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Mechanical and durability properties of ternary concretes containing silica fume and low reactivity blast furnace slag

Ali Reza Bagheri *, Hamed Zanganeh, Mohamad Mehdi Moalemi

Civil Engineering Dept., K.N. Toosi University of Technology, Tehran, Iran

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ABSTRACT

In this study, the effect of incorporation of silica fume in enhancing strength development rate and durability characteristics of binary concretes containing a low reactivity slag has been investigated. Binary concretes studied included mixes containing slag at cement replacement levels of 15%, 30% and 50% and mixes containing silica fume at cement replacement levels of 2.5%, 5%, 7.5% and 10%. Ternary concretes included combinations of silica fume and slag at various cement replacement levels. The w/b ratio and total cementitious materials content were kept constant for all mixes at 0.38 and 420 kg/m^3 respectively. Concrete mixes were evaluated for compressive strength, electrical resistance, chloride permeability (ASTM C1202 RCPT test) and chloride migration (AASHTO TP64 RCMT test), at various ages up to 180 days.

The results show that simultaneous use of silica fume has only a moderate effect in improving the slow rate of strength gain of binary mixes containing low reactivity slag. However it improves their durability considerably. Using appropriate combination of low reactivity slag and silica fume, it is possible to obtain ternary mixes with 28 day strength comparable to the control mix and improve durability particularly in the long term. Ternary mixes also have the added advantage of reduced water demand.

1. Introduction

Due to increasing production of steel in the world, the amount of blast furnace slag which is a by-product material is accordingly increasing [1]. A major area for utilization of vast amounts of slag produced is in the concrete industry as a supplementary cementitious material, although research has also shown good potential for utilization of slag as concrete aggregates [2,3]. The use of slag as partial replacement of cement in concrete has numerous benefits including: reduced greenhouse gas emissions, good long term strength and durability characteristics, reduced energy consumption and lessened pressure on natural resources [4,5].

Performance of slag as a supplementary cementitious material and its influence on rate of development of strength and durability of concrete depends on its physical and chemical characteristics. Chemical composition of slag depends mainly on the raw materials used in production of raw iron and the physical structure of the slag depends on the method used for its cooling. Concretes incorporating slags with higher alkalinity and higher amount of glass phase have a faster rate of development of properties [4,5]. ASTM C989 has classified slags according to their reactivity in concrete into three grades: Grade 80, Grade 100, and Grade 120 [6]. Grade 80 slag has the lowest reactivity among the three grades and the rate of development of properties of concretes containing this slag is slower than the control mix. Development of methods to improve the performance of slags in concrete, particularly the ones with lower reactivity, will facilitate higher utilization of these materials. In this paper the possibility of achieving enhanced concrete properties through the simultaneous use of a low reactivity slag (Grade 80) and silica fume is investigated. A brief review of previous research on ternary cement concretes based on slag and silica fume is first presented.

During the past decade the development of ternary concrete (Portland cement concrete with two supplementary cementitious materials), to combine the benefits of each supplementary material and minimize their adverse effects has been pursued by researchers [7–12]. Most of ternary cements have been based on the use of silica fume with another supplementary cementitious material such as slag or fly ash. It is well known that the addition of silica fume results in considerable improvement of mechanical and durability properties of concretes. But high cost and limited availability of silica fume and construction problems such as dispersion difficulties and increased water demand are drawbacks of using this material in dosages much higher than 5% [5,13]. Due to relatively low water demand of slag, combined use of this material with silica fume can overcome the high water demand of binary

* Corresponding author. Tel.: +98 2188779473; fax: +98 2188779476.
E-mail addresses: bagheri@kntu.ac.ir (A.R. Bagheri), Hamed_zangaaneh@yahoo.com (H. Zanganeh), mohsen.moalemi@yahoo.com (M.M. Moalemi).

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mixes containing silica fume. On the other hand increased bleeding and low cohesion which are sometimes attributed to mixes containing slag can be overcome through simultaneous use with silica fume [14–18].

Results of Thomas et al. [7] shows that compressive strength of ternary concrete containing 20–25% slag and 3–5% of silica fume at 7 days nearly equals compressive strength of the control mixture and at 28 days exceeds it. Results of Bleszynski et al. [10] indicate that the use of ternary mixtures containing 35% slag and 4–6% of silica fume could compensate for the drop in 28-day strength of binary mixtures containing 35% slag compared with the control mixture.

Lane and Ozyildirim [11] found that the expansion of ternary concretes due to alkali silica reaction were lower than the control concrete and the binary concretes containing same amount of each supplementary material. It was also observed that the expansion of ternary concrete containing 25% slag and 2.5% silica fume was lower than binary concrete containing 50% slag. Concerning the durability in sulfate environment the results of Thomas et al. [7] indicate that the expansion due to sulfate attack of ternary mixture containing silica fume and slag after 12 months is lower than mixture containing type V cement.

