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Compressive strength and chloride resistance of self-compacting concrete containing high level fly ash and silica fume

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abstract

The influence of high-calcium fly ash and silica fume as a binary and ternary blended cement on compressive strength and chloride resistance of self-compacting concrete (SCC) were investigated in this study. High-calcium fly ash (40–70%) and silica fume (0–10%) were used to replace part of cement at 50, 60 and 70 wt.%. Compressive strength, density, volume of permeable pore space (voids) and water absorption of SCC were investigated. The total charge passed in coulombs was assessed in order to determine chloride resistance of SCC. The results show that binary blended cement with high level fly ash generally reduced the compressive strength of SCC at all test ages (3, 7, 28 and 90 days). However, ternary blended cement with fly ash and silica fume gained higher compressive strength after 7 days when compared to binary blended fly ash cement at the same replacement level. The compressive strength more than 60 MPa (high strength concrete) can be obtained when using high-calcium fly ash and silica fume as ternary blended cement. Fly ash decreased the charge passed of SCC and tends to decrease with increasing fly ash content, although the volume of permeable pore space (voids) and water absorption of SCC were increased. In addition when compared to binary blended cement at the same replacement level, the charge passed of SCC that containing ternary blended cement was lower than binary blended cement with fly ash only. This indicated that fly ash and silica fume can improve chloride resistance of SCC at high volume content of Portland cement replacement.

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1. Introduction

Nowadays, high-volume fly ash (HVFA) concrete, with 50% or more of cement replaced by fly ash (FA) has been studied extensively. HVFA is often used to achieve good slump flow of self-compacting concrete (SCC). SCC is a new category of high-performance concrete characterized by its ability to spread into place under its own weight without the need of vibration, and self-compact without any segregation [1,2]. The use of FA in SCC reduces the dosage of superplasticizer needed to obtain similar slump flow as for concrete made with Portland cement [3]. Also, the use of FA improves rheological properties and reduces cracking of concrete due to lower heat of hydration [4,5]. However, the strengths of HVFA concrete are lower than that of pure Portland cement concrete, especially at early age due to the dilution effect and very low pozzolanic reaction [6–10].

Currently, the trend of SCC utilization is extensively in many subject area includes in marine area. It well known that corrosion of reinforcement embedded in concrete due to chloride ion attack is one of the most significant durability problems of concrete that subjected in marine zone. Generally, free chlorides play a vital role in the deterioration of steel reinforcement in concrete. Supplementary cementitious materials (SCM), such as fly ash, silica fume, ground granulated blast-furnace slag, and metakaolin have a significant impact on the ability of concrete to resist the penetration of chloride ions due to chlorides binding capacity of these materials. The process of chloride binding can be classified into two categories namely chemical binding and physical binding. The strongly bound chlorides are chemical binding. Chloride ions can react chemically with tricalciumaluminate (C_3A) to form calcium chloroaluminates ($3CaO \cdot Al_2O_3 \cdot CaCl_2 \cdot 10H_2O$:Friedel's salt) [11,12]. In addition, chloride ions can be physically adsorbed on the surface of the solid phases of hydrated products like C–S–H gel and other products of reactions [13,14].

Due to the low compressive strength at the early age, silica fume (SF) was used incorporating with FA and found that the compressive strength was improved [15–17]. However, there are a few study focused on the use of FA and SF in term of ternary blended cement on chloride penetration of SCC, especially the use of high-calcium fly ash incorporating with SF at high cement

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Table 1
Chemical compositions and physical properties of Portland cement, fly ash and silica fume.

Oxide	Percent chemical composition (%)		
	Portland cement	Fly ash	Silica fume
SiO_2	20.64	36.84	93.55
Al_2O_3	4.85	19.99	0.56
CaO	63.62	18.55	1.13
Fe_2O_3	3.17	15.25	0.17
MgO	1.14	2.22	0.75
Na_2O	0.51	0.80	0.14
K_2O	0.81	2.76	1.05
P_2O_5	0.32	0.21	0.53
TiO_2	0.21	0.53	0.00
SO_3	2.75	2.79	1.01
Loss on ignition	2.08	0.03	1.16
Physical properties			
BET surface area (m^2/g)	2.24	1.34	18.09
Specific gravity (g/cm^3)	3.15	2.1	2.2

Table 2
Physical properties and sieve size distributions of crushed limestone and river sand.

Sieve number	Sieve size (mm)	Percentage passing (%)	
		Limestone	River sand
1	25 (mm)	100	100
3/4	19	82.76	100
3/8	9.5	10.41	100
#4	4.75	0.1	98.7
#8	2.36	0	85.3
#16	1.18	0	57.7
#30	0.6	0	23
#50	0.3	0	3.5
#100	0.15	0	0.6
Specific gravity		2.65	2.6

replacement level. Therefore, in this study, the chloride penetration of SCC produced using high-calcium fly ash and SF was investigated at high level of cement replacement. In addition, compressive strength, apparent density, and volume of permeable pore space (voids) and water absorption of SCC were also tested.

2. Experimental details

Materials

Ordinary Portland cement type I (PC) of The Siam Cement Public Company Ltd., Lampang, Thailand was used. Fly ash (FA) obtained from Mae Moh power plant in Lampang, Thailand and undensified silica fume (SF) grade 920-U obtained by Elkem Silicon Materials Ltd., Singapore were used in partial replacement of cement by weight in different compositions. The chemical compositions and physical properties of Portland cement, fly ash

Table 3
The mix proportions of SCC.

