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Comparing the performance of fine fly ash and silica fume in enhancing the properties of concretes containing fly ash

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HIGHLIGHTS

- Pozzolanic reactivity of fine fly ash (FFA) was compared to that of conventional fly ash (FA).
- Strength and durability of binary and ternary mixes based on FA, FFA and silica fume were studied.
- FFA has somewhat lower water demand compared to FA.
- The rate of pozzolanic reactivity of FFA is only moderately higher than FA.
- Silica fume is substantially more effective than FFA in improving properties of FA based ternary mixes.

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ABSTRACT

Fine fly ash which is obtained by classification of conventional fly ash has become available to concrete industry in recent years. In the current research the possibility of using fine fly ash in binary and ternary mixes with the aim of overcoming the rather slow rate of strength development in concretes containing conventional fly ashes or enhancing their durability was investigated.

The results show that the rate of pozzolanic reaction of fine fly ash is only moderately higher than conventional fly ash and the water demand is slightly reduced. The results of ternary mixes show that fine fly ash is not an effective material for increasing the rate of development of properties in concretes containing slow reacting pozzolans such as conventional fly ashes. The results of tests assessing durability of concrete against chloride ingress such as RCPT, RCMT and electrical resistivity indicate that the use of this material does not improve concrete durability over that which can be achieved by conventional fly ash at equal replacement levels.

1. Introduction

The use of fly ash as partial replacement of cement in concrete has numerous benefits including; reduced greenhouse gas emissions, good long term strength and durability characteristics, reduced water demand, reduced energy consumption and lessened pressure on natural resources [1,2]. Results of pervious research have shown however that the use of fly ash has the disadvantage of reducing the rate of development of properties in concrete. To overcome this deficiency the use of ternary cements comprising of a fast reacting pozzolan such as silica fume and a slow pozzolan such as fly ash has been considered by various researchers in recent years. Using combinations of two different supplementary materials in appropriate quantities can also result in improved workability and reduced construction problems [3–6].

Ternary cements containing fly ash and silica fume are commercially produced in some countries [7]. With simultaneous use of silica fume and fly ash the advantage of silica fume such as reduced bleeding and relatively fast rate of pozzolanic reaction are combined with benefits of fly ash such as increased workability and improved long term durability.

In the past decade, fine fly ashes which are obtained by processing conventional fly ash have become available and are marketed by some fly ash suppliers. Such fly ashes have similar chemical compositions to conventional fly ashes but have higher specific surfaces. Some reports show that the pozzolanic activity of fine

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fly ash is higher and its performance in concrete is better than conventional fly ashes [8–10].

Simultaneous use of fine fly ash with conventional fly ash (ternary mixes), has only been considered to a limited extent by some researchers [11,12]. In the research reported by Akkaya et al. [11], the performance of a ternary mix based on 10% fine fly ash and 20% conventional fly ash was studied. Concrete strengths were only evaluated at 14 days which showed slightly lower performance for the above mentioned ternary mix compared to the ternary mix based on 8% silica fume and 20% conventional fly ash. This finding indicates a potential for fine fly ash to be used in conjunction with conventional fly ash, in order to improve the rate of strength development.

Kessler et al. [12] studied the chloride resistance of various mixes including one ternary fine fly ash based mix. They found that at 28 days the performance of a silica fume based ternary mix (8% silica fume + 20% fly ash) was considerably better than the ternary mix containing 12% fine fly ash and 20% fly ash. This was despite the fact that in their study the water to binder ratio of the fine fly ash based ternary mix was lower than the silica fume based ternary mix.

Due to the lack of consistent findings of the limited pervious research on performance of fine fly ash based ternary mixes, this research was carried out to compare the performance of fine fly ash with that of silica fume in improving the properties of concretes containing conventional fly ash.

2. Experimental programs

2.1. Materials and concrete mixes

In this research a locally produced type II Portland cement, imported class F fly ash, imported class F fine fly ash and silica fume from Azna ferrosilicon plant in central Iran were used for production of concrete mixes. Chemical composition and physical properties of the cement and pozzolanic materials are presented in Tables 1 and 2. The results show the conformance of the cement, silica fume, fly ash and fine fly ash with requirements of ASTM C150 [13], ASTM C1240 [14] and ASTM C618 [15] respectively. The average diameter of particles of fine fly ash and normal fly ash as determined by laser particle size analysis were 6 and 12 μm, respectively.

As shown in the Table 2 the water requirements for the fly ash and fine fly ash were 95% and 93% of the control mortar mix respectively. The results also show higher pozzolanic activity of fine fly ash at 7 and 28 days compared to the conventional fly ash. However part of the better performance of fine fly ash could be due to its somewhat lower water demand.

