Original Research

Advances in Structural Engineering

Durability evaluation of binary and ternary concrete mixtures by corrosion resistance approach

Advances in Structural Engineering
2023, Vol. 0(0) 1–13

DOI: 10.1177/13694332231161106
journals.sagepub.com/home/ase
SAGE

Mohammad Ali Ghanbari[1], Ali Amirabdollahian[2], Shahram Asayesh[3], Mohsen Nasri[2], Benyamin Mehri[3] and Ali Akbar Shirzadi Javid[3]

Abstract

The use of pozzolans as cement substitutes has become widespread in concrete technology in recent years. This is due to the improvement of concrete properties as well as from the perspective of sustainable development and reduction of cement consumption. In this study, the effect of 45% ground granulated blast furnace slag, 7% silica fume, 35% fly ash, and 15% zeolite as binary and ternary mixtures on durability and corrosion resistance of Self-compacting concrete specimens were investigated. The studied parameters included compressive strength, electrical resistivity, water absorption, rapid chloride ion penetration Test and corrosion test also scanning electron microscopy images were used to analyze the microstructure of the concrete samples. Results showed that replacement cement with slag, silica fume, fly ash, and zeolite is generally increased the durability parameters and corrosion resistance of concrete. In all experiments, silica fume has shown better behavior in terms of durability, so that its electrical resistance after 90 days is more than 3.3 times that of the control specimen and other parameters such as water absorption and chloride ion penetration showed approximately 37% And 74% less than conventional concrete respectively. Also, corrosion results indicated that samples containing silica fume had the highest corrosion resistance and reduced the corrosion rate by more than 6 times after 15 test cycles.

Keywords

durability, binary, ternary, concrete, corrosion resistance

Introduction

Chloride-induced corrosion of steel reinforcement in concrete structures is the main cause of deterioration. Chloride has several sources and can penetrate into concrete due to sea salt spray and direct sea water wetting. Also, chloride can penetrate into the concrete through the use of chloride deicing salts and storage of chloride materials in concrete tanks, etc. (Ketabdari et al., 2008; Valipour et al., 2014; Vedalakshmi et al., 2008).

In reinforced concrete structures, the steel reinforcement is protected from corrosion by a passive oxide layer on the rebar surface formed due to the high alkalinity of the concrete pores solution. Chloride ions penetrate through the concrete cover and eventually reach the steel surface. When the amount of chlorides exceeds the threshold value, the passive oxide layer around the steel reinforcement in concrete is destroyed and corrosion is initiated (Fakhri et al., 2020, 2021; Valipour et al., 2014). Corrosion products formed on the steel surface have a volume about two to six times larger than the primary steel. This extra volume creates tensile stresses in the concrete around the rebar higher than the tensile strength of the concrete and eventually leads to cracking and spalling of the concrete. Such damage reduces the service life of reinforced concrete structures, increases the cost of maintenance, repair and replacement and endangers public safety (Ababneh and Sheban, 2011). Therefore, solutions must be found to increase the service life of reinforced concrete structures and reduce their direct and indirect costs.

[1]Islamic Azad University- Science and Research Branch, School of Chemical Engineering, Tehran, Iran
[2]Department of Corrosion Monitoring and Control, Borna Electronics Co., Tehran, Iran
[3]School of Civil Engineering, Iran University of Science and Technology, Tehran, Iran

Corresponding author:
Ali Akbar Shirzadi Javid, School of Civil Engineering, Iran University of Science and Technology, P.O. Box 16765-163, Narmak, Tehran, Iran.
Email: shirzad@iust.ac.ir

Previous researches have been often conducted on reinforcing steel. For example, galvanized steel, epoxy-coated bars and phosphate conversion-coated steel are some of the options that have been studied and used. Ketabdari et al. (2008) Showed that the corrosion rates of epoxy-coated rebar is lower than the zinc-rich and zinc-aluminum rich coated rebars for the two types of concrete mixes. Epoxy-coated rebars have been widely used in bridge decks in North America and performed relatively well in areas where deicing salts are used. However, its performance in marine and humid environment was not satisfactory. Kamde and Pillai (2021) recommended avoiding the usage of fusion-bonded-epoxy (FBE) coated steel rebars unless adequate coating thickness cannot be achieved and damage to coating cannot be avoided. Jalili et al. (2009) found that the minimum corrosion current and maximum corrosion potential values are obtained for rebar with Zn–Ni phosphate conversion coating, implying its excellent resistance to corrosion. Also, using various corrosion inhibitors in concrete to inhibiting chloride penetration have been studied for several years.

Numerous studies have been reported that threshold chloride level and time takes for chloride to reach threshold level can change as a function of type of raw materials and admixtures, mix design, execution and curing circumstances (Yu et al., 2010). These studies also have conducted experiments on the durability characteristics of concretes. Ghorbani et al. (2018) investigated the effect of marble and granite waste dust on mechanical properties and corrosion of concrete samples with up to 20% replacement. The results showed that after 92 days of exposure to 3.5% salt solution, only a small amount of corrosion was observed in localized areas in 0%–10% samples. Also, mixes with 20% cement replacement generally correspond to higher corrosion potentials (i.e. less active corrosion probability) than those with lower waste content. The research of Choudhary et al. (2021) showed that concretes containing a combination of 10% marble, 15% fly ash and silica fume are useful in the development of the high strength concrete. However, the lowest chlorine penetration is related to the ternary mixtures containing 35% fly ash. Based on study of Samimi et al. (2018) on concretes containing 10% and 15% zeolite and pumice, it has been determined that concretes containing 10%–15% pumice and 15% zeolite have high resistance to acid attacks. Qureshi et al. (2020) investigated the properties of hardened concrete with recycled aggregate containing four mixtures with replacement percentages of 10% silica fume, 30% slag, 20% fly ash and 15% rice husk ash using 0%–1% metal fibre. The results indicated that the mechanical properties and durability of concrete containing recycled aggregate are improved by adding cement additives and metal fibre. The research of Vejmelková et al. (2015) on durability properties of concrete containing zeolite showed that replacement of 20% cement with zeolite increase resistance against freezing and aggressive chemical materials. Ramakrishnan et al. (2017) showed that in terms of durability, the addition of glass powder and slag reduces the absorption of volumetric water and capillary water absorption.