Mix	Proportion (kg/m^3)						
	Water	PC	FA	SF	Fine aggregate	Coarse aggregate	Superplasticizer (%)
W/B = 0.3							
PC	180	600	0	0	1084	595	1.19
50FA	180	300	300	0	958	595	0.25
60FA	180	240	360	0	933	595	0.17
70FA	180	180	420	0	908	595	0.12
5SF	180	570	0	30	1072	595	1.33
10SF	180	540	0	60	1059	595	1.43
45FA5SF	180	300	270	30	958	595	0.37
55FA5SF	180	240	330	30	933	595	0.30
65FA5SF	180	180	390	30	908	595	0.20
40FA10SF	180	300	240	60	958	595	0.60
50FA10SF	180	240	300	60	933	595	0.48
60FA10SF	180	180	360	60	908	595	0.38
W/B = 0.35							
PC	180	514	0	0	1131	621	1.50
50FA	180	257	257	0	1023	621	0.26
60FA	180	206	309	0	1001	621	0.19
70FA	180	154	360	0	980	621	0.13
5SF	180	489	0	26	1120	621	1.60
10SF	180	463	0	51	1110	621	1.75
45FA5SF	180	257	231	26	1023	621	0.40
55FA5SF	180	206	283	26	1001	621	0.32
65FA5SF	180	154	334	26	980	621	0.22
40FA10SF	180	257	206	51	1023	621	0.62
50FA10SF	180	206	257	51	1001	621	0.50
60FA10SF	180	154	309	51	980	621	0.40
W/B = 0.4							
PC	180	450	0	0	1166	640	1.80
50FA	180	225	225	0	1072	640	0.26
60FA	180	180	270	0	1053	640	0.21
70FA	180	135	315	0	1034	640	0.13
5SF	180	428	0	23	1157	640	1.90
10SF	180	405	0	45	1147	640	2.10
45FA5SF	180	225	203	23	1072	640	0.43
55FA5SF	180	180	248	23	1053	640	0.34
65FA5SF	180	135	293	23	1034	640	0.28
40FA10SF	180	225	180	45	1072	640	0.64
50FA10SF	180	180	225	45	1053	640	0.52
60FA10SF	180	135	270	45	1034	640	0.46

and silica fume are presented in Table 1. River sand and crushed limestone were used as a fine aggregate and coarse aggregate, respectively. The specific gravity and sieve size distributions of crushed limestone and river sand are presented in Table 2. River sand and crushed limestone were washed and dried before using.

Samples preparation and test methods

In this study, Portland cement was replaced with FA and SF at 50, 60 and 70 wt.%. Concrete samples were designed to have a constant slump flow at 600 ± 50 mm. The slump flow test was performed in accordance with the ASTM: C1611. The amount of superplasticizer was adjusted in order to obtain constant slump flow. The water content was kept constant at 180 kg/m^3. Water to binder ratio (w/b) of 0.3, 0.35 and 0.4 were investigated. The coarse aggregate to total aggregate ratio was kept fixed at 0.35 and the fine aggregate to total aggregate ratio was in the range of 0.65 (was adjusted in order to obtain the yield/volume). The mix proportions of concrete samples are indicated in Table 3.

Concrete samples were designed to use high volume FA incorporating with SF as a Portland cement replacement in self compacting concrete (SCC) application. Concrete were mixed using a rotary mixer. River sand (fine aggregate) and crushed limestone (coarse aggregate) were firstly mixed with half of water using rotary mixer for 1 min and then left for 4 min for aggregates absorption. After that, binder were added and mixed with another half of water that included superplasticizer for a further 3 min.

Cube specimens, 100 × 100 × 100 mm, were prepared for evaluating the compressive strength (BS EN 12390-3 [18]) while cylindrical mould, 100 mm in diameter and 200 mm high, were used to determine chloride penetration. After mixing, concretes were cast into oiled moulds without compaction, surfaced-smooth, covered with plastic film and left in the mould for 24 h. The specimens were removed from the moulds and cured in saturated lime water at 23 ± 1 °C until tested. The compressive strength was determined after 3, 7, 28 and 90 days of saturated lime water curing. The samples curing condition was applied from ASTM: C109. The chloride resistance test of concrete at 28 days was done in accordance with the ASTM: C1202.

For chloride resistance test, after casting, the specimens were left in the mould for 24 h and cured in saturated lime water for 28 days. After that, specimens were cut to obtain two samples of 50 ± 3 mm thick from the middle of 100 × 200 mm concrete cylinder using a diamond saw. The specimens were allowed to surface dried in air for at least 1 h, and then the side surface were coated with acrylic coating (both end face of specimen must be exposed), and leave in air for 24 h. Thereafter, specimens were placed in a vacuum desiccator and pumped (into vacuum) for 3 h., then drain sufficient water into the desiccator to cover and soak the specimen samples under water for 18 ± 2 h.

After that, specimens were removed from the desiccator and placed into the testing cell which containing ionic solutions. One of the testing cells was filled with 0.3 M NaOH solution (this side of the cell was connected to the positive terminal of the power supply) and the other cell with 3% NaCl solution (this side of the cell was connected to the negative terminal of the power supply). A 60 V DC was applied between the two cells. The resistance of concrete to chloride ion penetration was represented by the total charge passed in coulombs during a test period of 6 h.

In addition, density, water absorption and void percentage (volume of permeable pore space) of samples were also determined according to ASTM: C642. The samples were dried in an oven at a temperature of 110 °C for 24 h, then allowed samples to cool in an oven for 12 h and determined the mass. After cooling, the samples were immersed in water for 48 h and then boiled the sample for 5 h. After that, the samples were cooled by natural loss of heat to a final temperature of 20–25 °C. The surface moisture was removed with a towel and determined the mass of the specimen. Finally, the specimens were suspended in the water and determined the apparent mass in water. Density, water absorption and void percentage were calculated following:

Absorption after immersion and boiling; %
¼ ½ðB − AÞ=A] x 100 ð1Þ

Apparent density ¼ ½A=ðA − CÞ] · q ð2Þ

Volume of permeable pore spaceðvoidsÞ; %
¼ ½ðB − AÞ=ðB − CÞ] x 100 ð3Þ

where A is the mass of oven-dried sample in air (g), B is the mass of surface-dry sample in air after immersion and boiling (g), C is the apparent mass of sample in water after immersion and boiling (g), and q is the density of water (1 g/cm^3).