Results of Ahmed et al. [9] on penetration of chlorides in concrete shows that the ternary mixtures containing 10% of silica fume and variable amounts of slag have better performance in comparison with binary concrete containing slag and the control mixture. Results of Bleszynski et al. [10] show that the ternary concrete containing 25% slag and 3.8% silica fume after 8 years of exposure to chloride environment has lower depth of penetration of chloride ion in comparison with control mixture. Also chloride diffusion coefficient of ternary concrete containing slag and silica fume is lower than the control and binary concretes. Findings of Thomas et al. [7] show that chloride penetration resistance of ternary concrete containing slag and silica fume is nearly equal to that of binary concrete containing silica fume with equal water to binder ratio at 28 and 56 days. But after 2 years, chloride diffusion coefficient and amount of charger passed through concrete in RCPT test of ternary concrete is significantly lower than that of binary concrete containing equal amount of silica fume. Findings of Lee et al. [12] show that ternary concretes containing slag and silica fume have better performance in marine environments in comparison with binary and control mixtures.

In various research cited above, the slag used has been of adequate qualify or if the quality has not been explicitly stated, the results of binary slag mixes reported show it to be of grade 100 or higher. Unfortunately data with regards to performance of ternary concretes containing low reactivity slags and silica fume which could promote the utilization of such slags in concrete is lacking. The current research was therefore planned to study the effects of simultaneous use of a low reactivity grade 80 slag and silica fume on the mechanical and durability properties of concrete up to 180 days and compare it with performance of the control mix and the binary mixes containing each pozzolan separately.

2. Experimental programs

2.1. Materials and mixture proportions

Total cementitious materials content and water to binder ratio were kept constant for all mixes at 420 kg/m^3 and 0.38 respectively. Materials utilized included type 2 Portland cement, silica fume and blast furnace slag. Chemical analysis and physical and mechanical characteristics of these materials are given in Tables 1 and 2 respectively. The results show conformance of the cement and silica fume (SF) with requirements of ASTM C150 [19] and ASTM C1240 [20] respectively. The slag however only satisfied requirements of ASTM C989 [6] for grade 80. The workability of concretes mixes were kept constant in the slump range 125 ± 25 mm. The differences in water demand of various mixes were accounted for by use of required amount of a Polycarboxylic ether based superplasticiser (SP). The aggregates used for production of mixes were crushed coarse aggregate (CA) with nominal maximum size of 19 mm and specific gravity of 2.56 g/cm^3 and natural sand (FA) with specific gravity of 2.5 g/cm^3 and satisfied requirements of ASTM C33 [21]. Mixture proportions for the control, binary and ternary mixes considered in this study are given in Table 3.

Table 1
Chemical analysis of cement, slag and silica fume.

Oxide	Cement	Slag	Silica fume
SiO_2	22.57	36.00	94.30
Al_2O_3	4.12	13.00	1.10
Fe_2O_3	3.51	0.60	0.70
CaO	63.22	38.10	0.49
MgO	2.70	6.60	0.87
SO_3	1.50	0.60	–
Na_2O	0.18	0.50	0.42
K_2O	0.54	1.10	1.32

Table 2
Physical and mechanical properties of cement, slag and silica fume.

Property	Cement	Salg	Silica fume
Fineness (cm^2/g)	2962	3100	192,000
Density (g/cm^3)	3.14	2.89	2.21
Loss on ignition (%)	–	1.2	0.1
Material retained on sieve No. 325 (%)	–	10.0	0.3
Accelerated pozzolanic activity index 7 day (%)	–	–	145
Pozzolanic activity index 7 day (%)	–	58	–
Pozzolanic activity index 28 day (%)	–	75	–
Water requirement (%)	–	96	–

2.2. Tests carried out

The aim of the tests performed was to evaluate the strength and durability characteristics of the control and various binary and ternary mixes and their development over time. Compressive strength test was conducted at the ages of 7, 28, 90 and 180 days on 100 mm cubic concrete specimens in accordance with BS EN 12390 part 1 [22]. As the electrical resistance of concrete is largely dependent on its pore volume and pore connectivity, this property was measured as a general indication of concrete durability. The electrical resistance test was conducted at the age of 7, 28, 90 and 180 days according to the procedure proposed by Swedish national testing and research institute [23].

The rapid chloride permeability test (RCPT), described in ASTM C1202 [24], is widely used by researchers and engineers to assess the durability to concrete particularly against chloride ingress. This test was therefore performed on various mixes in this study at the ages of 28, 90 and 180 days. In the RCPT test the total electrical charge passing through a 50 mm thick concrete disk specimen, during a 6 h period under an electrical potential of 60 V, is determined. The test set up used comprising of the DC power supply, data logger and cells containing the specimen is shown in Fig. 1.

Table 3
Mixture proportions for concrete mixture studied.