The objective of this study is to assess the mechanical, durability and corrosion characteristics of binary and ternary self-compacting concretes containing the optimal amount of supplementary materials. According to the previous researches, the recommended optimal values provided for slag, silica fume, fly ash and zeolite are 40%–50%, 7%, 30%–40% and 15%, respectively (Ahmadi and Shekarchi, 2010; Kurtay et al., 2020; Manera et al., 2008; Najimi et al., 2012; Ramakrishnan et al., 2017; Song and Saraswathy, 2006; Vejmelková et al., 2015). So the portland cement was replaced with these proportions in binary and ternary mixtures. Also in order to investigate the corrosion potential of rebar, the corrosion test was done according to ASTM (2013b).

As a novelty, despite previous researches which only focus on the some mechanical and durability properties of binary and ternary mixtures, this study evaluates these mixtures comprehensively through mechanical, durability and especially corrosion experiments.

Experimental methods

Materials and specimens

In this study, Ordinary Portland cement Type 2 with the density of 3150 kg/m^3 has been used. The slag used in this project was from Isfahan Steel Plant with the density of 2900 kg/m^3. Also, silica fume, fly ash and zeolite with the density of 2250, 2390 and 2140 kg/m^3, respectively were used. The chemical composition of cement, slag, silica fume, fly ash and zeolite are presented in Table 1. Table 2 and Figure 1 show the physical properties and particle size distributions of aggregates, respectively. All samples were taken from the mold after 24 h and placed in a controlled water pool with a temperature of 22 ± 0.5°C. Mixture proportions used in this study are presented in Table 3.

Compressive strength test

In order to examine the compressive strength of concrete, the method presented in EN (2009) has been used. This test was performed by applying an axial compressive load to cubic samples. To perform this test, the sample was placed vertically under the compression-testing machine, and loading was applied at a constant rate of 2 kg/cm^2. The compressive strength value of the sample was calculated by dividing the failure load applied to the cross-section area of the sample.

Table 1. The chemical composition of cement, slag, silica fume, fly ash and zeolite.

	Composition (%)				
Constituents	Cement (type 2)	Slag	Silica fume	Fly ash	Zeolite
SiO_2	20.74	37.22	91.64	58.58	69.78
CaO	62.95	36	0.66	11.12	3.61
Al_2O_3	4.9	9.02	0.5	14.3	12.45
Fe_2O_3	3.5	0,69	0.81	3.72	0.66
K_2O		0.84	0.79	1.89	0.63
Na_2O		1.47	2.52	5.91	1.93
MgO	1.22	7.57	0.71	1.66	1.15
TiO_2		2.73	0	0.62	
SO_3	3.1	3.23	0.36	0.46	2.23
MnO	-	1.20	0.07	0.09	
LOI	2.3	0	1.56	1.89	

Table 2. The physical properties of aggregates.

	Aggregates		
Physical property	Coarse gravel	Fine gravel	Fine(Sand)
Maximum grain size (mm)	19	12.5	4.75
Fineness modulus			3.4
Specific gravity	2.59	2.54	2.55
Water absorption (%)	1.5	2.4	2.6

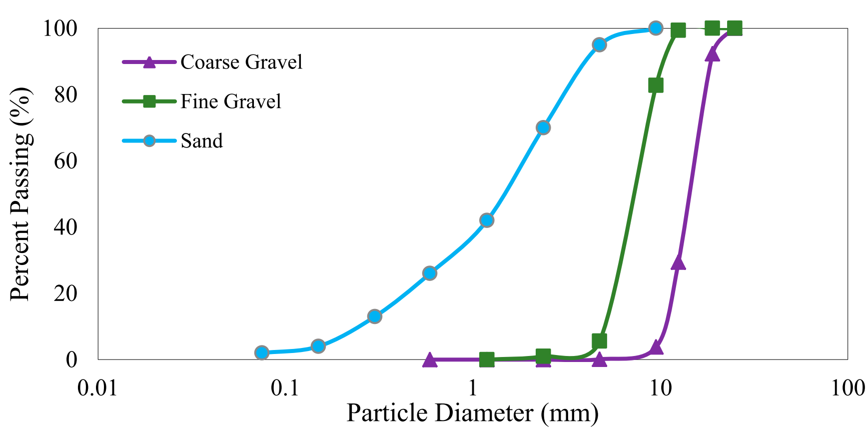

Figure 1. The particle size distribution of aggregates.

Electrical resistivity test

Electrical resistance test was performed according to AASHTO (2019). In this test, electrical resistance can be obtained by placing four electrodes on a concrete surface and making electrical contact. Two internal electrodes of the device introduce alternating electrical potential difference to the contact surface. This experiment was performed on cylindrical specimens with a diameter of 10 and a height of 20 cm at the ages of 7, 28 and 90 days.

Water absorption test

This test was performed according to the ASTM (2013a). Water absorption of concretes as a percentage by weight was obtained by averaging the results of three cubic specimens. According to this standard, at the desired age, the concrete samples were placed outside the pond and inside in oven at the temperature of 105°C. After 24 h of storage of the specimens in oven and its complete drying, the weighing dry samples were recorded. Then the specimens were placed in the open air to reach room temperature. After the concrete temperature reaches ambient temperature, the samples were placed in a water container and after 24 h, the samples were taken out and theirs surface were dried and weighted with a

Table 3. Mixture proportions.

Mix	W/c	Cement (Kg/m^3)	Slag (Kg/m^3)	Fly ash (Kg/m^3)	Silica fume (Kg/m^3)	Zeolite (Kg/ m^3)	Water (Kg/ m^3)	Coarse gravel (Kg/ m^3)	Fine gravel (Kg/m^3)	Sand (Kg/m^3)	Super plasticizer (Kg/m^3)
Control	0.5	355	0	0	0	0	177.5	480.5	260.6	1040.4	1.71
Sl45	0.5	195	160	0	0	0	177.5	445.0	240.0	1075.0	1.8
SF7	0.5	330	0	0	25	0	177.5	450.0	240.0	1075.0	1.83
FA35	0.5	230	0	125	0	0	177.5	440.0	235.0	1060.0	1.40
Ze15	0.5	301	0	0	0	54	177.5	440.0	240.0	1065.0	3.0
Ze15SF7	0.5	276	0	0	25	54	177.5	450.0	240.0	1075.0	2.24
Sl45SF7	0.5	170	160	0	25	0	177.5	440.0	240.0	1065.0	2.24
FA35SF7	0.5	205	0	125	25	0	177.5	450.0	240.0	1075.0	2.24

cloth. Thus, the weight of the specimens is obtained in the saturated state with the dry surface. Then, using equation (1), water absorption of the samples is calculated.

$$W_a = [(B - A)/A] \times 100 \quad (1)$$

Where, A is oven-dried weight of specimen and B is the saturated surface dried weight of specimen after 72 h of immersing in water.

