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Corrosion resistant self-compacting concrete using micro and nano silica admixtures

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Abstract. In this paper, enhancement of corrosion and chloride resistance of high performance self compacting concrete (SCC) through incorporating nanosilica into the binder has been investigated. For this purpose, different mixtures were designed with different amounts of silica fume and nano silica admixtures. Different binder contents were also investigated to observe the binder content effect on the concrete properties. Corrosion behavior was evaluated by chloride penetration and resitivity tests. Water absorption and capillary absorption were also measured as other durability-related properties. The results showed that water absorption, capillary absorption and Cl ion percentage decreased rather significantly in the mixtures containing admixtures especially blend of silica fume and nano silica. By addition of the admixtures, resistivity of the SCC mixtures increased which can lead to reduction of corrosion probability.

Keywords: concrete; nano silica; corrosion; durability; chloride penetration; resistivity

1. Introduction

High strength concrete, according to American Concrete Institute Committee ACI 363 R (1997), is the concrete which has specific compressive strength of 41 MPa or more at 28 days. The HPC offers significant economic and architectural advantages over NSC in similar situations, and is suited well for constructions that require high durability.

Self-compacting concrete (SCC) is also considered as a concrete which can be placed and compacted under its own weight with little or no vibration without segregation or bleeding. It is used to facilitate and ensure proper filling and good structural performance of restricted areas and heavily reinforced structural members. It has gained significant importance in recent years because of the advantages it offers (Bartos 1999, Okamura and Ouchi 2003, Collepardi *et al*. 2003, Bouzoubaa and Lachemi 2001). Many researchers have used SCC containing admixtures to satisfy the great demand for fines needed for this type of concrete, thereby improving its mechanical, rheological and durability properties in comparison with normal vibrated concrete (NVC). Siddique (2010) investigated the properties of SCC made with different amounts of fly ash. El-Dieb (2009) studied mechanical and durability properties of ultra high strength-fiber reinforced concrete with self compacting characteristics. Kulakowski *et al*. (2009) reviewed the silica fume influence on reinforcement corrosion in concrete. There are some works on incorporating

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nanoparticles into concrete specimens to achieve improved physical and mechanical properties using nano SiO_2 and silica fume (Ji 2005, Jo *et al*. 2007, Qing 2007, Lin *et al*. 2008, Bleszynski *et al*. 2002). Also some earlier works of the author on application of nano SiO2 and TiO2 in SCC show mechanical and durability enhancement and water permeation reduction due to more packed microstructure (Jalal *et al*. 2012, 2013). Concrete strength is influenced by lots of factors like concrete ingredients, age, ratio of water to cementitious materials, etc. The pore structure determines the transport properties of cement paste, such as permeability and ion migration. In the hydrated paste, the capillary and gel pores can be distinguished. The gel pores are very small. Although they constitute a network of open pores, the permeability of this network is very low. Conversely, the capillary pores are relatively large spaces existing between the cement grains. It is the capillary porosity that greatly affects the permeability of concrete (Perraton *et al*. 1994). Permeability of cement paste is a fundamental property in view of the durability of concrete: it represents the ease with which water or other fluids can move through concrete, thereby transporting aggressive agents. It is therefore of utmost importance to investigate the quantitative relationships between the pore structure and the permeability. Through experimental studies of the pore structure and the permeability of cement-based materials, a better understanding of transport phenomena and associated degradation mechanisms will hopefully be reached (Ye *et al*. 2006).

2. Materials and methods

2.1 Materials

An ASTM Type II Portland cement (PC) was used to produce the various SCC mixtures. In addition, silica fume and nano silica were used as admixtures which are hereafter called Silica Fume (SF) and Nano Silica (NS) respectively. Table 1 summarizes physical properties and chemical composition of the cement and silica fume and Table 2 shows the properties of Nano Silica used. The coarse aggregate used was limestone gravel with a nominal maximum size of 12.5 mm. As fine aggregate, a mixture of silica aggregate sand and crushed limestone (as filler) was used with a maximum size of 4.75 mm. All aggregates in this research were used in dry form and

Table 1 Chemical composition and physical properties of cement and silica fume

Chemical analysis (%)	Cement	Silica fume
Sio_2	20<	93.6
Al_2O_3	6<	1.3
Fe_2O_3	6<	0.9
CaO	<50	0.5
MgO	<5	1
SO_3	<3	0.4
K_2O	<1	1.52
Na_2O	<1	0.45
Loss of ignition	<3	3.1
Specific gravity	3.15	2.2
Blaine fineness (cm^2/g)	3260	21090