Mix designation	w/b	Cement (kg/m^3)	Slag (kg/m^3)	SF (kg/m^3)	SP (%)	CA SSD (kg/m^3)	FA SSD (kg/m^3)	Concrete temperature (°C)
Control	0.38	420.0	0.0	0.0	0.44	876	876	20.0
SF-2.5	0.38	409.5	0.0	10.5	0.48	874	874	20.6
SF-5	0.38	399.0	0.0	21.0	0.51	872	872	21.6
SF-7.5	0.38	388.5	0.0	31.5	0.54	870	870	22.0
SF-10	0.38	378.0	0.0	42.0	0.56	869	869	21.0
SL15	0.38	357.0	63.0	0.0	0.40	873	873	22.0
SL30	0.38	294.0	126.0	0.0	0.37	870	870	22.0
SL50	0.38	210.0	210.0	0.0	0.33	866	866	20.0
SL15-SF2.5	0.38	346.5	63.0	10.5	0.42	872	872	19.0
SL15-SF5	0.38	336.0	63.0	21.0	0.44	870	870	20.0
SL15-SF7.5	0.38	325.5	63.0	31.5	0.46	868	868	21.0
SL30-SF2.5	0.38	283.5	126.0	10.5	0.38	869	869	18.0
SL30-SF5	0.38	273.0	126.0	21.0	0.40	867	867	19.0
SL30-SF7.5	0.38	262.5	126.0	31.5	0.42	865	865	22.0
SL50-SF2.5	0.38	199.5	210.0	10.5	0.34	865	865	20.0
SL50-SF5	0.38	189.0	210.0	21.0	0.36	863	863	20.0
SL50-SF7.5	0.38	178.5	210.0	31.5	0.38	861	861	21.0

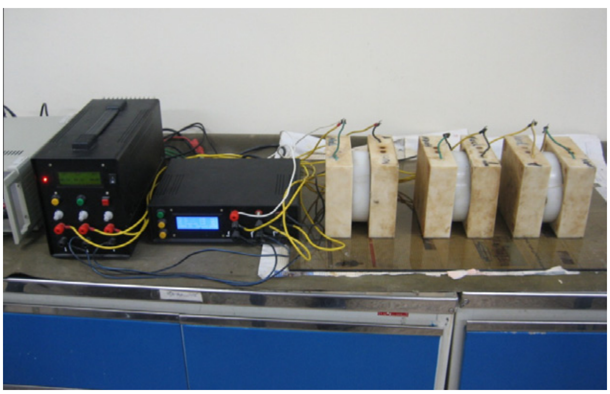

Fig. 1. The RCPT test set-up and apparatus used in this study.

Despite its widespread application, the RCPT test suffers from certain drawbacks. As the RCPT test is in fact a prolonged resistivity test, a main concern expressed has been the rise in temperature of concrete specimens under the high electrical potential applied, particularly those with higher conductivities. This rise in temperature has been reported to result in an increase in the passed charge [25,26]. The other criticism towards the RCPT test is the possible role of ions such as $(OH)^-$ in conduction of electrical charge. It has therefore be suggested that some supplementary cementitious materials can cause a reduction in the electrical charge passed, by reducing the concentration of $(OH)^-$ ions in pore solution. Whereas such reduction do not necessarily mean higher resistance to chloride ion penetration [26,27].

Fig. 3. Depth of chloride penetration in a sample at the end of the RCMT test.

It should be noted that the influence of pore solution chemistry just described for the RCPT test is equally applicable to the shorter duration electrical resistivity test. In order to avoid such possible influences it was decided to include the rapid chloride migration test (RCMT) which is not affected by the aforementioned parameters. This test which is standardized by AASHTO under designation TP64 [28], is based on actual measurement of chloride ion penetration depth under an applied electrical charge. Test duration is 18 h at the end of which the specimens are split and chloride font is determined by applying silver nitrate solution to the split surface. The RCMT test set up used is shown in Fig. 2 and a split specimen

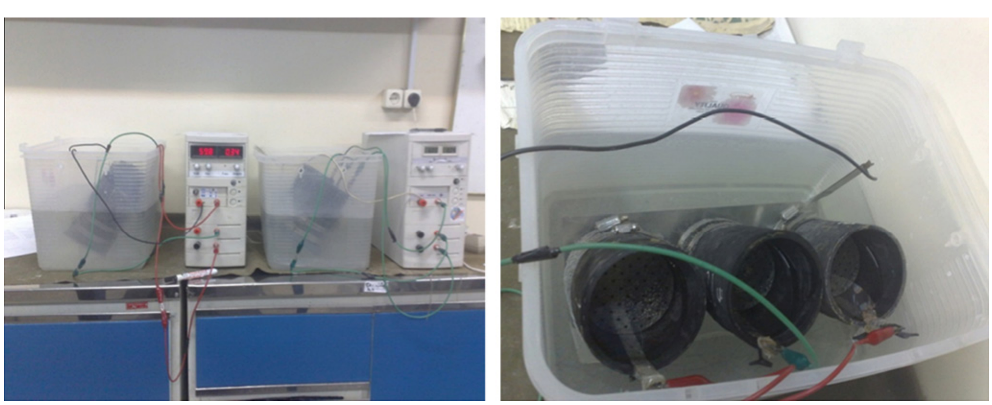

Fig. 2. The RCMT test set-up and apparatus used in this study.

showing the chloride front is shown in Fig. 3. Three specimens were tested at each test age for each of the aforementioned tests and the average value of these specimens is reported.

3. Test results and discussion

3.1. Water demand

The required amount of superplasticiser for achieving the specified slump of 125 ± 25 mm can be considered as an indication of water demand of various mixes. In Fig. 4 the normalized superplasticiser content 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 slag has decreased the water demand.

The combination of slag 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% slag, 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 slag.