3. Results and discussion

3.1. Density, water absorption and volume of permeable pore space

The apparent density of all SCC at 28 days with different w/b ratios of 0.3, 0.35 and 0.4 is shown in Fig. 1. In term of binary blended Portland cement, at the same water to binder (w/b) ratio, there appeared to be no significantly difference in the apparent density of all SCC when containing FA. In term of ternary blended Portland cement, it was observed that there is no general trend when FA and SF were used to replace part of cement. However, in general with exception of 60FA10SF the apparent density of binary and ternary blended Portland cement at all w/b seems to be slightly lower than Portland cement control.

Density of hardened mortar or concrete varies, depending on the amount and density of the aggregate, the amount of air voids that is entrained or entrapped and the water and cement contents [19]. However, if the amount and density of the aggregate and water content constant, density of hardened mortar or concrete depend on the amount of air voids and cements content. In fact, the density (specific gravity) of overall cement matrix is decreased during hydration reaction. All hydration products of cement compounds have lower specific gravity and larger specific volumes than the cement compounds [20]. In addition, the amount and size of air voids are affected by hydration products and pozzolanic materials which filled the voids in the cement paste. Thus, density of hardened mortar or concrete also depends on the amount and density of hydration products and pozzolanic materials content.

Fig. 2 shows volume of permeable pore space (voids) of all SCC at 28 days. In term of binary blended Portland cement, the voids of all SCC containing only FA seem to be higher than Portland cement control, at the same w/b ratio and tend to increase with increasing FA content. This is due to the cement dilution effect and slow pozzolanic reaction of FA. While, the voids of all SCC containing only SF seem to be lower than Portland cement control, at the same w/b ratio. This is due to the high pozzolanic reaction and filler effect of SF. In term of ternary blended Portland cement, the voids of all SCC tend to decrease with increasing SF content. This is due to the filler effect by SF, hydration products and pozzolanic materials. When varying w/b ratio, the voids of SCC seem to be increased with increasing w/b ratio. This is due to the increasing of porosity when increasing w/b ratio.

Fig. 3 shows water absorption of all SCC at 28 days. Water absorption has a direct relationship with the voids so the absorption decreased as the voids decreased. Thus, at the same w/b ratio,

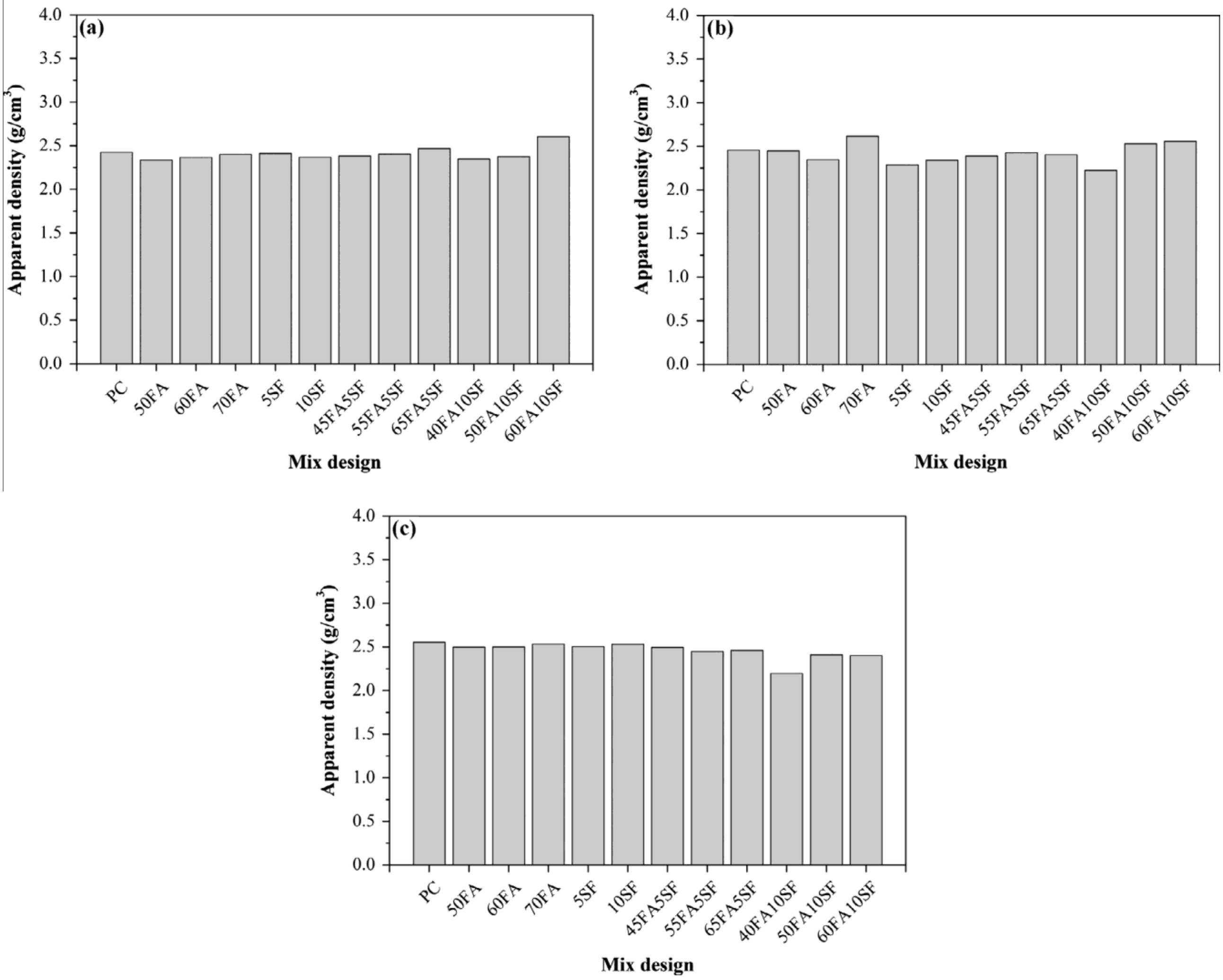

Fig. 1. Apparent density of all SCC (a) at c of 0.3, (b) at w/b of 0.35 and (c) at w/b of 0.4.

the water absorption of all SCC containing FA was higher than Portland cement control and tends to decrease with increasing SF content.