Table 2 Properties of nano silica

Diameter (nm)	Surface volume ratio (m^2/g)	Density (g/cm^3)	Purity (%)
15±3	165±17	<0.15	>99.9

Table 3 Mix proportions of the concrete specimens

No	Concrete ID	*w/b*	Cement	Silica fume	Nano silica	Filler	Fine aggregate	Coarse aggregate	Sp	VMA
			(kg/m^3)							
1	SCC400	0.38	400	-	-	177	1003	578	2.5	2
2	SCC450	0.38	450	-	-	177	1003	578	2.81	2.25
3	SCC500	0.38	500	-	-	177	1003	578	3.12	2.5
4	SCC400SF10%	0.38	360	40	-	177	1003	578	2.5	2
5	SCC450 SF 10%	0.38	405	45	-	177	1003	578	2.81	2.25
6	SCC500 SF 10%	0.38	450	50	-	177	1003	578	3.12	2.5
7	SCC400NS2%	0.38	392	-	8	177	1003	578	2.5	2
8	SCC450 NS 2%	0.38	441	-	9	177	1003	578	2.81	2.25
9	SCC500 NS 2%	0.38	490	-	10	177	1003	578	3.12	2.5
10	SCC400SF10NS2%	0.38	352	40	8	177	1003	578	2.5	2
11	SCC450SF10NS2%	0.38	396	45	9	177	1003	578	2.81	2.25
12	SCC500SF10NS2%	0.38	440	50	10	177	1003	578	3.12	2.5

the aggregates are a mixture of eight particle sizes of fine and coarse aggregates. A polycarboxylic-ether type superplasticizer (SP) with a specific gravity of between 1.06 and 1.08 was employed to achieve the desired workability in all concrete mixtures. Furthermore viscosity modifying agent (VMA) for better stability was used.

2.1 Mix proportions

A total number of 12 concrete mixtures were designed with a constant water/binder (*w/b*) ratio of 0.38 and total binder content of 400, 450 and 500 kg/m^3. Concrete samples were prepared with 10% and 2% (by weight) replacement of Portland cement by Silica Fume and Nano Silica respectively. The mixture proportions of concrete and binder paste are given in Table 3. The abbreviations used in the study for labeling the mixtures were adopted in such a way that they clearly show the main parameters and their amount. SCC stands for high performance self compacting concrete which is followed by the binder content. SF and NS denote Silica Fume and Nano Silica respectively which are followed by their percentages.

2.3 Durability tests

2.3.1 Absorption test

This test is based on BS 1881-Part 122 for testing water absorption in hardened concrete. The 100×100×100 mm specimens were dried in an oven at 45℃ for a week and after 14 days specimens reached to constant weight. The specimens were then immersed in water and scaled after 0.5, 1, 24, 72 and 168 hours to check the weight increase and to calculate the water absorption percentage. In this test, water absorption can only take place in pores which are emptied during drying and filled with water during the immersion period.

2.3.2 Capillary test

When a non-saturated concrete element is in contact with water at one side and absorbed water evaporation is possible from the other side, a permanent flowing regime through capillary absorption is established (Audenaert 2006). The test carried out in this study for determination of capillary water absorption is based on RILEM CPC 11.2, TC 14-CPC for testing capillary absorption in hardened concrete. The 100×100×100 mm specimens were dried in the oven at 40±5°C. They were put on rods in a water bath in such a way that they were immersed in water for no more than 5 mm. In this test, unidirectional flow depths of the specimens were measured and results of capillary depths were reported.

2.3.3 Cl ion percentage

After curing period of 90 days, 150×150×150 mm cubic specimens were immersed in 3% NaCl solution for 90 days. Then specimens were dried in the oven for 24 hours. After that, in order to prepare some pulverized concrete samples (powder samples) for the test, all 6 faces of the cubic specimens were drilled by depths of 0-5, 5-10, 10-15, 15-20 and 20-30 mm and the concrete powder samples obtained from all 6 faces for each depth were blended and in this way, the samples were prepared for the next step of the test (ASTM C1218).