Concrete mixes considered included, the control mix, the fly ash based binary mixes at 15% and 30% cement replacement levels, the fine fly ash based binary mixes, incorporating 7.5% and 15% of this pozzolan, and the silica fume based binary mixes incorporating 2.5%, 5%, 7.5% and 10% of silica fume. Two series of ternary mixes were considered. The first series was based on various combinations of fly ash and fine fly ash and the second group comprised of various combinations of fly ash and silica fume. Two base values of 15% and 30% for the fly ash content in ternary mixes were chosen to encompass the low and high dosage range for this material. As previous research indicates that the suitable range for silica fume in ternary mixes to be around 5%, three levels of 2.5%, 5% and 7.5% for silica fume were considered in the current study. Two replacement levels of 7.5% and 15% for fine fly ash in ternary mixes were considered so that the range used in the limited previous research [11,12] could be covered and a direct comparison with the 7.5% silica fume based ternary mix could be made. Mixture proportions for various mixes considered in this study are given in Table 3. Mix designations describe the type and replacement levels of pozzolans used. For instance mix SF7.5 represents the binary mix containing 7.5% silica fume and mix FA15-SF5 represents the ternary mix containing 15% fly ash and 5% silica fume.

As ternary mixes are generally intended for situations where high durability is required, the w/b ratio and total cementitious materials content were kept constant for all mixes at 0.38 and 420 kg/m^3. The workability of all mixes based on the slump test were kept in the range 125 ± 25 mm by using required amounts of a Polycarboxylic ether based superplasticizer.

The aggregates used for production of mixes were crushed coarse aggregate with maximum size of 19 mm and specific gravity of 2560 kg/m^3 and natural sand with a specific gravity of 2500 kg/m^3. Aggregates satisfied requirements of ASTM C33 [16].

After production of each concrete mix, the required specimens were cast according to standard procedures. The specimens were demoulded after the initial 24 h protection and were wet cured until the time of testing.

2.2. Tests

Compressive strength and electrical resistance tests were conducted at the ages of 7, 28, 90 and 180 days on 100 mm cubic concrete specimens. The electrical resistance test was carried out in accordance to the procedure proposed by the Swedish national testing and research institute [17]. The method involved connecting two copper plate electrodes to the opposite faces of the specimen via two thin wet sponges. The electrodes were then connected to a resistivity meter as shown in Fig. 1. Since resistivity measurement by direct current induces errors due to polarization effects, the resistivity meter used, applied an alternating current and measured the potential drop across the opposite face of the specimen. After applying the correction for potential drop due to the wet sponges, specific electrical resistance ρ in Ω m was determined by using (Eq. (1)).

$$\rho = A(R/L) \qquad (1)$$

where R is the electrical resistance determined in Ω, A is the cross sectional area of concrete specimen in m^2 and L is the length of cubes in m. The resistivity results can also be expressed as electrical conductivity which is the inverse of resistivity.

Resistance of various mixes to chloride-ion penetration was evaluated using the rapid chloride permeability test (RCPT) according to ASTM C1202 [18] and the rapid chloride migration test (RCMT) according to AASHTO TP64 [19] at the ages of 28, 90 and 180 days. The RCMT test is based on actual measurement of chloride ion penetration depth under an applied electrical charge (Fig. 2). Test duration is 18 h at the end of which the specimens are split and chloride front is determined by applying silver nitrate solution to the spilt surfaces. Three specimens were tested at each test

Table 1
Chemical analysis of cement, silica fume, normal fly ash and fine fly ash.

Composition%	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	Na_2O	K_2O
Cement	22.60	4.12	3.51	63.22	2.7	1.50	0.18	0.54
Silica fume (SF)	94.30	1.10	0.70	0.49	0.87	–	0.42	1.32
Fly ash (FA)	58.70	31.40	3.70	0.73	0.70	–	0.24	0.92
Fine fly ash (FFA)	58.80	32.17	3.83	2.00	0.70	–	0.22	0.86

Table 2
Physical properties of cement, silica fume, normal fly ash and fine fly ash.