3.2. Compressive strength

In Fig. 5 compressive strength of the binary mixes and the control mix at various ages are presented. 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 use of the low reactivity slag at 15% cement replacement level has caused a small reduction in compressive strength compared to the control mix. For mixes containing higher amounts of slag especially for the mix incorporating 50% slag, the strength reduction is considerable at all ages.

Fig. 6 shows the compressive strength of ternary mixes at various ages. Addition of various dosages of silica fume to the mix containing 15% slag improves its rate of strength gain and the drop in its 28 day strength compared to the control mix is compensated for and at later ages shows improvements over control. For ternary mixes containing 30% slag and various dosages of silica fume,

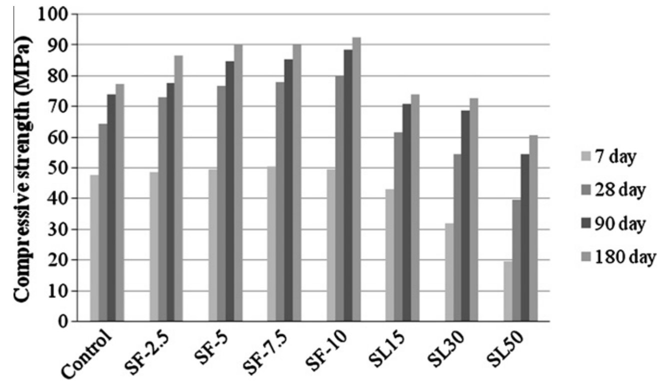

Fig. 5. The results of compressive strength of binary mixes.

compressive strengths are still lower than the control mix, however with progress of pozzolanic reactions at 90 and 180 days the difference in strength becomes smaller. For ternary mixes containing 50% slag and various dosages of silica fume, compressive strengths are still much lower than the control mix at all ages.

In ternary mixtures containing silica fume and slag it seems that silica fume has two different effects on the development of properties. Silica fume due to its high specific surface and its micro-filler 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 lead to a reduction in pore solution alkalinity [29,30].

Slag hydration reactions however depend on alkalinity of pore solution and reduction in alkalinity will have an adverse effect on slag contribution to strength. For ternary mixes containing higher slag contents; i.e. 30% and 50%, it appears that the micro-filler and pozzolanic action of silica fume has not been able to compensate for reduced slag activity caused by lower alkalinity, and despite the use of 7.5% of silica fume the strengths are lower than the control mix.

It is interesting to note that Bleszynski et al. [10] have reported similar 28 day strengths for ternary concrete containing 35% slag and 3–6% silica fume with the control mix. This is believed to be due to the higher reactivity of slag used in their investigation compared with the slag used in the current study.

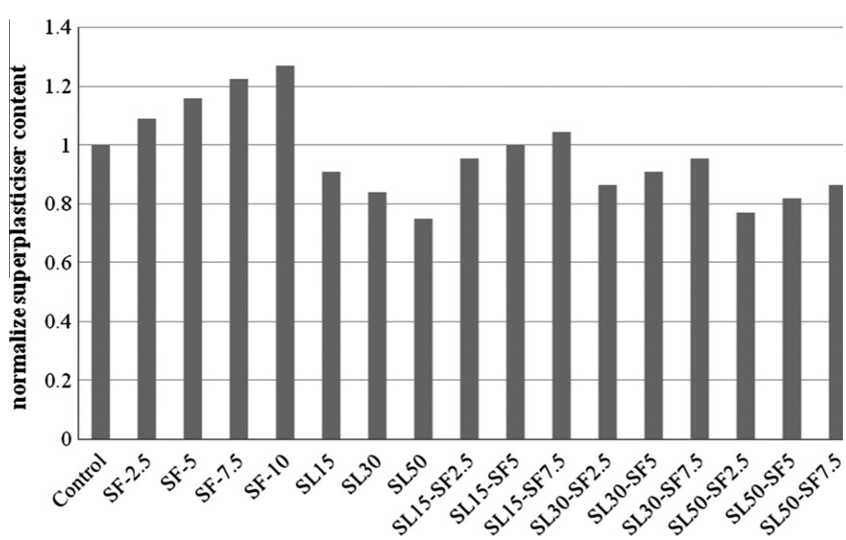

Fig. 4. Normalized superplasticiser content for various mixes with respect to the control mix.

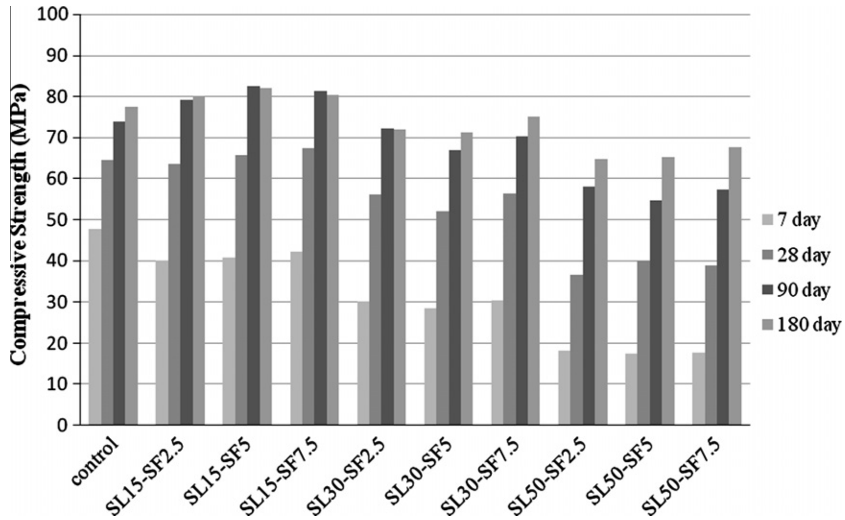

Fig. 6. The results of compressive strength of ternary mixes.