In this test method, total chloride content of pulverized concrete sample is determined by the potentiometric titration of chloride with silver nitrate (ASTM C114). The pulverized concrete sample prepared is solved in nitric acid solution and then if the solution is acidic, a little of $NaHCO_3$ is added to this solution until pH value reaches 6 or 7. Then the K_2CrO_4 indicator is added so that the color of the solution changes to light yellow. Eventually, 0.05 N $AgNO_3$ is added until the color of the solution turns to orange-yellow (weak brown) and the volume of the $AgNO_3$ solution is measured. In order to determine the Cl ion percentage, the volume of the $AgNO_3$ solution is substituted in Eq. (1).

$$Cl^{-}(\%) = \frac{3.5453(V.N)}{W} \tag{1}$$

W: weigh of pulverized (powder) concrete prepared from the sample
N: normality of $AgNO_3$ solution
V: volume of $AgNO_3$ solution

2.3.4 Resistivity test

Resistivity test setup includes an electrical resistance measurement device and two electrodes which both can be attached to the concrete sample surfaces or one may be attached to a steel rebar embedded in the concrete sample and the other attached to the concrete sample surface (Mays 1992, Kay 1992, McCarter *et al*. 1981). For this test, 100×100×100 mm cubes were used and measurements were made at 7, 28 and 90 days. The resistivity values were calculated by using Eq. (2).

$$r = \frac{RA}{L} \tag{2}$$

Where R, A, L and r are resistance (Ω), area of sample (m^2), length of sample (m) and resistivity

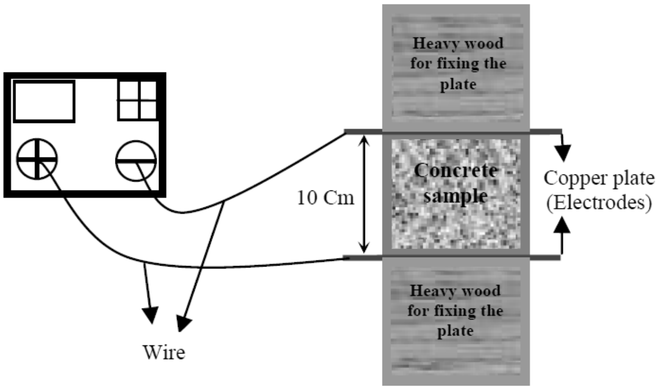

Fig. 1 Schematic of resistivity test setup

Table 4 Relation between electrical resistivity and probability of corrosion

electrical resistivity (Ω.m)	probability of corrosion
120<	Not Probable
50 to 120	Probable
<50	Inevitable

(Ω.*m*) respectively.

The test procedure can be summarized in this way: after curing the sample in the water for specific ages (7, 28 and 90 days), the surfaces of the sample were dried. Two copper plates were attached to the upper and lower surfaces of the concrete sample by cement paste and two wooden nonconductive blocks were placed under and on the concrete sample. Schematic of the test setup is illustrated in Fig. 1.

The electrical resistance values (R) read from the electrical device are substituted in Eq. (2) and then the resistivity values are calculated and then the resistivity values were calculated. By using Table 4, probability of corrosion can be determined.

3. Results and discussion

3.1 Water sorption

The water absorption results of the concrete samples at different time intervals are presented in Table 5. As can be seen, increase in binder content from 400 to 450 and 500 kg/m^3 resulted in water absorption decrease by 11.5% and 15.3% respectively at the first time step of water absorption (0.5 h) in the samples without any admixtures. Water absorption decrease in the samples containing 2% NS in the first time step appeared to be 35, 28 and 32% for binder content of 400, 450 and 500 respectively. Addition of 10% SF resulted in water absorption decreases in the same duration by 31, 26 and 34% for binder content of 400, 450 and 500 respectively, which is similar to the values obtained in the mixtures containing 2% NS. The reductions in water