3.2. Compressive strength

The compressive strengths of all SCC at 3, 7, 28 and 90 days are shown in Tables 4–6. The compressive strength of all SCC increased with increasing curing time. In term of binary blended Portland cement concrete, the results show that the compressive strength of SCC at high volume cement replacement decreased with increasing FA content, at all test ages. The compressive strength of SCC containing FA was lower than the Portland cement control. The reduction in compressive strength of binary blended Portland cement containing FA is due to its slow pozzolanic reaction and the dilution effect. While the compressive strength of binary blended Portland cement SCC with SF at 5 and 10 wt.% was higher than the Portland cement control. This is due to the greater pozzolanic reaction and micro filler effect of SF [21].

For ternary blended Portland cement concrete, the compressive strength of SCC containing ternary blended Portland cement was higher than SCC containing binary blended Portland fly ash cement, at the same replacement level. Moreover, the compressive strength of SCC increased with increasing SF content. The improvement of the compressive strength of SCC containing ternary blended Portland cement is due to the higher pozzolanic reaction of SF than that of FA and the micro filler effect of SF. However, the compressive strength of all SCC containing ternary blended Portland cement at 50, 60 and 70 wt.% cement replacement are still lower than that of the Portland cement control. This is because the micro filler effect and pozzolanic reaction cannot compensate for the dilution effect at the tested age (28 days).

At the same replacement level, the compressive strength of all SCC containing binary and ternary blended Portland cement decreased with increasing w/b ratio. This is due to a higher water/cement ratio decreases the gel/space ratio that increasing the porosity and accompanied the decreasing strength of concrete.

In addition, it can be observed that the high strength self-compacting concrete was obtained when using high calcium fly ash incorporating with SF at high cement replacement level. Metha and Monteiro [22] reported that concrete having a 28 days compressive strength more than 60 MPa was designed as a high strength concrete. In this study, the mixtures of 45FA5SF, 55FA5SF, 40FA10SF, 50FA10SF and 60FA10SF at w/b ratio of 0.3 showed 28 days compressive strength over 60 MPa. Moreover, 40FA10SF mixture showed compressive strength similar to PC control at 28 days. For the mixtures at w/b of 0.35, 45FA5SF, 40FA10SF and 50FA10SF mixtures also showed 28 days compressive strength over 60 MPa. Therefore, in this study the mixtures containing high calcium fly ash and SF that contributed 28 days compressive