Rapid chloride penetration test (RCPT)

According to ASTM (2012); this test was performed on discs cut from a cylindrical specimens with a diameter of 10 cm and a height of 20 cm. After cutting, the samples were placed in a vacuum device (desiccator) and exposed to a pressure of less than 5 mmHg for 3 h. The vacuum was then filled with water and the specimens were saturated for 1 hour. The vacuum valve was then opened and the samples remained immersed in water for 18 h. Finally, the specimens were placed in the cells filled with a 3% chloride sodium solution and 0.3 M sodium hydroxide and a voltage of 60 V was applied on it for 6 h. At the end of 6 h, the flow rate was read at 30 min intervals and the flow rate of chloride ion is calculated using equation (2).

$$Q = 900(I_0 + 2I_{30} + 2I_{60} + \ldots + 2I_{300} + 2I_{330} + 2I_{360}) \quad (2)$$

In this equation Q is the amount of flux passing through the device (Coulombs) and I is the amount of current (mA) at different time intervals of 30 min. The rapid chloride penetration test setup is shown in Figure 2.

Corrosion tests (macro-cell and half-cell)

According to ASTM G109, macro-cell corrosion condition was created by forming chloride concentration gradient in concrete. Specimens size was 280 mm × 150 mm×115 Maximum grain size (mm). Samples were made with two rebars 25 mm from the bottom, and one rebar 25 mm from the top, and a 100 Ω resistor was placed between the upper rebar and the lower rebars. Then a plastic pool with 150 mm × 75 mm × 75 mm dimensions and 13 mm distance from each side was placed on each specimen. In order to seal the pool, silicone caulk and epoxy sealer were used. Other parts of the samples outside the pool were covered with epoxy sealer. The steel rebars and molds to constructing corrosion test specimens and the constructed corrosion test specimens are shown in Figures 3 and 4, respectively.

In order to repeatability the results, three samples were made from each mixture. The pool of specimens was filled with 3% sodium chloride solution for 2 weeks. After 2 weeks, the samples were emptied and allowed to dry for 2 weeks. This cycle was repeated.

At 28 day periods, the voltage across the resistor was measured using Fluke 289 voltmeter. The current, was calculated using equation (3).

$$I = V/100 \quad (3)$$

In this equation I is the current (mA), and V is the measured voltage (mV) across the 100 Ω resistor.

At the same time, the corrosion potential of the upper rebar was measured against a saturated calomel reference electrode that is placed in the pool containing the sodium chloride solution. The macro-cell corrosion potential, corrosion current and half-cell potential measurements were used to determine the rate of corrosion and time of corrosion initiation. The schematically corrosion potential measurement and half-cell potential measurement according to ASTM G109 standard is shown in Figure 5.

Scanning electron microscopy test (SEM)

Evaluation of concrete microstructure was performed using a Quanta 200 scanning electron microscope.

Figure 2. The rapid chloride penetration test setup.

Results and discussion

Fresh properties

All the concrete mixtures were designed to have a slump flow diameter of 600 ± 25 mm which was obtained by use of varying amounts of super plasticizer. The super plasticizer dosages of the mixtures containing natural zeolite were 3.0 kg and 2.24 kg in 1 m^3 volume of concrete, which are higher than that of the control mixture, 1.71 kg. The higher the replacement of cement by natural zeolite, the more the super plasticizer is required to achieve the target slump flow. This is due to the large number of pores in the frame structure and high surface area of natural zeolite which increases the absorbed water on the particle. For a given slump flow the water demand increases with greater surface area of binder.

Figure 3. The steel rebars and molds to constructing corrosion test specimens.

Figure 4. The constructed corrosion test specimens.

Compressive strength

The effect of replacement of cement with slag, silica fume, fly ash and zeolite pozzolans in binary and ternary mixtures on compressive strength after 3, 7, 28 and 90 days are shown in Figure 6. The results of compressive strength showed that cement substituted by pozzolanic materials at an early age did not have a significant effect on compressive strength, but with increasing age of concrete increase significantly and showed more resistance than the

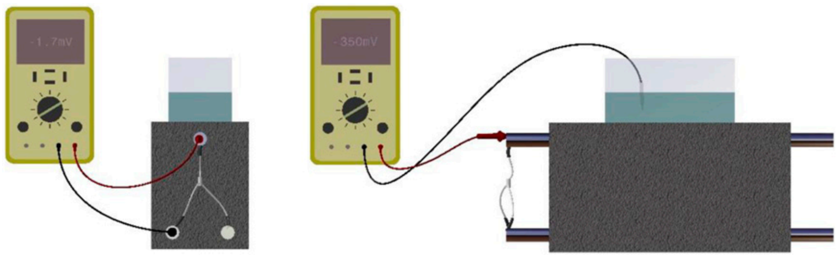

Figure 5. The schematically corrosion potential measurement and half-cell potential measurement.

control mixture. For example, a ternary mixture containing 7% silica fume and 45% slag had a strength of 18 MPa at the age of 3 days, but at the ages of 7, 28 and 90 days reached to 30.2, 36 and 50.1 MPa, respectively. Among all the mixtures, the ternary mixtures had better strength than the other mixtures. The ternary mixture containing slag and silica fume increased the strength by approximately 42% compared to the control mixture. Ternary mixture containing zeolite and silica fume as well as ternary mixture containing fly ash and silica fume increased the strength by 32% and 25% respectively. Also binary mixtures showed less strength than ternary mixtures but had better strength than control one. Binary mixtures containing 7% silica fume, 35% fly ash and 15% zeolite improved the strength by 30%, 11% and 8%, respectively. The mixture containing 45% slag had no effect on the final strength of control mixture. The reason that binary and ternary mixtures are less resistant in early age is that the pozzolans are usually activated by the calcium hydroxide released by hydration and form products such as calcium silicate gel. Since the curing process in the concretes containing supplementary materials is gradual and the amount of calcium hydroxide is low at the beginning of curing. Therefore, supplementary materials do not react much in the early ages, but as soon as calcium hydroxide increases, pozzolanic activity begins.