	Cement	Silica fume	Fly ash	Fine fly ash
Average diameter (μm)	–	0.15	12	6
Specific surface area (cm^2/g) (Blain method)	2962	–	4096	6628
Specific surface area (cm^2/g) (BET method)	–	192000	–	–
Specific gravity (g/cm^3)	3.14	2.21	2.22	2.24
L.O.I (%)	–	0.1	3.33	5.33
Percent retained on 45 mm sieve	–	0.3	12	2.0
Pozzolanic activity index with portland cement in 7 days (%)	–	–	96	115
Pozzolanic activity index with portland cement in 28 days (%)	–	–	110	123
Accelerated pozzolanic strength activity index	–	145	–	–
Water requirement (%)	–	–	95	93

Table 3
Mixture proportions for concrete mixture studied.

Mixes	Total cementitious material (kg/m^3)	*w*/*b* ratio	Superplasticizer% of total cementitious material	Coarse aggregate (kg/m^3)	Fine aggregate (kg/m^3)	Cement (kg/m^3)	Fly ash (kg/m^3)	Silica fume (kg/m^3)	Fine fly ash (kg/m^3)
Control	420	0.38	0.44	876	876	420.0	–	–	–
SF2.5	420	0.38	0.48	869	869	409.5	–	10.5	–
SF5	420	0.38	0.51	868	868	399.0	–	21.0	–
SF7.5	420	0.38	0.54	865	865	388.5	–	31.5	–
SF10	420	0.38	0.56	869	869	378.0	–	42.0	–
FFA7.5	420	0.38	0.4	871	871	388.5	–	–	31.5
FFA15	420	0.38	0.33	866	866	357.0	–	–	63.0
FA15	420	0.38	0.39	865	865	357.0	63.0	–	–
FA30	420	0.38	0.3	855	855	294.0	126.0	–	–
FA15-SF2.5	420	0.38	0.4	864	864	346.5	63.0	10.5	–
FA15-SF5	420	0.38	0.42	861	861	336.0	63.0	21.0	–
FA15-SF7.5	420	0.38	0.45	860	860	325.5	63.0	31.5	–
FA30-SF2.5	420	0.38	0.32	853	853	283.5	126.0	10.5	–
FA30-SF5	420	0.38	0.33	851	851	273.0	126.0	21.0	–
FA30-SF7.5	420	0.38	0.34	849	849	262.5	126.0	31.5	–
FA15FFA7.5	420	0.38	0.32	861	861	325.5	63.0	–	31.5
FA15FFA15	420	0.38	0.28	856	856	294.0	63.0	–	63.0
FA30FFA7.5	420	0.38	0.26	851	851	262.5	126.0	–	31.5
FA30FFA15	420	0.38	0.22	846	846	231.0	126.0	–	63.0

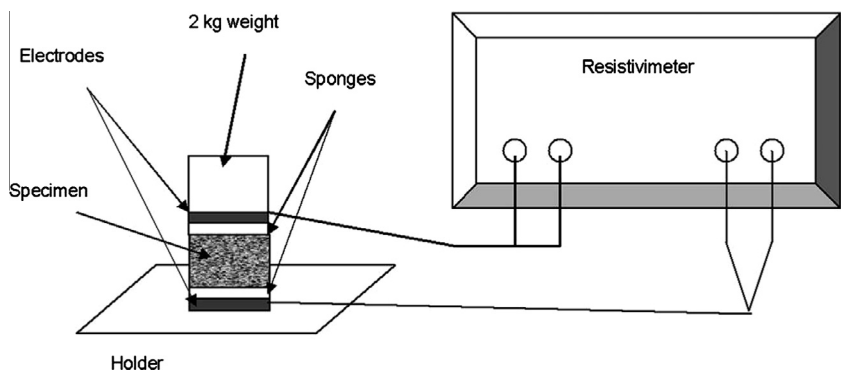

Fig. 1. Schematic presentation of the electrical resistivity test setup.

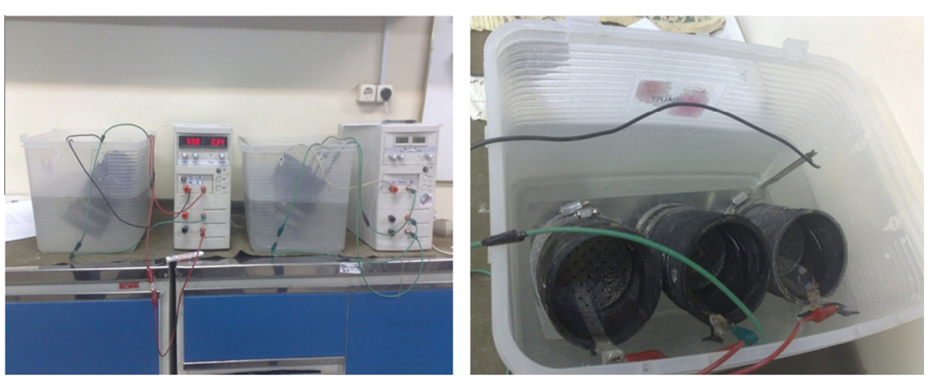

Fig. 2. The RCMT test set-up and apparatus used in this study.