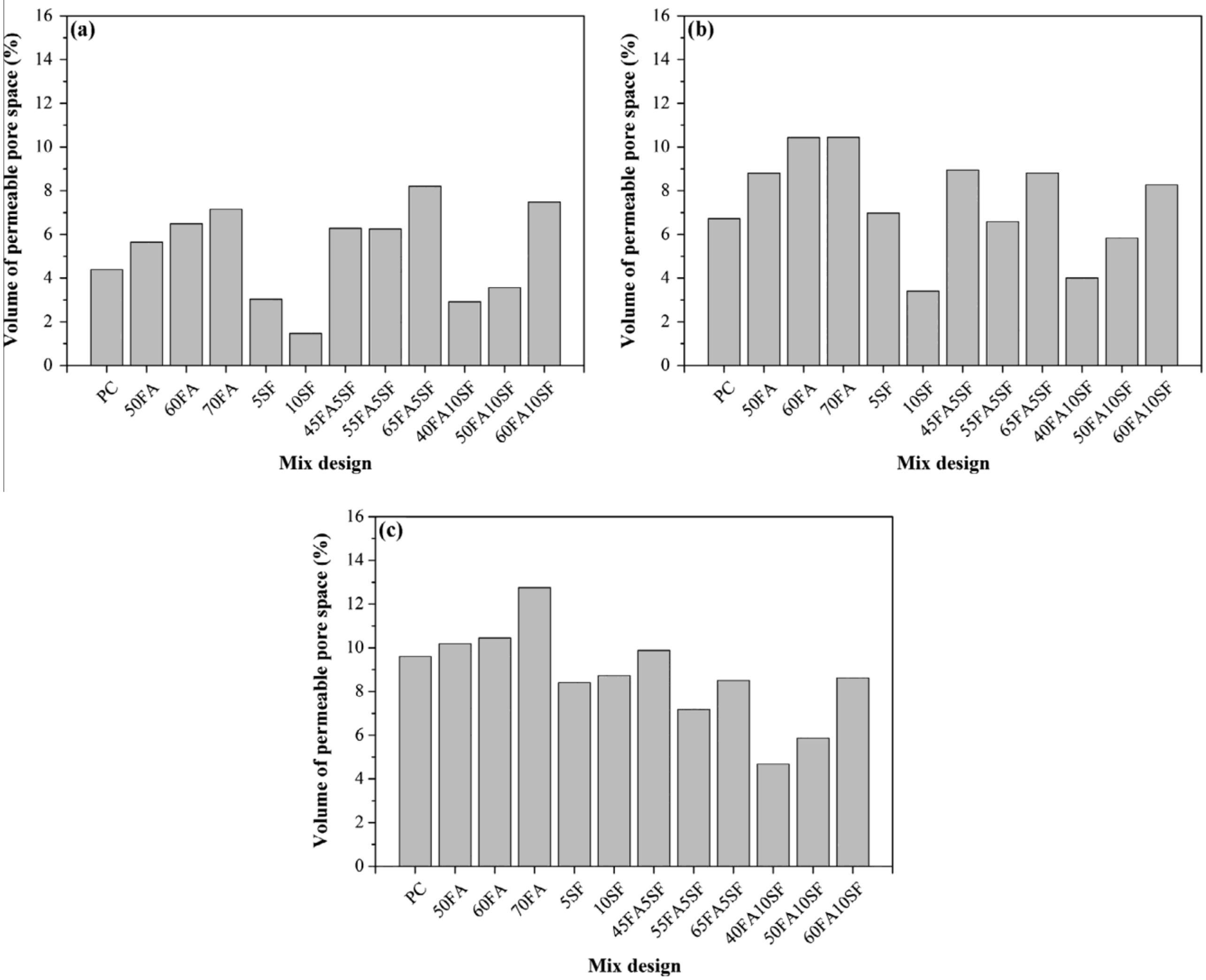

Fig. 2. Volume of permeable pore space of all SCC (a) at w/b of 0.3, (b) at w/b of 0.35and (c) at w/b of 0.4.

strength more than 60 MPa can be designed as a high strength self-compacting concrete.

3.3. Chloride resistance

To evaluate the resistance of concrete to chloride ion ingress, the charges passed through concrete specimens in coulombs is measured. The charges passed of all SCC performed at 28 days are shown in Figs. 4–7. The charges passed through SCC containing binary blended Portland cement with FA and SF is shown in Fig. 4. The results show that, at the same w/b ratio, the charges passed of Portland cement control concrete were higher than that of FA and SF concretes. Moreover, the charges passed of SCC containing binary FA and binary SF mixes decreased with increasing FA and SF content, up to 49.4% reduction and 92.2% reduction respectively (as shown in Fig. 4). Furthermore, the charges passed of FA concrete were higher than that of SF concrete.

The reduction of charges passed of SCC containing FA is due to the chloride chemical binding affect. Usually, chloride ions can react with tricalcium aluminates (C_3A) and C_4AF to form $3CaO \cdot Al_2O_3 \cdot CaCl_2 \cdot 10H_2O$ (calcium chloroaluminates: Friedel's salt) and $3CaO$. $Fe_2O_3 \cdot Al_2O_3 \cdot CaCl_2 \cdot 10H_2O$ (calcium chloroferrites) which are stable forms and lead to decrease of free chlorides available [8]. The presence of FA leads to an increase in the amount of C_3A due to the higher amount of alumina present in the mix [23]. In addition, FA leads to an increase of calcium silicate hydrate (C–S–H) content that is formed in the pozzolanic reactions to chloride physical binding [23,24]. Thus, the chloride binding capacity of concrete tends to increase with increasing FA content. For SCC containing SF, the reduction of charges passed is due to improvement of pore structure (finer-pore) by SF that reduces permeability of hardened concrete.

In addition, Uysal and Akyuncu [24] reported that the formation of a less porous, denser microstructure and a discontinuous pore system all has an influence on the reduction of chloride ion permeability and found that pozzolanic reactions were able to develop a discontinuous pore system. Thus, pozzolanic materials especially SF led to a decrease in the total chloride charges passed through SCC.

The charges passed of SCC containing ternary blended cement concrete with FA and SF at 50, 60 and 70 wt.%, compared to Portland cement control concretes are presented in Figs. 5–7. At the same replacement level and w/b ratio, the charges passed of SCC containing ternary blended cement were lower than SCC containing binary blended cement with the relative percentages of charge to the control Portland cement concrete are in the range from 11.3% to 33.6% for ternary blend mixes compared to 50.6–68.6% of binary fly ash cement mixes. Moreover, the charges passed of ternary blended cement SCC decreased with increasing SF content. This is due to the pore structures of SCC were improved in the