Electrical resistivity

The results of the electrical resistivity test after 7, 28 and 90 days are shown in Figure 7. According to this Figure, by adding supplementary materials to cement, there is a significant increase in electrical resistivity, so that this change is evident at later ages. Among all mixtures, the largest increase was related to the binary mixture containing 7% silica fume, which increased the resistance approximately 39 Ω.m compared to the control mixture. Between other binary mixtures after silica fume, fly ash, slag and zeolite increased the electrical resistance values 29.4, 20.9 and 19.2 Ω.m, respectively. Ternary mixtures also significantly improved electrical resistance. The mixture containing slag and silica fume showed a greater amount of resistance improvement.

At early ages, due to the lack of pozzolanic reaction, cement substitutes appear only in the role of filler and the resistance is low. As soon as the pozzolanic reactions begin and new products are formed, the resistance increases. As shown in Figure 7, the binary mixture containing silica fume at early ages does not have significant resistance compared to the control mixture, but after 28 days has grown significantly and its resistance is higher than other mixtures. The results of current work are in agreement with the research work done by Sabet et al. (2013) They reported that replacing cement by silica fume and zeolite can change electrical resistivity of mixtures about 4 times in compare with control mixture. Also this research showed that effect of silica fume is more considerable than mixtures including zeolite or fly ash.

Water absorption

The effect of replacement of slag, silica fume, fly ash and zeolite pozzolans with cement in binary and ternary mixtures on water absorption are shown in Figure 8. As the results show, supplementary materials to cement can reduce water absorption. The largest decrease was related to specimen containing silica fume with 37% decreasing compared to the control sample. After silica fume, the highest reductions for samples containing zeolite, fly ash and slag were 27%, 25% and 17%, respectively. Ternary mixtures also significantly affected the control mixture; but did not differ significantly compared to binary mixtures. The main reason for reducing the water absorption of binary and ternary mixtures is to reduce the porosity and increase the filling capacity by cement substitutes. These results are consistent with the results of similar research (Huang et al., 2021; Khoshroo et al., 2018).

Rapid chloride penetration

The results of the rapid chloride penetration test are shown in Figure 9. According to these results, it can be seen that cement replacement has a significant effect on reducing the penetration of chloride in concrete. As shown in Figure 9, the amount of charge passing through the control mixture is approximately 2609 C. While this

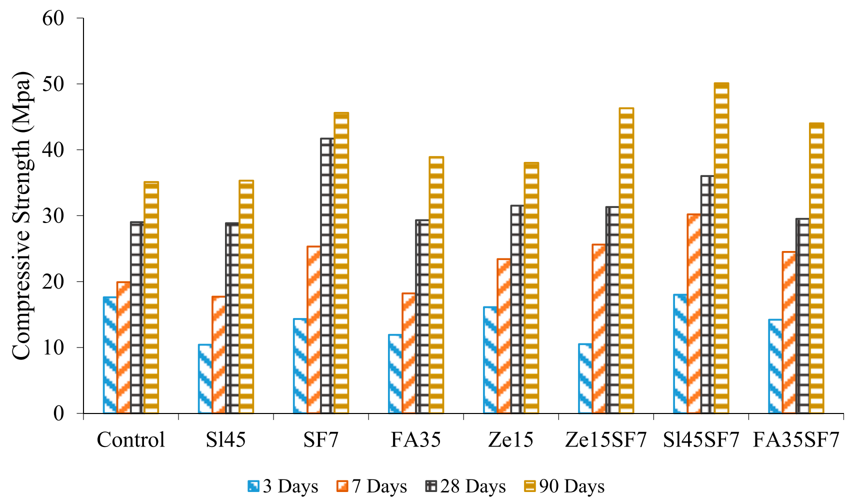

Figure 6. The effect of replacement of pozzolans with cement in binary and ternary mixtures on compressive strength after 3, 7, 28 and 90 days.

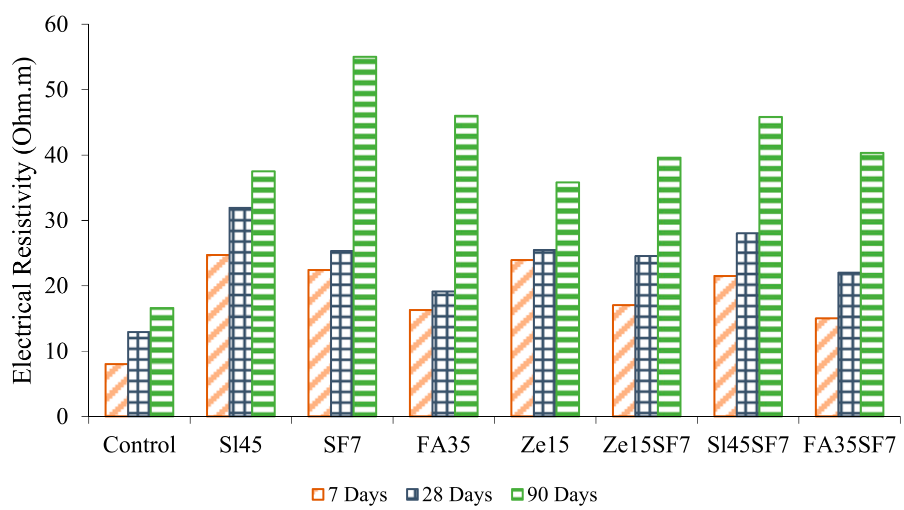

Figure 7. The results of electrical resistivity test after 7, 28 and 90 days.

value is less than 1000 C for concretes containing supplementary materials, which indicates the role of pozzolan in this change. Among the binary mixtures, the mixture containing 7% silica fume such as water absorption had the highest decrease, followed by the binary mixtures containing zeolite, fly ash and slag. Ternary mixtures have similar results. Among the binary mixtures, the mixture containing 7% silica fume such as water absorption had the highest decrease, followed by the binary mixtures containing zeolite, fly ash and slag. Ternary mixtures showed similar results. Among ternary mixtures, mixture containing zeolite and silica fume showed better strength against permeability with 890 passing charges.

Also, by comparing the results of the rapid chloride ion penetration (RCPT) test and water absorption, it can be seen that they are related to each other. As can be seen in Figure 10, these two parameters are directly related to each other and have a significant correlation. These results agree with previous research. Motahari Karein et al. (2017) concluded that silica fume can reduce the ion penetration significantly. In their research both slurry silica fume and agglomerated silica fume reduce passing charge about 3100 coulombs at 90 days. Another study conducted by Ahmadi et al. (2014) revealed that silica fume had more effect on the transport properties than natural zeolite and fly ash and ternary mixture containing zeolite and silica fume performed better than other ternary mixtures.