age for each mixture and the average value of these specimens is used to calculate rate of chloride penetration (Eq. (2)). The chloride diffusion coefficient can also be obtained by (Eq. (3)) [20].

$$M = \frac{h}{Vt} \tag{2}$$

$$D_{RCMT} = \frac{0.0239(273+T)L}{(V-2)t}\left(h - 0.0238\sqrt{\frac{(273+T)Lh}{V-2}}\right) \tag{3}$$

where M is the rate of chloride penetration in mm/(V h), t is the test duration in hours and h is the average value of the penetration depths in mm, D_{RCMT} is the chloride diffusion coefficient in m^2/s, T average value of the initial and final temperatures in the analyte solution in °C, V is the absolute value of the applied voltage in V, L is the thickness of the specimen in mm.

3. Test results and discussion

3.1. Water demand

The required amount of superplasticizer for achieving the specified slump of 125 ± 25 mm was considered as an indication of water demand of various mixes. In Table 3 and Fig. 3 the superplasticizer requirement for various mixes are presented. As seen the use of silica fume has resulted in increased water demand compared to the control mix, which increases for higher silica fume contents. As expected the use of fly ash and fine fly ash has decreased the water demand. Despite the higher specific surface area of fine fly ash compared to conventional fly ash the results show that the effect of fine fly ash in reduction of water demand of concrete is higher than that of fly ash. This could be due to broadening of the size range in the powder phase (cement and pozzolan). This allows a better particle packing between cement and fine fly ash particles which lowers the inter particle porosity of the powder phase, which lowers the amount of water required to fill such porosities.

The combination of fly ash and silica fume has resulted in decreased water demand compared to the binary concretes containing equal amounts of silica fume. Except the ternary concrete containing 7.5% silica fume and 15% fly ash, all other ternary concretes had lower water demand than the control mix. Based on the results obtained, the high water requirements of mixtures containing silica fume can be overcome by using ternary cements containing silica fume and fly ash. The combination of fly ash and fine fly ash has resulted in decreased water demand compared to the binary concretes containing equal amounts of fly ash.

3.2. Compressive strength

In Fig. 4 the results of compressive strength of binary mixes at the ages of 7 up to 180 days are compared. As expected the compressive strength of concretes containing silica fume are higher than control concrete at all ages and with increasing dosage of silica fume the gain in strength becomes higher. The mixture containing 15% fly ash had lower compressive strength than control concrete at 7 and 28 days, but at 90 and 180 days the strength became slightly higher than the control mix. For mixture containing 30% fly ash, the compressive strength was lower than the control mix at all ages.

In Fig. 5. The compressive strength of ternary mixes are compared with the control mix and the fly ash based binary mixes. The combination of 5% silica fume with 15% fly ash has resulted in considerable strength improvement at all ages over the control and the binary mix containing 15% fly ash. The incorporation of silica fume in mixes containing 30% fly ash however had only a slight effect in improving its strength properties. In ternary mixtures containing silica fume and fly ash it seems that silica fume has two different effects on the development of properties. Silica fume due to its high specific surface and its nucleation effect results in strength enhancement from 7 days onwards. Pozzolanic reaction of silica fume and consumption of $Ca(OH)_2$ and also the incorporation of ionic species such as Na^+ and K^+ in reaction products of silica fume leads to a reduction in pore solution alkalinity [21,22]. Considering the dependence of the rate of pozzolanic reactivity of fly ash on alkalinity of pore solution, it appears that in ternary mixes containing 30% fly ash the nucleation effect and fast

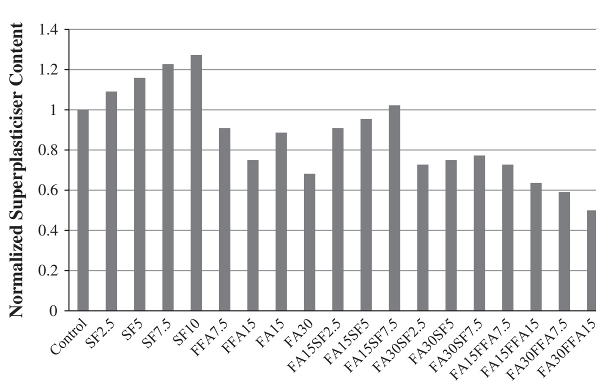

Fig. 3. The comparison of the effect of supplementary cementitious materials on the superplasticizer dosage.