Table 5 Results of water absorption by time

No	Concrete ID	Water absorption (%)					
		Time (hour)	Time (hour)	Time (hour)	Time (hour)	Time (hour)	Time (hour)
		0.5h	1h	24h	48h	72h	168h
1	SCC400	2.6	3.2	5.3	5.5	5.6	5.8
2	SCC450	2.3	3.15	4.5	4.7	4.8	4.9
3	SCC500	2.2	3.1	4.3	4.4	4.6	4.9
4	SCC400NS2%	1.7	2.2	2.7	2.8	2.85	3
5	SCC450NS2%	1.65	2.1	2.4	2.6	2.6	2.8
6	SCC500NS2%	1.5	1.95	2.4	2.5	2.6	2.7
7	SCC400SF10%	1.8	2.25	2.65	2.7	2.74	3
8	SCC450SF10%	1.7	2.2	2.6	2.64	2.7	2.9
9	SCC500SF10%	1.44	1.7	2.2	2.3	2.4	2.5
10	SCC400SF10NS2%	1.4	1.8	2	2.2	2.3	2.4
11	SCC450SF10NS2%	1.3	1.65	1.9	1.8	2	2.1
12	SCC500SF10NS2%	1.1	1.4	1.6	1.7	1.9	2

absorption in the mixtures containing 2% NS and 10% SF were obtained as 46, 43 and 50% for binder content of 400, 450 and 500 respectively, which is noticeable and reveals the good performance of SF and NS blends in the SCC mixtures.

From the results, the influence of different binder contents and addition of SF and NS various on water absorption properties of SCC can be seen and compared. The trends generally show desirable effect of admixtures especially micro and nano silica blends on water absorption properties of the SCC samples. With this respect, more desirable performances were observed in the mixtures containing 10% SF and 2% NS with binder content of 500 kg/m3.

3.2 Capillary water sorption

The capillary water absorption results of the SCC samples at different time intervals are presented in table 6. The results show that the height of absorbed water in the concrete samples has decreased by increasing the binder content from 400 to 500 and addition of SF and NS admixtures. Increase in binder content from 400 to 450 and 500 lead to capillary water absorption from 2.8 to 2.64 and 2.5 mm during three hours and from 8.6 to 6.9 and 6.6 mm during 72 hours respectively, which the capillary water height decreases seem more significant at longer times. It may be due to the fact that the samples fully dried in the oven have more tendency to absorb water at earlier times, however at longer times the effect of binder content and SF and NS admixtures comes to be revealed more and the results considered to be more realistic and reliable. Addition of 2% NS resulted in capillary water absorption of 3.6, 3.3 and 3 mm for binder content of 400, 450 and 500 respectively during 72 hours for which the reductions of 58, 52 and 54% compared to the mixtures without any admixture can be considered. Addition of 10% SF with binder content of 400, 450 and 500 resulted in capillary water absorption decrease by 60, 52 and 53% respectively during 72 hours compared to the mixtures without any admixture. The same reductions observed for mixtures containing blend of 2% NS and 10% SF were 66, 65 and 66% respectively. As can be seen, the water proofing effects of SF and NS on SCC tend to appear more obviously in the

Table 6 Results of capillary absorption by time

No	Concrete ID	Capillary water sorption (%)			
		Time (hour)	Time (hour)	Time (hour)	Time (hour)
		3	6	24	72
1	SCC400	2.8	2.82	6.5	8.6
2	SCC450	2.64	3.5	5.8	6.9
3	SCC500	2.5	3.4	5.5	6.6
4	SCC400NS2%	2.2	2.7	3.4	3.6
5	SCC450NS2%	2	2.4	3.1	3.3
6	SCC500NS2%	1.8	2.3	2.9	3
7	SCC400SF10%	2.1	2.5	3.3	3.4
8	SCC450SF10%	1.9	2.2	3	3.3
9	SCC500SF10%	1.7	2.16	2.9	3.1
10	SCC400SF10NS2%	1.9	2	2.8	2.9
11	SCC450SF10NS2%	1.7	1.9	2.5	2.4
12	SCC500SF10NS2%	1.5	1.7	2.1	2.2

mixtures containing both SF and NS with higher binder content. As can be inferred from the water absorption results, this performance may be attributed to the more packed and refined microstructure and pore structure of the concrete achieved by addition of SF and NS.

As is clear from the results, the mixture containing SF and NS blends with binder content of 500 has the lowest capillary water absorption values. On the whole, the addition of silica micro and especially nano particles improves the pore structure of concrete. On the one hand, nano particles can act as a filler to enhance the density of concrete, which leads to the porosity of concrete reduced significantly. On the other hand, nano particles can not only act as an activator to accelerate cement hydration due to their high activity, but also act as a kernel in cement paste which makes the size of $Ca(OH)_2$ crystal smaller and the tropism more stochastic.