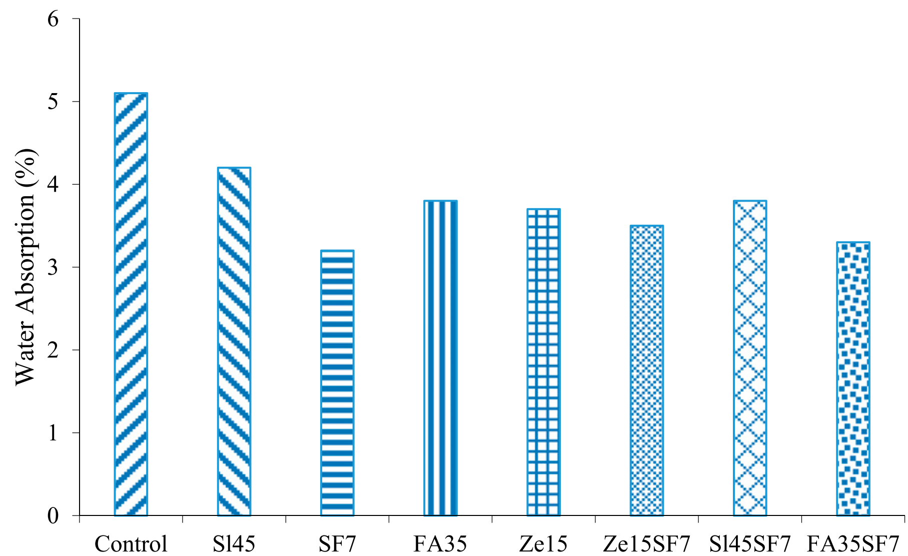

Figure 8. The effect of replacement of pozzolans with cement in binary and ternary mixtures on water absorption.

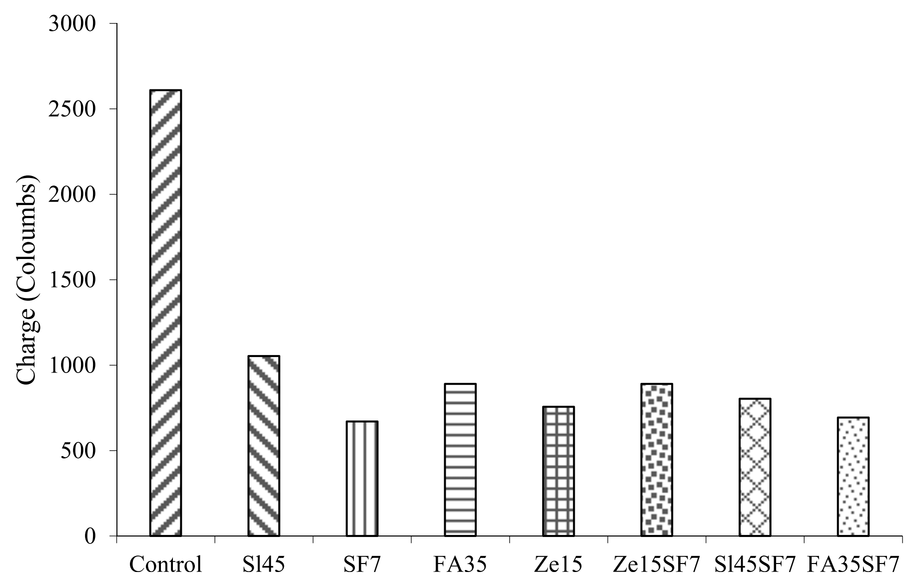

Figure 9. The results of rapid chloride penetration test.

Corrosion

The effect of replacement of slag, silica fume, fly ash and zeolite pozzolans with cement in binary and ternary mixtures on macro-cell corrosion current and half-cell potential are shown in Figures 11 and 12 respectively.

As can be seen, by replacing pozzolans such as slag, silica fume, fly ash and zeolite, instead of cement in the specimens, the amount of corrosion current and half-cell potential is reduced. This indicates an increase in the impermeability of concrete specimens containing pozzolans. Due to its extreme fineness and high pozzolanic reactivity, these minerals allow a remarkable reduction in the rate of chlorides penetration.

Also, the use of pozzolanic materials reduces the porosity of the concrete, which is directly related to electrical resistivity and it is known that low porosity influences the ingress of chlorides (Fajardo et al., 2009). In other words, increasing the electrical resistivity of concrete reduces the penetration of chloride and subsequent corrosion.

According to ASTM G109 standard, a macro-cell current of 10 μA indicates the corrosion threshold that is

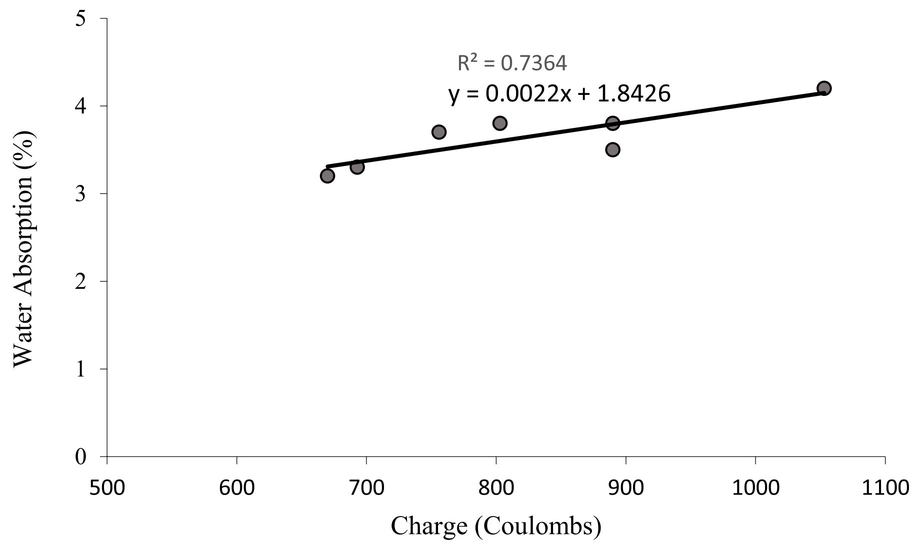

Figure 10. Relation between passing charge and water absorption.

