which is demonstrated by the Rapid Chloride Penetration Test (RCPT). Green Mix 7 (GM7) exhibited the highest resistance to chloride penetration, which was indicated by the *negligible* passing charge after one-day of curing. In GM7, 20% of the cement was replaced with silica fume, 50% of the cement was replaced with GGBS, and 10% of the cement was replaced with fly ash. The control mix with 100% Type 1 cement exhibited the lowest resistance to chloride penetration.
- Models meant to predict the 28-day average compressive strength using the seven-day compressive strength were developed by using regression analysis. It was found that, when including all SCC mixes in this study, the average 28-day compressive strength is 9.5 times the square root of 7-day strength, which is the same relationship for binary GGBS + cement SCC mixes. For binary fly + cement, the average 28-day compressive strength is 9 times the square root of the seven-day compressive strength. Similarly, in silica fume + cement binary mixes, the average 28-day compressive strength equals to 10.5 times the square root of the seven-day compressive strength. This higher factor of 10.5 is due to the higher strength development at 28-days for mixes containing silica fume. For green mixes (GM1 to GM7), however, the 28-day strength equals 7.6 times the square root of the seven-day compressive strength. The lower coefficient of 7.6 is due to replacing 80% of the cement by supplementary cementitious composites, which leads to slower strength development after 28 days.
- Models that predict the 28-day average compressive strength using the three-day compressive strength were developed by using regression analysis. It was found that, when including all SCC mixes in the analysis, the average 28-day compressive strength is 10 times the square root of the three-day compressive strength, which is the same relationship for binary GGBS + cement SCC mixes and approximately the same relationship for binary fly ash + cement SCC mixes. For binary silica fume + cement, the average 28-day compressive strength is 12.5 times the square of the three-day compressive strength.

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