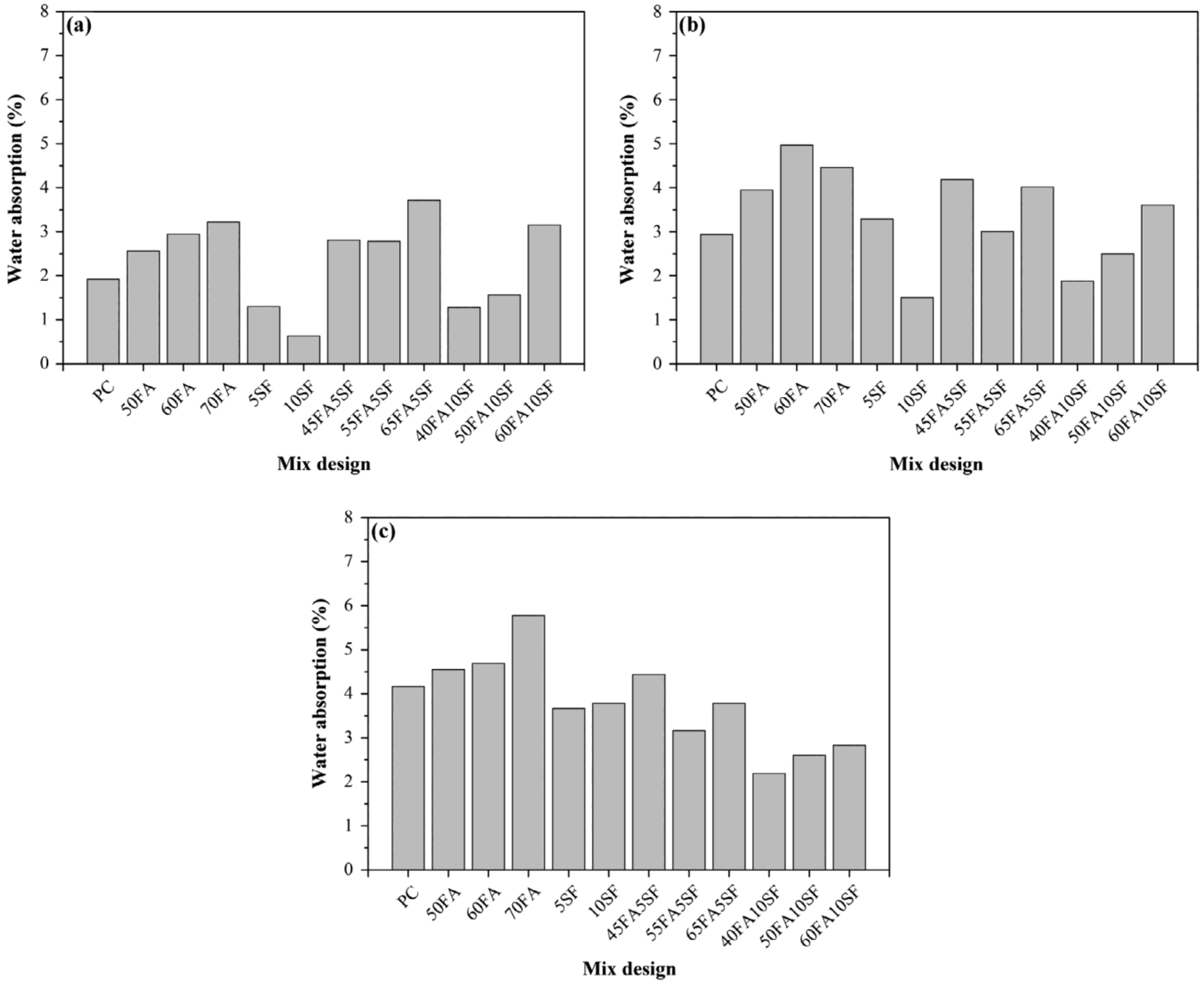

Fig. 3. Water absorption of all SCC (a) at w/b of 0.3, (b) at w/b of 0.35 and (c) at w/b of 0.4.

Table 4
Compressive strength of SCC at w/b ratio of 0.3.

Mix	Compressive strength (MPa)							
	3 days		7 days		28 days		90 days	
	Strength (MPa)	S.D.	Strength (MPa)	S.D.	Strength (MPa)	S.D.	Strength (MPa)	S.D.
PC	76.0	0.9	79.3	1.5	84.0	0.6	88.3	1.9
50FA	40.8	1.5	48.9	2.0	66.4	2.7	81.1	3.1
60FA	30.6	0.6	37.9	2.1	58.0	1.4	68.8	2.4
70FA	26.0	0.3	28.9	0.7	45.6	0.4	55.2	1.0
5SF	73.7	2.6	81.6	1.4	95.3	1.1	99.0	1.0
10SF	78.3	2.0	84.5	0.6	100.5	1.5	106.6	6.2
45FA5SF	43.5	0.6	56.0	2.5	75.2	1.6	89.5	2.6
55FA5SF	34.9	0.9	49.1	0.3	63.4	2.2	74.1	2.1
65FA5SF	29.0	0.3	39.5	1.7	52.7	2.7	61.6	0.6
40FA10SF	48.1	1.2	66.1	1.5	85.2	0.9	96.6	1.2
50FA10SF	40.0	0.5	55.1	2.7	73.6	4.4	85.9	1.6
60FA10SF	35.8	0.8	46.9	1.6	61.2	1.9	80.6	4.0

presence of SF. Moreover, SF is more reactive than FA that results to an increase of C–S–H at a faster rate for chloride physical binding.

At the same replacement level, the charges passed of all SCC containing binary and ternary blended Portland cement increased with increasing w/b ratio. This is due to pore structure of SCC increased with increasing w/b ratio and resulted to an increase permeability of SCC [25].

The classification of concrete resistance to chloride ion penetrability as obtained from ASTM: C1202 is indicated in Table 7. In this study, all SCC containing FA in term of binary blended cement were

Table 5
Compressive strength of SCC at w/b ratio of 0.35.

Mix	Compressive strength (MPa)							
	3 days		7 days		28 days		90 days	
	Strength (MPa)	S.D.	Strength (MPa)	S.D.	Strength (MPa)	S.D.	Strength (MPa)	S.D.
PC	65.5	1.2	75.2	1.0	83.0	2.9	85.4	0.7
50FA	35.9	1.4	44.6	1.2	59.2	0.5	70.9	1.6
60FA	25.4	1.3	33.7	0.4	52.6	1.5	64.0	0.8
70FA	20.5	0.6	23.6	0.8	39.8	1.0	50.1	0.4
5SF	63.4	0.7	77.6	0.9	85.3	1.1	90.9	1.3
10SF	70.8	1.2	81.2	0.9	91.6	1.9	100.4	0.8
45FA5SF	39.8	1.6	50.4	0.6	68.4	3.2	82.5	2.1
55FA5SF	30.3	0.5	44.0	1.6	57.4	2.1	69.6	0.8
65FA5SF	24.1	1.4	33.5	2.0	45.9	1.3	57.3	1.4
40FA10SF	34.9	1.8	53.1	1.6	75.4	1.6	86.6	1.4
50FA10SF	30.6	0.7	48.2	2.0	64.7	1.8	78.9	0.5
60FA10SF	24.9	0.9	40.5	0.5	51.1	0.6	70.4	0.8

Table 6
Compressive strength of SCC at w/b ratio of 0.4.