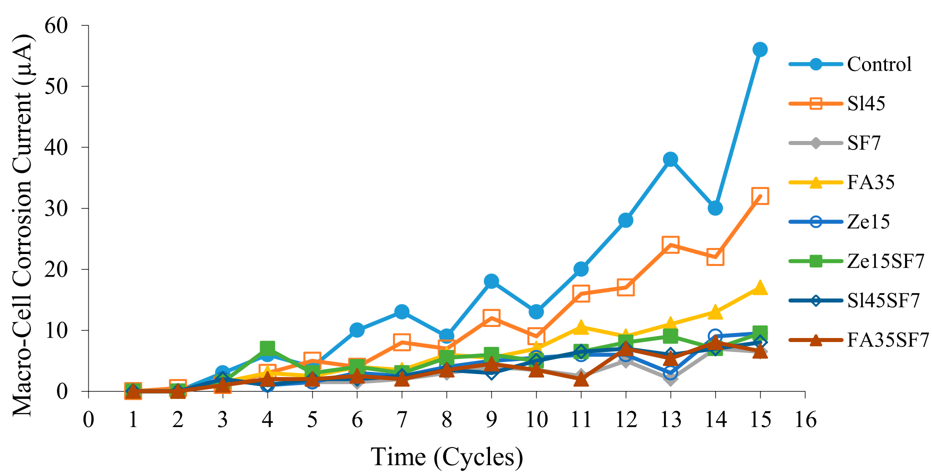

Figure 11. The effect of replacement of pozzolans with cement in binary and ternary mixtures on macro-cell corrosion current.

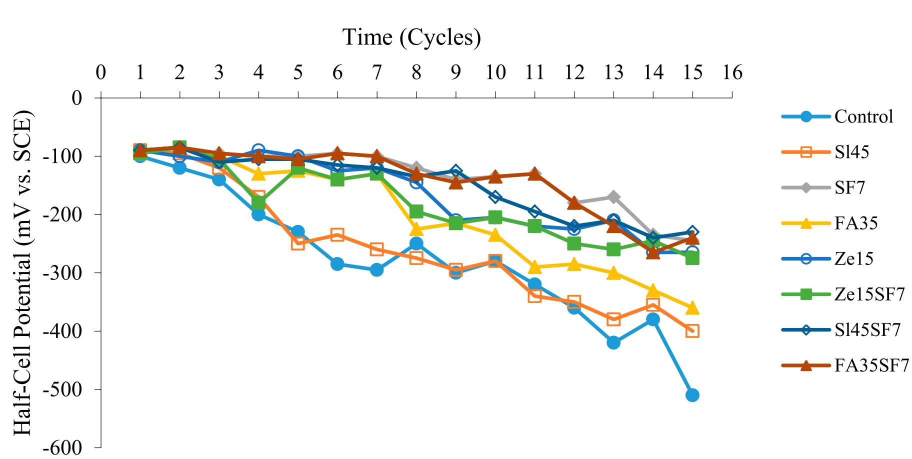

Figure 12. The effect of replacement of pozzolans with cement in binary and ternary mixtures on half-cell potential.

sufficient to ensure the presence of sufficient corrosion for visual evaluation. Based on this, the control specimen after nine cycles, binary mixture containing slag after 11 cycles and binary mixture containing fly ash after 13 cycles of testing exceeded the corrosion threshold definitely. After 15 cycles of testing, the binary mixtures containing silica fume and zeolite and ternary mixtures did not exceed it.

According to ASTM (2009) standard, if the rebar potential in concrete is more positive than −200 mV versus CSE (−130 mV vs. SCE), there is a greater 90% probability that the rebar will not corroded at the time of measurement. If it is between −200 and −350 mV versus CSE (−130 to −280 mV vs. SCE), the corrosion of the rebar cannot be certain, and if it is more negative than −350 mV versus CSE (−280 mV vs. SCE), there is a greater 90% probability that the rebar is corroded at the time of measurement. Similarly, the half-cell potentials of control specimen after nine cycles, binary mixture containing slag after 11 cycles and binary mixture containing fly ash after 13 cycles of testing are more negative than −280 mV versus SCE definitely. After 15 cycles of testing, the half-cell potentials of the binary mixtures containing silica fume and zeolite and ternary mixtures remain more positive than −280 mV. These results are compatible with the results of macro-cell measurements.

Microstructure

The microstructural images of binary and ternary mixtures are shown in Figure 13. Evaluation of microstructure showed that in the binary mixture containing silica fume, the porosity reduced and the structure became denser compared to the control specimen. Also, the number of porosity in the binary mixtures containing slag and the ternary mixtures containing slag and silica fume decreased, but not as well as the only silica fume. When supplementary cementitious materials are used in concrete, they do not only reduce the porosity but also the pores become finer and the change in mineralogy of the cement hydrates leads to the reduction in mobility of chloride ions (Song and Saraswathy, 2006). The microstructure results are consistent with the results of electrical resistance, water absorption, RCPT and corrosion tests.

On the other side, the presence of finely ground pozzolanic materials leads to the densification of the microstructure and hence as a result the compressive strength increases (Dave et al., 2017). Also, this result is consistent with the results of the compressive strength test.

Correlation between corrosion test and durability results

The results of the corrosion test illustrated that the lowest corrosion value is related to the binary mixture containing 7% silica fume. This result is confirmed by the lowest charge passing in the RCPT test. The highest electrical resistivity after 90 days this sample in the electrical resistivity test, the lowest amount of water absorption in the water absorption test and lowest porosity in the microstructure image shows the effect of replacing silica fume with cement in concrete. As Manera et al. (2008) showed that by replacing of 7% silica fume instead of cement, this mineral significantly reduces the permeability of concrete against the chloride penetration.

According to Figures 11 and 12, after silica fume, zeolite has the best performance in corrosion resistance of concrete. This result is in line with RCPT and water absorption Tests. Zeolite is a crystalline, hydrated alumino-silicate of alkali and alkaline earth cations having infinite, open, three-dimensional structures. Natural zeolite has a cryptocrystalline structure, and like other pozzolans, it undergoes pozzolanic activity due to its high quantity of reactive SiO_2 and Al_2O_3, which combines with $Ca(OH)_2$ to form additional C–S–H gel. Valipour et al. (2014) indicated that the presence of zeolite could retard the hydration process, thereby reducing the permeability, sorptivity and diffusivity of concrete because it reduces porosity and improves the transition zone structure between the blended cement paste and the aggregate. Pozzolanic activity of natural zeolite is lower than silica fume but that there is a high rate of lime consumption.