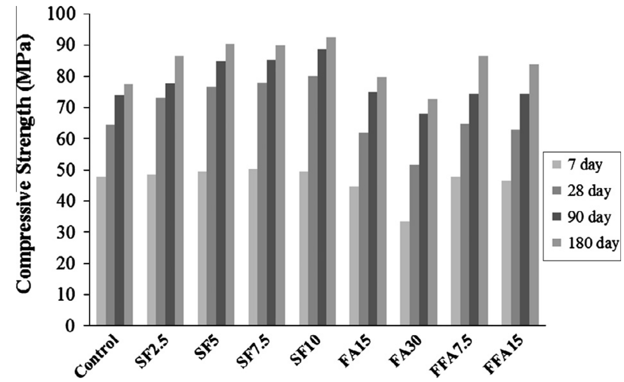

Fig. 4. The comparison of compressive strength of binary and control mixes.

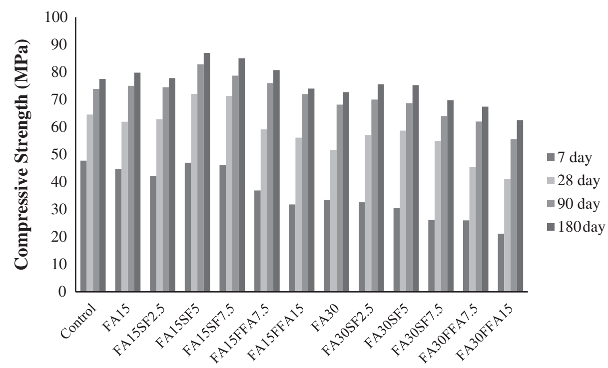

Fig. 5. The compressive strength of ternary mixes compared to the control and binary mixes containing fly ash.

pozzolanic action of silica fume has not been able to compensate for reduced fly ash activity caused by lower pore solution alkalinity.

The use of 7.5% fine fly ash in mixes containing 15% ordinary fly ash has resulted in a slight reduction in 28 day strength while slight increase in later age strength was observed. The use of fine fly ash in mixes containing 30% fly ash has resulted in considerable strength reduction at all ages. It appears that despite smaller particle size of fine fly ash, compared to the conventional fly ash, its rate of pozzolanic activity and nucleation effects are substantially lower than that of silica fume. It should be noted that the foregoing discussions were based on comparison of strength development of various mixes at equal *w*/*b* ratios, where the differences in water demands of various mixes had been taken into account by using the required amounts of superplasticizer for each mix to achieve similar levels of workability. If however, the different water requirements of various mixes are allowed to reflect in their w/b ratios, the pozzolans with lower water requirements would perform better than that indicated by the results of the current study.

3.3. The electrical resistance

The results of the electrical resistance of binary mixes at various ages are presented in Fig. 6. The addition of SF has substantially increased the electrical resistance, especially at ages of 28 days and higher. The use of FA did not improve the 28 day electrical resistance of concrete, although at the ages of 90 and 180 days with increasing pozzolanic reaction of fly ash, the electrical resistance of fly ash concretes increased. However the effect of SF in increasing the electrical resistance was higher than fly ash at all ages. The effect of fine fly ash on electrical resistance of concrete at various ages was similar to that of conventional fly ash.

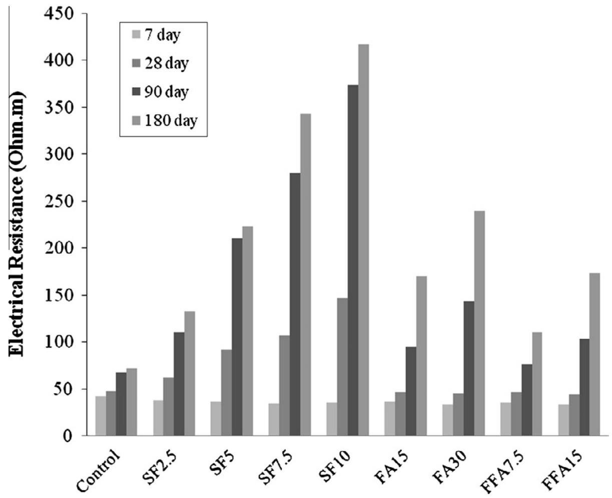

Fig. 6. The electrical resistance of binary mixes compared to control mix.