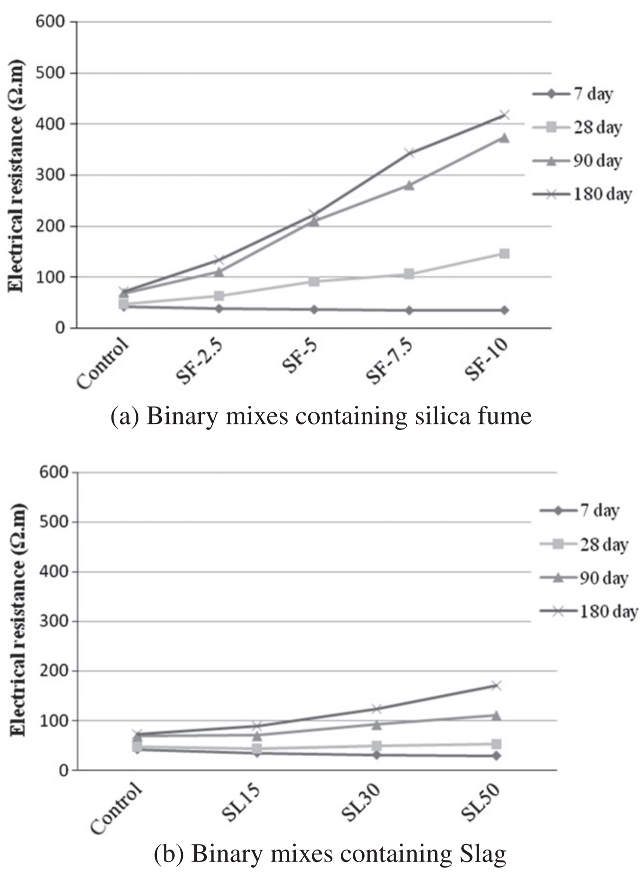

Fig. 7. Comparison of the electrical resistance of binary concrete mixes with the control mix.

3.3. Electrical resistance

The results of the electrical resistance test of binary mixes are given in Fig. 7. The addition of silica fume has substantially increased the electrical resistance, especially at the ages of 90 and 180 days. The increase in electrical resistance of concrete was higher for higher dosages of silica fume. The addition of slag did not improve the electrical resistance of concrete at 7 and 28 days. However improvements over control were observed at 90 and 180. The effect of silica fume in increasing the electrical resistance was substantially higher than that of slag at all ages.

In Fig. 8 the results of the electrical resistance test of ternary mixes are presented. Incorporation of silica fume has caused considerable increase in electrical resistance of mixes containing various amounts of slag, showing the clear advantage of ternary mixes over binary mixes containing slag. It is interesting to note that at 90 and 180 days the ternary mixes had better performance than the binary mixes containing equal amounts of silica fume.

It is apparent that the performance of ternary mixes containing high amounts of slag (30% and 50%) in the electrical resistance test is considerably different to that 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 slag 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 [31].

3.4. Rapid chloride penetration test (RCPT)

In Fig. 9 the passed charge through silica fume binary mixes and slag binary mixes are compared with the control mix. The results show substantial reduction in the passed charge at all ages due to incorporation of silica fume and the reduction increased for higher dosages of silica fume. The use of slag increased the passed charge through concrete at 28 days. However at the ages of 90 and 180 days caused considerable reduction of the RCPT result compared to the control mix. It is also observed that with increasing slag content the resistance to chloride penetration of binary mixes is improved.

The influence of simultaneous use of 15%, 30% and 50% slag with different amounts of silica fume on the passed electrical charge is presented in Fig. 10. Simultaneous use of silica fume with slag has