The high enhancement of durability properties in the SF and NS blended SCC is due to the rapid consuming of $Ca(OH)_2$ which was formed during hydration of Portland cement specially at early ages related to the high reactivity of NS particles. As a consequence, the hydration of cement is accelerated and larger volumes of reaction products are formed. Also NS particles recover the particle packing density of the blended cement, directing to a reduced volume of larger pores in the cement paste.

3.3 Cl ion percentage

In this test, the Cl ion percentage has been determined as a fraction of the concrete sample weight. Presented in Table 7 are the results of Cl ion presence at different depths of the concrete samples. The results show a general decrease in Cl ion presence by depth of concrete sample which conveys the fact that the concrete ingredients especially aggregates are clear from Cl ions. In depth of 0 to 5 mm, increase in binder content from 400 to 450 and 500 in the samples without any admixture resulted in reductions of Cl ion amount by 16.6% and 29% respectively. In depth of 0 to 5 mm of the samples containing 2% NS, Cl ion penetration decreased by 43, 40 and 43% for binder contents of 400, 450 and 500 respectively. The reductions in the samples containing 10% SF were obtained as 52, 40 and 43% for the same binder contents respectively. The samples

Table 7 Cl ion percentage at different average depths of the concrete samples

No	Concrete ID	Cl ion percentage				
		Mean of Depth (mm)				
		2.5 (mm)	7.5 (mm)	12.5 (mm)	17.5 (mm)	25 (mm)
1	SCC400	4.2	1.7	0.8	0.52	0.19
2	SCC450	3.5	1.5	0.74	0.43	0.17
3	SCC500	2.98	1.4	0.65	0.37	0.14
4	SCC400NS2%	2.4	1.1	0.62	0.42	0.15
5	SCC450NS2%	2.1	0.9	0.48	0.37	0.13
6	SCC500NS2%	2	0.85	0.43	0.32	0.12
7	SCC400SF10%	2.3	0.81	0.51	0.32	0.14
8	SCC450SF10%	2.1	0.78	0.49	0.3	0.12
9	SCC500SF10%	1.7	0.4	0.43	0.23	0.09
10	SCC400SF10NS2%	1.6	1	0.4	0.29	0.09
11	SCC450SF10NS2%	1.4	0.75	0.38	0.25	0.07
12	SCC500SF10NS2%	1.3	0.55	0.33	0.11	0.03

Table 8 Results of electrical resistivity for different mixtures

No	Concrete ID	Resistivity (Ω.m)		
		7(days)	28(days)	90(days)
1	SCC400	47	72	110
2	SCC450	49	89	120
3	SCC500	54	95	144
4	SCC400NS2%	47	128	402
5	SCC450NS2%	53	162	423
6	SCC500NS2%	77	223	478
7	SCC400SF10%	44	121	313
8	SCC450SF10%	49	151	388
9	SCC500SF10%	73	211	541
10	SCC400SF10NS2%	89	157	437
11	SCC450SF10NS2%	95	216	523
12	SCC500SF10NS2%	125	320	589

containing blend of 10% SF and 2% NS showed significant Cl ion penetration decrease as 62, 60 and 56% for the same binder contents respectively. As can be considered, SF and NS addition has resulted in relatively significant decrease in Cl ion percentage which may be in virtue of more refined pore structure of the concrete obtained by addition of the admixtures especially nano particles and pozzolanic effect of this material.

The results obviously show descending trends by increase in depth. Comparison is easier in lower depths, however in higher depths the curves get closer together and the differences get smaller. According to the results, again it is confirmed that the mixture with binder content of 500 containing NS and SF has the most desirable durability performance.

3.4 Resistivity

Considering the results presented in Table 8, at earlier ages (7 days) with different binder contents and admixtures amount, corrosion is probable. However, at higher ages by increase in binder content and addition of SF and NS admixtures, probability of corrosion occurrence decreases and approaches to the improbable level. Only for mixtures with binder content of 400 without any admixture at the age of 90 days, the electrical resistivity results fall in the range where corrosion is probable. In the mixtures containing 2% NS, 10% SF and blend of SF and NS, the increase in electrical resistivity values are considerable and the corrosion tend to become impossible. As can be inferred from the results, resistivity values for the mixture with binder content of 500 and without admixture obtained as 54, 95 and 144 at the ages of 7, 28 and 90 days respectively. The resistivity values for the mixture with the same binder content containing 2% NS and 10% SF increased from 125 at the age of 7 days to 320 and 589 at the ages of 28 and 90 days respectively, which are considered to be outstanding.