Mix	Compressive strength (MPa)							
	3 days		7 days		28 days		90 days	
	Strength (MPa)	S.D.	Strength (MPa)	S.D.	Strength (MPa)	S.D.	Strength (MPa)	S.D.
PC	56.8	1.4	65.6	1.4	72.4	1.3	80.4	0.8
50FA	21.6	1.0	25.7	1.2	41.9	1.4	53.1	1.7
60FA	18.0	0.3	21.2	0.4	35.7	0.2	48.0	0.7
70FA	14.1	0.3	17.7	0.5	31.7	0.8	41.8	2.1
5SF	55.6	0.6	65.8	1.5	75.3	1.1	82.4	1.3
10SF	59.8	1.1	69.7	0.8	79.0	1.1	86.1	2.0
45FA5SF	25.3	0.8	32.1	1.0	51.5	3.3	64.0	2.0
55FA5SF	17.1	0.2	29.8	1.3	39.2	2.8	51.3	0.8
65FA5SF	12.6	0.1	18.2	0.3	28.2	0.3	42.3	0.2
40FA10SF	26.8	0.8	36.5	0.9	60.3	1.8	71.4	1.2
50FA10SF	20.3	0.2	37.0	0.3	49.1	1.4	63.8	2.4
60FA10SF	15.3	0.4	22.9	0.1	33.1	0.3	52.5	1.0

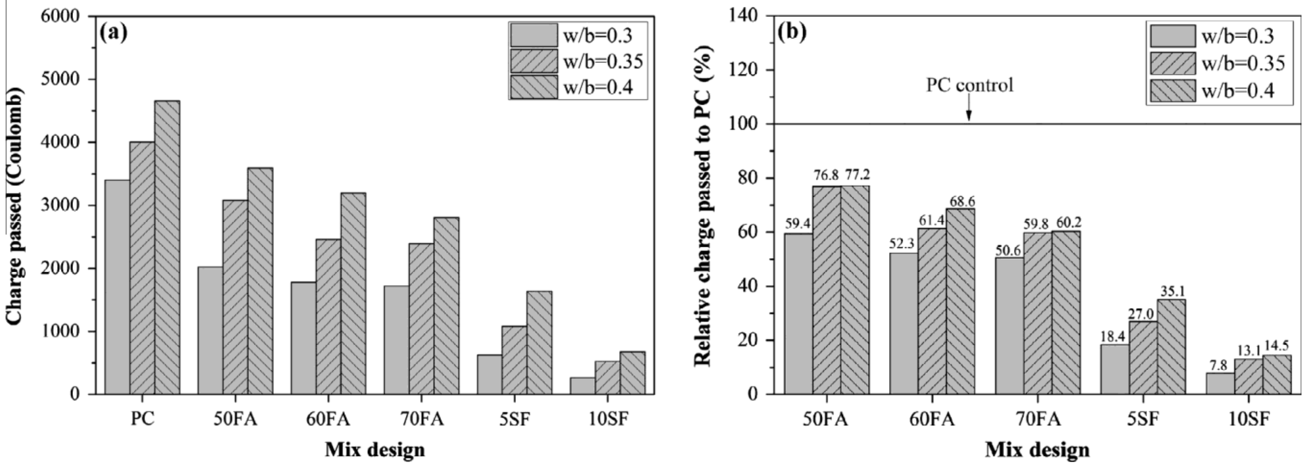

Fig. 4. Chloride resistances (charge passed) of SCC containing binary blended Portland cement (a) charge passed and (b) relative charge passed.

classified as a moderate chloride ion penetrability (2000–4000 coulombs), except the mixtures at w/b ratio of 0.3 which can be classified as a low chloride ion penetrability (1000–2000 coulombs). Moreover, the incorporation of FA and SF in term of ternary blended cement reduced the charge passed of SCC and showed the low chloride ion penetrability classification. Particularly, mixtures of 40FA10SF and 50FA10SF showed the very low (100–1000 coulombs) chloride ion penetrability classification. Therefore, the benefit of using high volume ternary cement with fly ash and silica fume can be seen to obtain a much lower chloride penetration compared to the high penetration found with Portland cement control concrete.

4. Conclusions

In this study, the influence of high calcium fly ash and SF as a binary and ternary blended cement at high volume replacement on properties of SCC was investigated. From these results it can be concluded that the apparent densities of all SCC in general were not significantly different when containing FA and SF. The volume

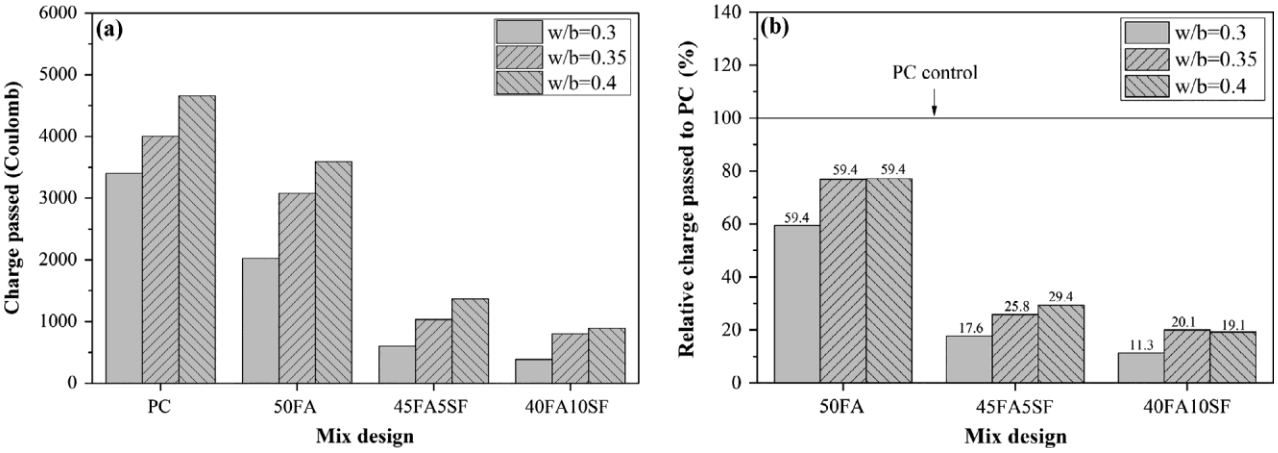

Fig. 5. Chloride resistances (charge passed) of SCC containing ternary blended Portland cement at 50 wt.% replacement (a) charge passed and (b) relative charge passed.