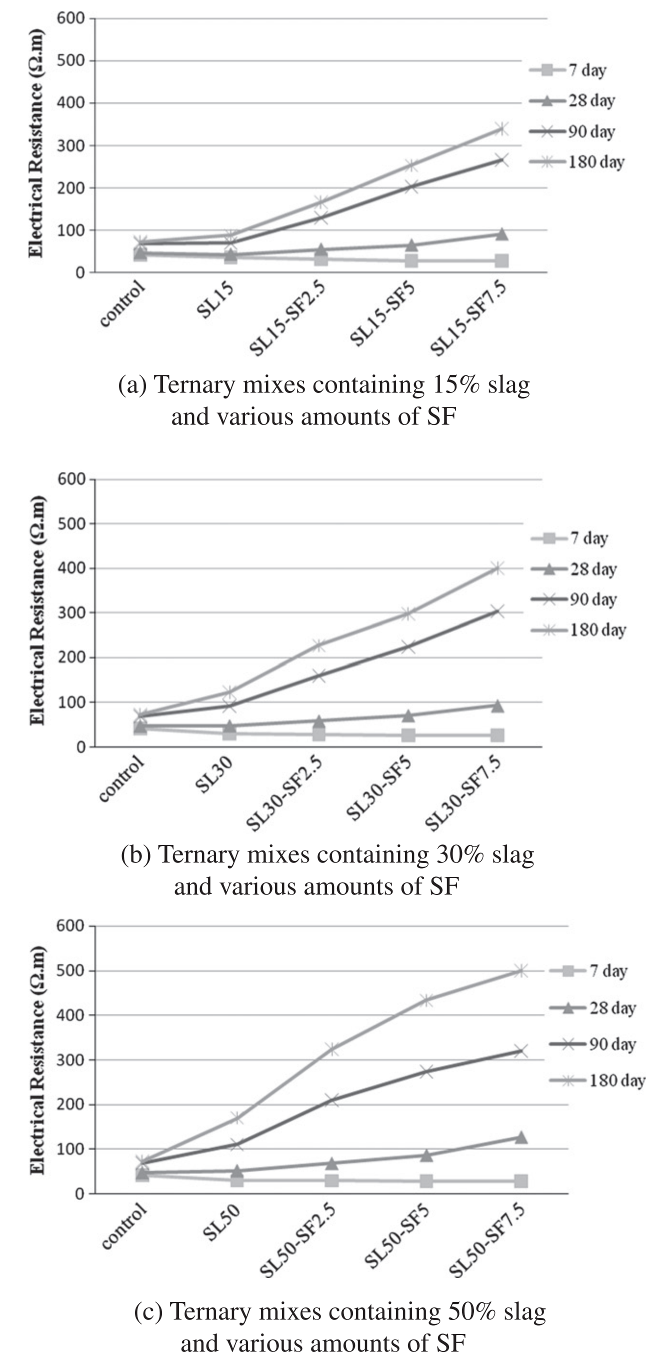

Fig. 8. The results of electrical resistance test of ternary mixes.

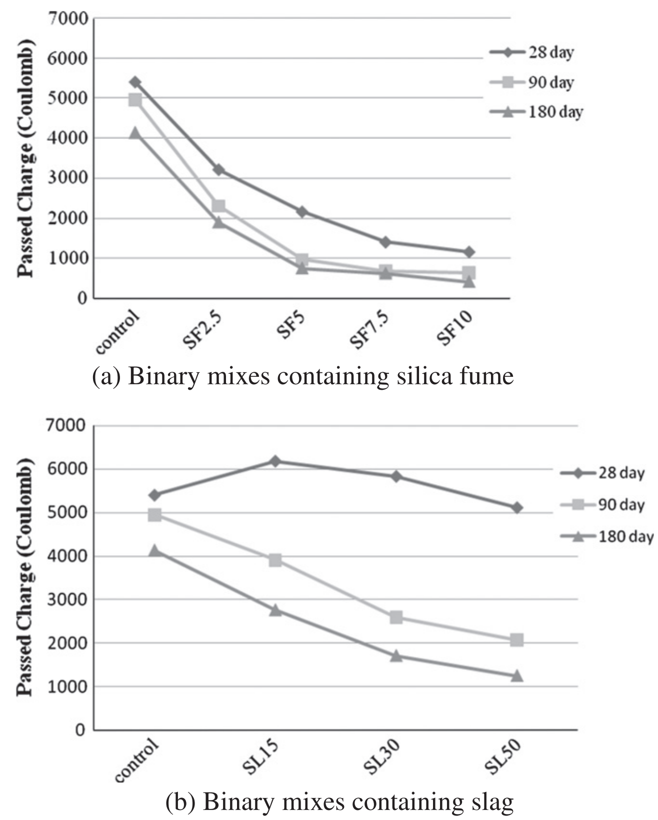

Fig. 9. Comparison of the passed charge through binary concrete mixes with the control mix.

resulted in considerable reduction of the electrical charge passed through concrete at all ages including 28 days. The trends observed in the RCPT test are in general similar to the results of the electrical resistance test discussed in the pervious section.

By the use of ternary mixes, it is therefore possible to overcome the relatively low 28 day durability performance of slag based binary mixes compared to the control and also substantial increase in chloride resistance in later ages can be achieved. Similar trends have been reported by other researches on chloride resistance of ternary mixes containing silica fume and normal reactivity slags [7,9]. 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, the discussion presented for the observed trends in the electrical resistance section is also applicable here.

3.5. Rapid chloride migration test (RCMT)

The results of the RCMT test at the ages of 28, 90 and 180 days are presented in Fig. 11. The results show substantial reductions in penetration rate of chlorides at all ages by the incorporation of silica fume. The use of slag increased penetration of chloride ions into concrete at 28 days. However at the ages of 90 and 180 days caused a reduction compared to the control mix. It is also observed that with increasing slag content from 15% to 30% the resistance to chloride penetration is improved at 90 and 180 days. However increasing slag concrete from 30% to 50% did not cause further improvement.

The influence of simultaneous use of 15%, 30% and 50% slag with different amounts of silica fume on chloride penetration at 28, 90 and 180 days is presented in Fig. 12. The use of silica fume has caused considerable reduction in chloride penetration of mixes containing various amounts of slag at all ages and the chloride penetration of ternary mixes are lower than control even at the age of 28 days.