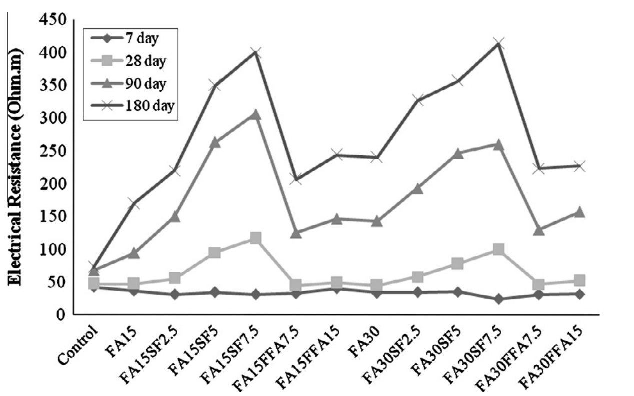

Fig. 7. The electrical resistance of ternary mixes compared to control and binary mixes containing fly ash.

In Fig. 7, the performance of ternary mixes with regards to electrical resistance are compared with the control mix and the binary mixes containing fly ash. Incorporation of SF has caused considerable increase in electrical resistance of mixes containing FA, showing the clear advantage of ternary mixes over binary mixes containing fly ash alone. Ternary mixes have similar levels of electrical resistance at the age of 28 days compared to binary mixes containing equal amount of SF. However at ages of 90 and 180 days the ternary mixes outperform silica fume based binary mixes.

The simultaneous use of fine fly ash in the mix containing 15% fly ash did not improve the 7 and 28 day electrical resistance, however it caused some improvement in later ages. The use of fine fly ash in the mix containing 30% fly ash did not improve its electrical resistance at any age.

It is noted that the performance of various binary and ternary mixes in the electrical resistance test is considerably better compared to their performance in the compressive strength test. This is probably due to the fact that the total pore volume of concrete is not reduced by the pozzolanic reactions, but the pore structure becomes more discrete. The effect of pore connectivity on durability is much higher than that on the strength. In addition to pore structure, electrical resistance of concrete depends on the pore solution chemistry and chemical binding of various ions by the reaction products, whereas these parameters do not affect the strength properties. The use of fly ash and silica fume dilutes the pore solution and increases the binding of different ions such as Na^+ and K^+ by the reaction products. Consequently the $(OH)^-$ ions in the pores is reduced. Because of the important role of $(OH)^-$ ions in the electrical conductivity of concrete, reduction of $(OH)^-$ in pore solution of concrete containing supplementary cementitious materials can increase the electrical resistance of concrete [23]. The relative effects of pore solution chemistry and pore structure on electrical resistance of concrete, based on the results of the RCPT test has recently been quantified by Neithalath et al. [24]. They showed that about 70% of the improvement in the electrical resistance of concrete mixes containing silica fume was due to pore structure improvement and the remaining 30% was attributed to reduction in pore solution alkalinity. For the concrete mixes containing fly ash however, more than 90% of the improvement was attributed to pore structure refinement.

3.4. The rapid chloride permeability test results

The results of the rapid chloride permeability test (ASTM1202) of binary mixes at the ages of 28, 90 and 180 days are presented in Fig. 8. The results show substantial reduction in the passed charge at all ages due to incorporation of silica fume. The use of FA at both 15% and 30% replacement levels has not resulted in a notable reduction in passed charge through concrete at the age of 28 days. But at 90 and 180 days considerable reduction of the rate of chloride penetration was observed. Effect of fine fly ash on the rate of chloride penetration was similar to that of fly ash at all ages.

The results of the RCPT test of ternary mixes are presented in Fig. 9. As shown ternary mixes based on silica fume and 15% fly ash showed substantial reduction in the passed charge compared to the control and the 15% fly ash binary mix. However the addition of silica fume to the 30% fly ash mix only moderately improved its performance. The addition of fine fly ash to the mix containing 15% of conventional fly ash only slightly improved chloride resistance at 90 and 180 days. For the mix with 30% fly ash the addition of fine fly ash did not result in any improvement in chloride resistance.

Since the charge passed through concrete in the RCPT test is dependent on both the microstructure of the paste and chemical composition of pore solution particularly $(OH)^-$ and $(Cl)^-$ ions, the discussion presented for the observed trends in the electrical resistance section is also applicable here.