Comparison of corrosion and RCPT tests results show shows that the fly ash and slag pozzolans do not have better corrosion resistance performance than silica fume and zeolite, but by replacing them with cement in concrete; they increase the impermeability and corrosion resistance of concrete. Adding fly ash into concrete can increase the resistivity of concrete and slow down the corrosion process of steel rebar in concrete. Wang and Lu (2018) showed that the pozzolanic reaction between fly ash and calcium hydroxide could reduce the porosity and permeability of concrete thereby enhancing the durability of concrete. In other words, the addition of fly ash can change the pore solution chemistry by binding alkali, pozzolanic reaction and removing free calcium; adding fly ash will lead to the dielectric used to conduct electricity decreases, which eventually increases resistivity of concrete.

Song and Saraswathy (2006) found that the slag can be effectively used to reduce the pore sizes and cumulative pore volume considerably, leading to more durable and impermeable concrete. The pore structure of concrete with slag is drastically altered and can significantly reduce corrosion by increasing the resistivity of concrete. When

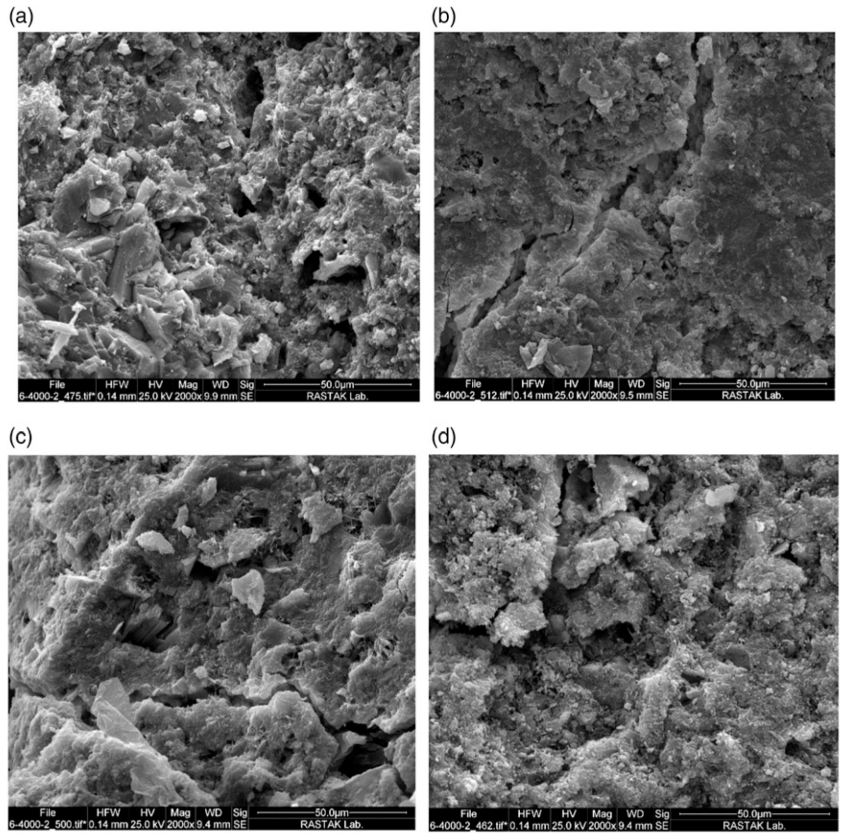

Figure 13. The SEM images of (a) control specimen, (b) binary mixture containing silica fume, (c) binary mixture containing slag, and (d) Ternary mixture containing silica fume and slag.

slag is used in concrete, not only reduced the porosity but also the pores become finer and the change in mineralogy of the cement hydrates leads to a reduction in the mobility of chloride ions. The beneficial effects of slag in concrete results from the modified microstructure of cementitious paste, which has more capillary pores filled with low-density C–S–H gel than Portland cement paste. It can be observed that slag can be effectively used to reduce the pore sizes and cumulative pore volume.

These results are consistent with Valipour et al. (2014) studies, which compared the effects of silica fume, zeolite and slag on corrosion resistant of concrete and indicated that natural zeolite operates better than slag, but not as well as silica fume. Also, investigations on chloride diffusivity and initial surface absorption have shown that zeolite is better than fly ash but not as good as silica fume.

Based on the results of corrosion and RCPT tests, it can be concluded that the binary mixtures using silica fume and zeolite are more effective than the binary mixtures using fly ash and slag. Also, ternary mixtures using silica fume have better results than binary mixtures using fly ash and slag, but they are not more effective than binary mixtures using silica fume and zeolite.

Conclusions

In this research, the effect of substituting cement with 45% slag, 7% silica fume, 35% fly ash, 15% zeolite in binary and ternary mixtures on durability and corrosion resistance of concrete was studied. The main conclusions that can be drawn from this study are as follows:

1. Replacement slag, silica fume, fly ash, zeolite with Portland cement is generally increased the durability parameters and corrosion resistance of concrete. In RCPT test, the amount of charge passing through the control mixture is approximately 2609 coulomb while this value for concretes containing supplementary materials is less than 1000 coulomb.
2. Replacement of silica fume with Portland cement has the greatest effect on increasing durability and corrosion resistance. After silica fume, zeolite has the best performance in durability and corrosion resistance of concrete. In corrosion tests, the binary mixtures containing silica fume after 15 cycles of testing did not exceed the corrosion threshold

definitely but the binary mixture containing slag after 11 cycles and binary mixture containing fly ash after 13 cycles of testing exceeded it.

3. Ternary mixtures using silica fume have better results than binary mixtures using fly ash and slag, but they are not more effective than binary mixtures using silica fume and zeolite.

Declaration of conflicting interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Funding

The author(s) received no financial support for the research, authorship, and/or publication of this article.

ORCID iD

Ali Akbar Shirzadi Javid https://orcid.org/0000-0002-6105-5991

References

AASHTO T358:2019 (2019) Standard method of test for surface resistivity indication of concrete's ability to resist chloride ion penetration.

Ababneh A and Sheban M (2011) Impact of mechanical loading on the corrosion of steel reinforcement in concrete structures. *Materials and structures* 44(6): 1123–1137.