In general the RCMT results confirm the trends observed for the results of the electrical resistance and the RCPT tests. The combined use of silica fume and slag can compensate for the weak performance of binary concretes containing slag at 28 days and also results in significant improvements in long term durability.

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 the pore solution chemistry, particularly $(OH)^-$ ion concentration. As the use of supplementary cementitious 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 [27]. Since the RCMT method directly

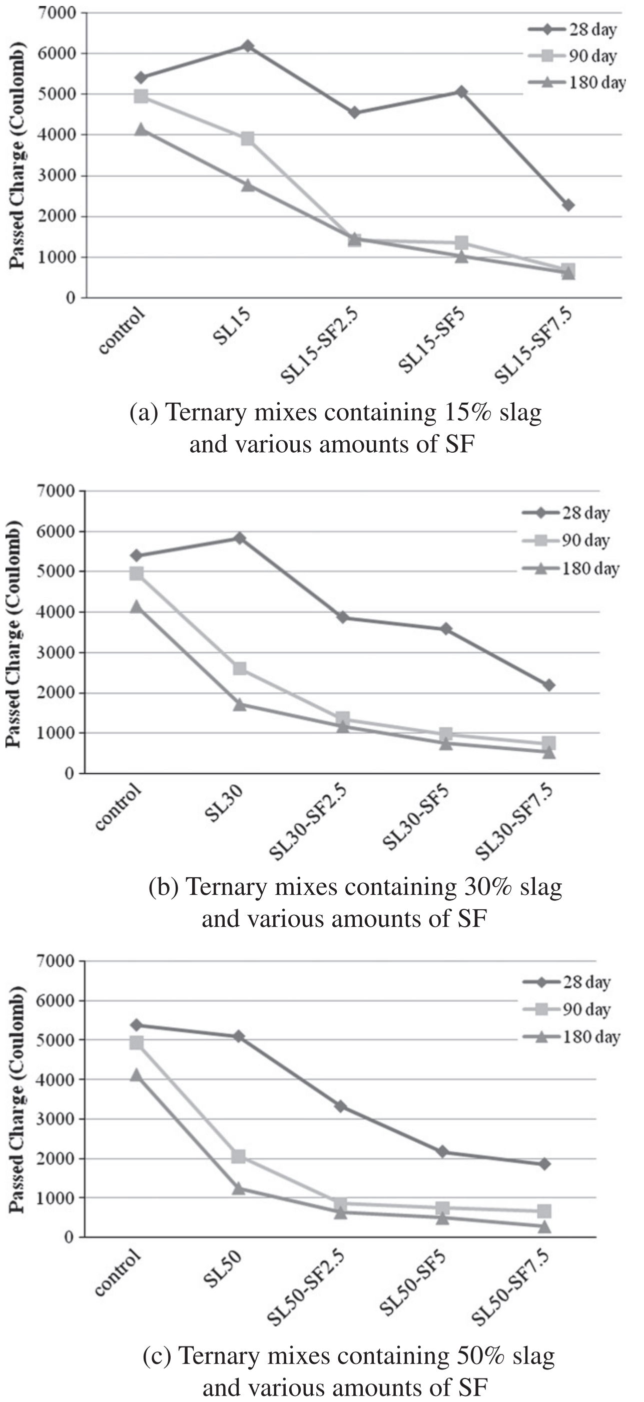

Fig. 10. The effect of simultaneous use of slag and silica fume on the passed charge through concrete.

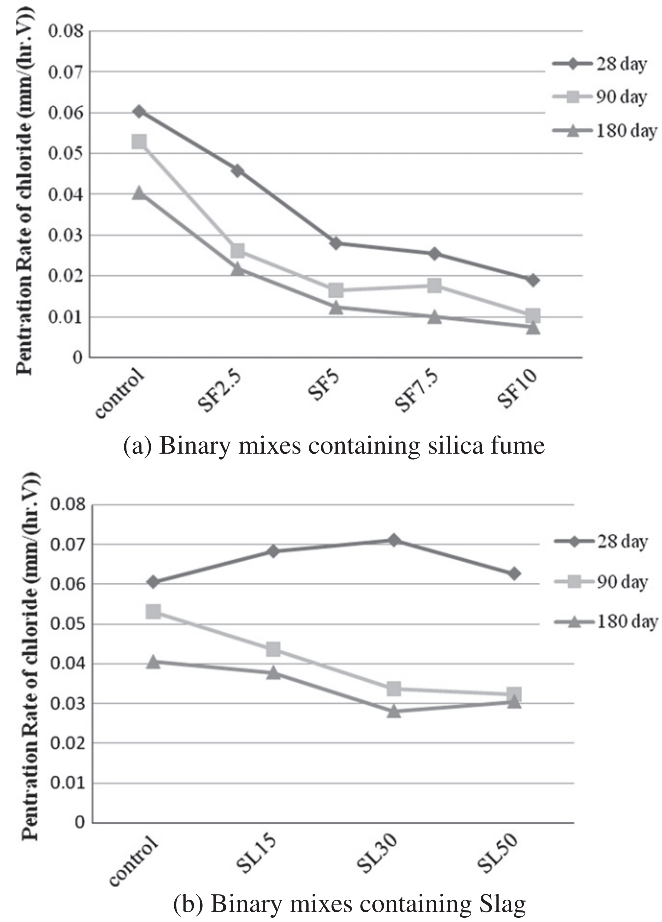

Fig. 11. Comparison of the chloride penetration rate of binary concrete mixes with the control mix.