3.5. The results of rapid chloride migration test (RCMT)

The results of chloride diffusion coefficient of binary and control mixes which were obtained by the rapid chloride migration test,

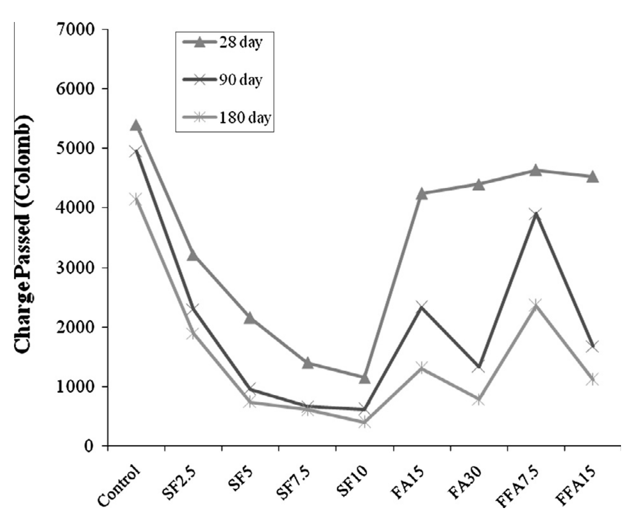

Fig. 8. The passed charge of the binary mixes compared to control mix.

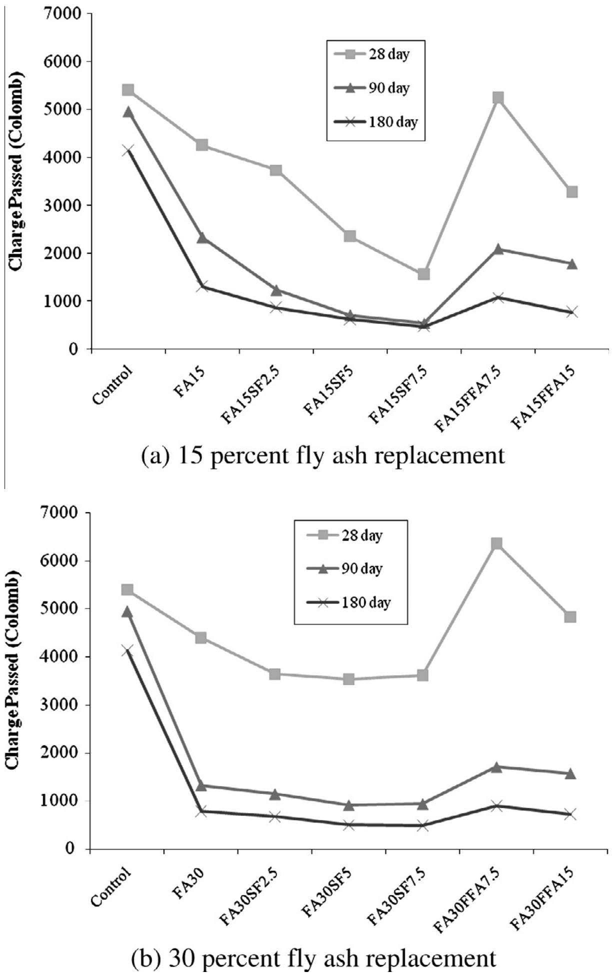

Fig. 9. The passed charge of ternary mixes compared to control and binary mixes containing fly ash.

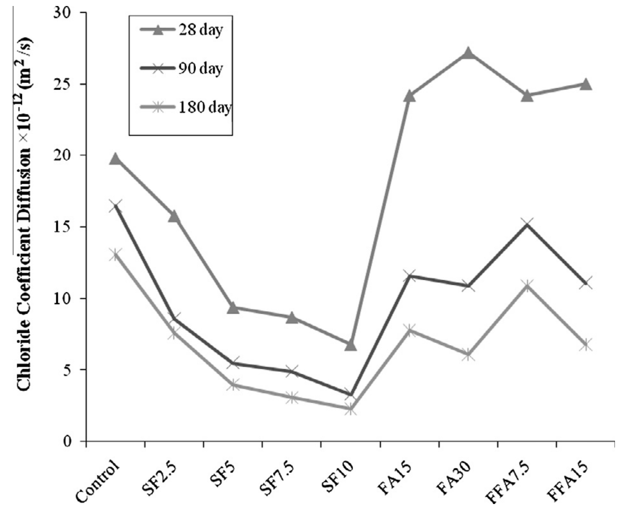

Fig. 10. The chloride coefficient diffusion of binary mixes compared to control mix.