Ahmadi B and Shekarchi M (2010) Use of natural zeolite as a supplementary cementitious material. *Cement and concrete composites* 32(2): 134–141.

Ahmadi B, Sobhani J, Shekarchi M, et al. (2014) Transport properties of ternary concrete mixtures containing natural zeolite with silica fume or fly ash. *Magazine of Concrete Research* 66(3): 150–158.

ASTM C1202:2012 (2012) Standard test method for electrical indication of concrete's ability to resist chloride ion penetration.

ASTM C642:2013 (2013a) Standard test method for density, absorption, and voids in hardened concrete.

ASTM C876:2009 (2009) Standard test method for corrosion potentials of uncoated reinforcing steel in concrete.

ASTM G109:2013 (2013b) Standard test method for determining effects of chemical admixtures on corrosion of embedded steel reinforcement in concrete exposed to chloride environments.

Choudhary R, Gupta R, Alomayri T, et al. (2021) Permeation, corrosion, and drying shrinkage assessment of self-compacting high strength concrete comprising waste marble slurry and fly ash, with silica fume. *Structures* 33: 971–985.

Dave N, Misra AK, Srivastava A, et al. (2017) Study on quaternary concrete micro-structure, strength, durability considering the influence of multi-factors. *Construction and Building Materials* 139: 447–457.

EN 12390–3:2009 (2009) Testing hardened concrete-part 3: compressive strength of test specimens.

Fajardo G, Valdez P and Pacheco J (2009) Corrosion of steel rebar embedded in natural pozzolan based mortars exposed to chlorides. *Construction and Building Materials* 23(2): 768–774.

Fakhri H, Fishman KL and Ranade R (2020) A novel experimental method to determine the critical chloride content in cement-based composites. *Construction and Building Materials* 263: 120101.

Fakhri H, Fishman KL and Ranade R (2021) Rapid determination of critical chloride content in cement-based composites. *Construction and Building Materials* 268: 121148.

Ghorbani S, Taji I, Tavakkolizadeh M, et al. (2018) Improving corrosion resistance of steel rebars in concrete with marble and granite waste dust as partial cement replacement. *Construction and Building Materials* 185: 110–119.

Huang Q, Zhu X, Liu D, et al. (2021) Modification of water absorption and pore structure of high-volume fly ash cement pastes by incorporating nanosilica. *Journal of Building Engineering* 33: 101638.

Jalili MM, Moradian S and Hosseinpour D (2009) The use of inorganic conversion coatings to enhance the corrosion resistance of reinforcement and the bond strength at the rebar/concrete. *Construction and Building Materials* 23(1): 233–238.

Kamde DK and Pillai RG (2021) Corrosion initiation mechanisms and service life estimation of concrete systems with fusion-bonded-epoxy (FBE) coated steel exposed to chlorides. *Construction and Building Materials* 277: 122314.

Ketabdari MJ, Arabpour Dahooei F and Maghsoudi AA (2008) Corrosion of coated rebar in selfconsolidating concrete with nanosilica in marine environment. In: 8th International Conference on Coasts, Ports and Marine Structures. Tehran, Iran, November 2008, pp. 24–26.

Khoshroo M, Shirzadi Javid AA and Katebi A (2018) Effects of micro nano bubble water and binary mineral admixtures on the mechanical and durability properties of concrete. *Construction and Building Materials* 164: 371–385.

Kurtay M, Gerengi H, Kocak Y, et al. (2020) The potency of zeolite and diatomite on the corrosive destruction of reinforcing steel in 1 M HNO3 environment. *Construction and Building Materials* 236: 117572.

Manera M, Vennesland Ø and Bertolini L (2008) Chloride threshold for rebar corrosion in concrete with addition of silica fume. *Corrosion Science* 50(2): 554–560.

Motahari Karein SM, Ramezanianpour AA, Ebadi T, et al. (2017) A new approach for application of silica fume in concrete: wet granulation. *Construction and Building Materials* 157: 573–581.

Najimi M, Sobhani J, Ahmadi B, et al. (2012) An experimental study on durability properties of concrete containing zeolite as a highly reactive natural pozzolan. *Construction and building materials* 35: 1023–1033.

Qureshi LA, Ali B and Ali A (2020) Combined effects of supplementary cementitious materials (silica fume, GGBS, fly ash and rice husk ash) and steel fiber on the hardened properties of recycled aggregate concrete. *Construction and Building Materials* 263: 120636.

Ramakrishnan K, Pugazhmani G, Sripragadeesh R, Muthu D and Venkatasubramanian C. (2017) Experimental study on the mechanical and durability properties of concrete with waste glass powder and ground granulated blast furnace slag as supplementary cementitious materials. *Construction and Building Materials* 156: 739–749.

Sabet FA, Libre NA and Shekarchi M (2013) Mechanical and durability properties of self- consolidating high performance concrete incorporating natural zeolite, silica fume and fly ash. *Construction and Building Materials* 44: 175–184.

Samimi K, Kamali-Bernard S and Maghsoudi AA (2018) Durability of self-compacting concretecontaining pumice and zeolite against acid attack, carbonation and marine environment. *Construction and building materials* 165: 247–263.

Song HW and Saraswathy V (2006) Studies on the corrosion resistance of reinforced steel in concrete with ground granulated blast-furnace slag—an overview. *Journal of Hazardous materials* 138(2): 226–233.

Valipour M, Shekarchi M and Ghods P (2014) Comparative studies of experimental and numerical techniques in measurement of corrosion rate and time-to-corrosion-initiation of rebar in concrete in marine environments. *Cement and Concrete Composites* 48: 98–107.

Vedalakshmi R, Rajagopal K and Palaniswamy N (2008) Longterm corrosion performance of rebar embedded in blended cement concrete under macro cell corrosion condition. *Construction and Building Materials* 22(3): 186–199.

Vejmelková E, Koňáková D, Kulovaná T, et al. (2015) Engineering properties of concrete containing natural zeolite as sup plementary cementitious material: strength, toughness, durability, and hygrothermal performance. *Cement and Concrete Composites* 55: 259–267.

Wang W and Lu C (2018) Time-varying law of rebar corrosion rate in fly ash concrete. *Journal of hazardous materials* 360: 520–528.

Yu H, Shi X, Hartt WH, et al. (2010) Laboratory investigation of reinforcement corrosion initiation and chloride threshold content for self-compacting concrete. *Cement and Concrete Research* 40(10): 1507–1516.