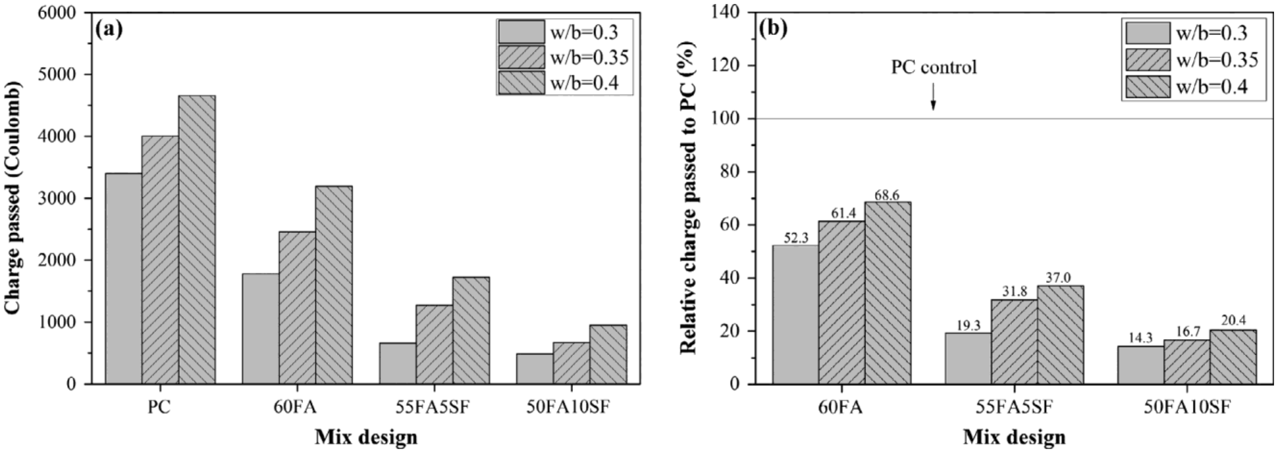

Fig. 6. Chloride resistances (charge passed) of SCC containing ternary blended Portland cement at 60 wt.% replacement (a) charge passed and (b) relative charge passed.

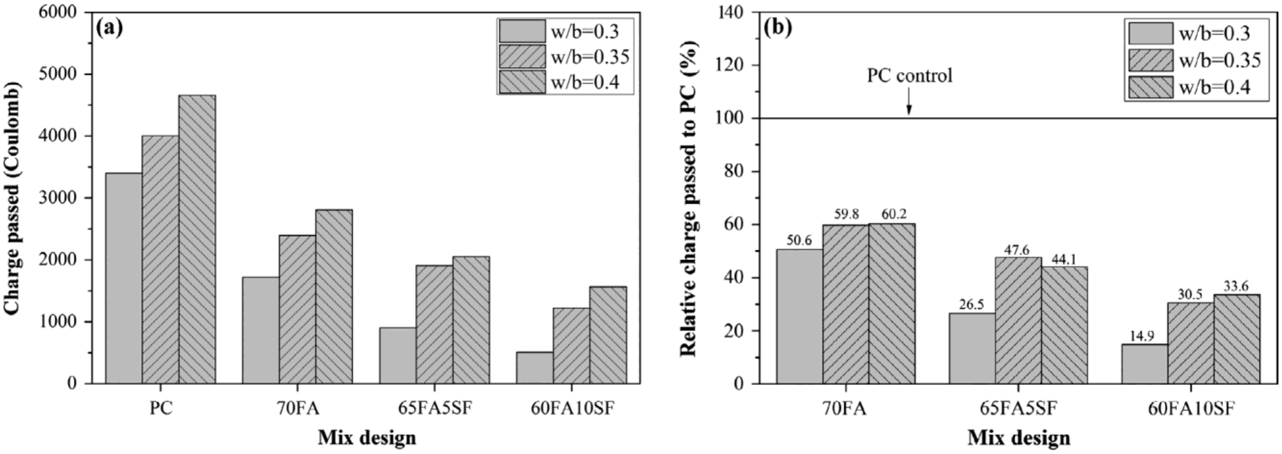

Fig. 7. Chloride resistances (charge passed) of SCC containing ternary blended Portland cement at 70 wt.% replacement (a) charge passed and (b) relative charge passed.

of permeable pore space (voids) and water absorption of SCC containing FA was higher than Portland cement control and tends to increase with increasing FA content. The influence of SF seems to decrease voids and water absorption of SCC in both binary and ternary blended Portland cement.

The compressive strength of SCC decreased with increasing FA content at all test ages and was lower than SCC control. For ternary blended Portland cement SCC, at the same replacement level, the compressive strength of SCC increased with increasing SF content and was higher than SCC containing binary blended Portland fly ash cement after 7 days. The high strength self-compacting concrete was obtained when using high calcium fly ash incorporating with SF at high cement replacement level. Particularly, the mixture of 40FA10SF at w/b ratio of 0.3 showed high strength self-compacting concrete and equivalent compressive strength to PC control at 28 days.

Table 7
Chloride ion penetrability based on charge passed.

Charge passed (coulombs)	Chloride ion penetrability
>4000	High
2000–4000	Moderate
1000–2000	Low
100–1000	Very low
<100	Negligible

SCC containing FA or SF as a binary blended cement decreased the charge passed and tends to decrease with increasing FA or SF content. For ternary blended Portland cement SCC, at the same replacement level, the charges passed of SCC were decreased with increasing SF content and more reduction were found when compared to binary blended Portland fly ash cement. Therefore, the very low chloride ion penetrability can be obtained when using high calcium fly ash and SF as ternary blended cement at high volume cement replacement.

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