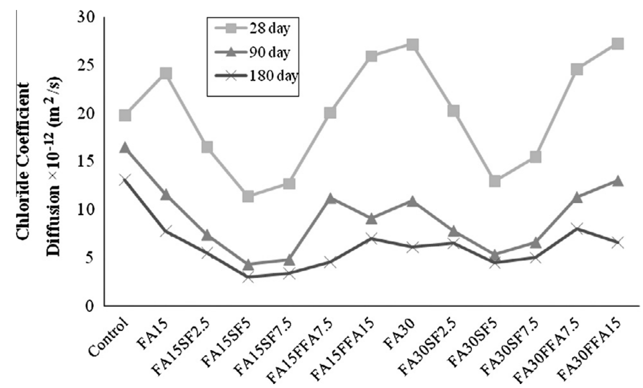

Fig. 11. The chloride coefficient diffusion of ternary mixes compared to control and binary mixes containing fly ash.

described in AASHTO TP64 [19] are presented in Fig. 10. The addition of silica fume caused substantial reductions in penetration rate of chlorides at all ages tested and the level of improvement increased with increasing dosage of silica fume. However the addition of fly ash and fine fly ash caused an increase in penetration rate of chlorides at the age of 28 days. With the progresses of pozzolanic reactions at the ages of 90 and 180 days, the performance of binary mixes containing fly ash or fine fly ash became better than the control mix. Even in the long term the performance of binary mixes containing silica fume was substantially better than those containing fly ash or fine fly ash.

In Fig. 11 the chloride diffusion coefficient of ternary mixes are compared with the control and binary mixes containing fly ash at the ages of 28, 90 and 180 days. The results show that the use of silica fume has caused considerable reduction in chloride penetration of mixes containing various amounts of fly ash at all ages and the chloride penetration of ternary mixes are substantially lower than control even at the age of 28 days. It appears that the optimum silica fume content in ternary mixes is about 5% and further increase in silica fume content does not result in further improvement in chloride resistance. The addition of fine fly ash to the mix containing 15% fly ash did not improve the resistance at 28 day, however it resulted in improved performance at 90 and 180 day. The addition of fine fly ash to mixes containing 30% of conventional fly ash did not result in improved performance at any age.

It should be noted that apart from the pore structure characteristics of concrete, the results of the RCPT and the electrical resistance tests are also influenced by pore solution chemistry, particularly $(OH)^-$ ion concentration. As the use of supplementary cementiteous materials also affect pore solution chemistry particularly by lowering the $(OH)^-$ ion concentration, some researchers consider the improvements in chloride resistance indicated by such tests, as exaggerated [25]. As mentioned in section 3.3, findings of Neithalath et al. [24], indicate that about 70% of improvements in chloride resistance of concrete mixes with silica fume, as indicated by the RCPT and electrical conductivity methods, are due to actual pore structure improvement. The corresponding value reported for the concrete mixes containing fly ash was about 90%. Nokken et al. [26] also reported that influence of pore solution chemistry on the improvements in the chloride resistance of mixes containing supplementary cementitious materials as indicated by the RCPT and electrical conductivity test were only secondary compared to the effects of improvements in the pore structure. Since the RCMT method directly determines the chloride penetration depth, its results are much less affected by pore solution chemistry. Confirmation of RCPT and electrical resistance test results on performance of ternary mixes by the RCMT method, confirms the improved micro-structure and reduced pore connectivity of ternary concrete mixes containing silica fume.

4. Conclusions

The appraisal of pozzolanic activity index and water demand, performed according to ASTM C618 show that fine fly ash had somewhat faster rate of pozzolanic reaction and slightly lower water demand compared to the conventional fly ash.

The results of tests on concrete mixes at equal water to binder ratio show that binary concrete mixes containing fine fly ash had somewhat lower water demand compared to the conventional fly ash mixes. They also had moderately higher compressive strength at 7 days compared to mixes with conventional fly ash but at later ages performed similarly. Among the binary mixes, the ones containing silica fume had the best performance. Silica fume caused substantial improvement in strength and durability at ages of 28 days and later compared to the control and other binary mixes.

Ternary concrete mixes based on combined use of fine fly ash and fly ash did not show a notable improvement in the rate of strength development and durability over binary mixes containing conventional fly ash. Their water demand however was slightly lower. Ternary concrete mixes based on silica fume and conventional fly ash had excellent strength and durability performance at the age of 28 days and later. These mixes had lower water demand compared to the binary silica fume mixes and also outperformed them with regards to long term durability.

The findings of current research show that fine fly ash is not an effective material for increasing the rate of development of properties in concretes containing slow reacting pozzolans such as conventional fly ashes. The results of tests assessing the durability of concrete against chloride ingress, such as RCPT, RCMT and electrical resistance indicate that fine fly ash does not improve concrete durability over that which can be achieved by conventional fly ah at equal replacement levels.

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