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.

4. Conclusions

This research was carried out to investigate the possibility of enhancing the properties of concretes containing low reactivity slags through combined use with silica fume. The following conclusions could be drawn from the work.

Combined use of silica fume and slag results in reduced water demand compared to mixes containing silica fume. Using ternary mixes it is also possible to reduce water demand compared to the control concrete.

Use of grade 80 slag at 15% replacement level of cement caused a relatively small reduction in strength properties at all ages. However for increasing slag contents of 30% and 50%, strength reductions compared to control were substantial at all ages. Addition of silica fume compensated for the strength drop of the mix containing 15% slag at 28 days and increased its later age strengths compared to control. However silica fume addition could not compensate for the strength drop of binary mixes containing 30% and 50% slag. Therefore for situations where equal 28 strengths compared to control mix are required, the slag content in ternary mixes cannot be far in excess of 15%. This compares with values of about 25–35% reported in the literature for normal reactivity slags.

With regards to durability, binary mixes containing 15%, 30% and 50% slag showed somewhat lower performance than the control at 28 fays, however at 90 and 180 days they performed better than the control mix. Ternary mixes based on silica fume with various amounts of slag showed improvements in durability over control at 28 days and at later ages the enhancements were substantial. Unlike the trend observed for the strength, the durability of ternary mixes increased with higher slag contents. Therefore if achieving equal 28 day strength to the control mix is not critical, the use of ternary mixes with high contents of low reactivity slags

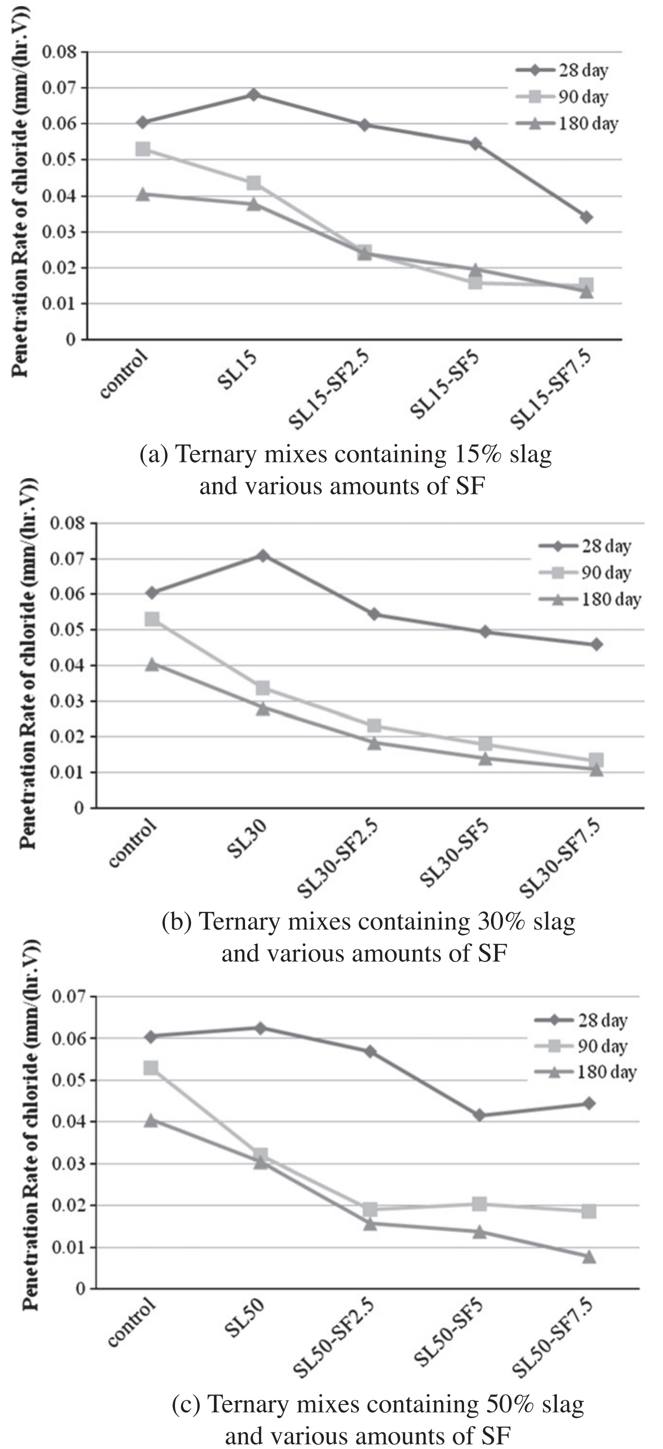

Fig. 12. The effect of simultaneous use of slag and silica fume on the penetration rate of chlorides into concrete.

will provide a high durability concrete with added environmental and energy conservation benefits.

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