It is noted from the results that by passing time, the resistivity values have increased. The resistivity curves also show incremental trends by increasing the binder content. It can be deduced from the resistivity results that although both binder content and admixture factors seem to be effective on resistivity values of SCC, however the role of SF and NS admixtures appears to be much more influential. It is clear that the highest resistivity belongs to the SCC500SF10NS2% mixture.

4. Conclusions

The following conclusion obtained from this study:

- Both water absorption and capillary absorption results showed rather significant improvement by addition of admixtures especially blend of micro and nano materials for binder content of 500 kg/m^3.
- The resistivity results showed increases at higher ages, especially for the mixtures containing higher percentages of admixtures. Binder content increase also had an increasing effect on the resistivity values.
- Cl ion percentage decreased by depth, by addition of micro and nano particles and by binder content increase which could be as a result of more packed microstructure achieved by addition of nano particles and paste volume increase.
- From the microstructure point of view, more refined microstructure and smaller pores may be achieved by addition of silica fume and nano silica, which can lead to enhanced durability and microstructural properties of the SCC mixtures.

References

ACI Committee 363 R (1997), “State-of-the-art report on high-strength concrete”, Farmington Hills, American Concrete Institute, USA.

Audenaert, K. (2006), “Transport mechanismen in zelfverdichtend beton in relatie met carbonatatie en chloride penetratie”, PhD Thesis, Ghent, Ghent University.

Bartos, P.J.M. (1999), “Self-compacting concrete”, *Concrete*, **3**(4), 9-14.

Bleszynski, R.F., Hooton, R.D., Thomas, M.D.A. and Rogers, C.A. (2002), “Durability of ternary blend concretes with silica fume and blast furnace slag: laboratory and outdoor exposure site studies", *ACI Mater. J.*, **99**, 499-508.

Bouzoubaa, N. and Lachemi, M. (2001), "Self-compacting concrete incorporating high volumes of class F fly ash-preliminary results", *Cement Concrete Res.*, **31**, 413-20.

Collepardi, M., Collepardi, S., Ogoumah Olagat, J.J. and Troli, R. (2003), "Laboratory-test and filled-experience SCC's", *Proceedings of the 3rd international symposium on self compacting concrete*, Reykjavik, Iceland, August.

El-Dieb, A.S. (2009), "Mechanical, durability and microstructural characteristics of ultra-high-strength self-compacting concrete incorporating steel fibers", *Mater. Des.*, **30**(10), 4286-4292.

Jalal, M., Fathi, M. and Farzad, M. (2013), "Effects of fly ash and TiO2 nanoparticles on rheological, mechanical, microstructural and thermal properties of high strength self compacting concrete", *Mech. Mater.*, **61**, 11-27.

Jalal, M., Mansouri, E., Sharifipour, M. and Pouladkhan, A.R. (2012), "Mechanical, rheological, durability and microstructural properties of high performance self-compacting concrete containing SiO_2 micro and nanoparticles", *Mater. Des.*, **34**, 389-400.

Jalal, M., Ramezanianpour, A.A. and Khazaei Pool, M. (2013), "Split tensile strength of binary blended self compacting concrete containing low volume fly ash and TiO_2 nanoparticles", *Compos. Part B: Eng.*, **55**, 324-337

Ji, T. (2005), "Preliminary study on the water permeability and microstructure of concrete incorporating nano-SiO2", *Cement Concrete Res.*, **35**, 1943-7.

Jo, B.W., Kim, C.H. and Tae, G.H. (2007), "Characteristics of cement mortar with nano-SiO_2 particles", *Construct. Build. Mater.*, **21**, 1351-5.

Kay, T. (1992), *Assessment & Renovation of Concrete Structure*, Longman scientific and Technical Publication.

Kulakowski, M.P., Pereira, F.M. and Dal Molin, D.C.C. (2009), "Carbonation induced reinforcement corrosion in silica fume concrete", *Construct. Build. Mater.*, **23**, 11897-1195.

Lin, K.L., Chang, W.C. and Lin, D.F. (2008), "Effects of nano-SiO_2 and different ash particle sizes on sludge ash-cement mortar", *J. Environ. Manage.*, **88**, 708-14.

Mays, G. (1992), *Durability of Concrete Structure, Investigation, Repair, Protection*, E & FN Spon Publication.

McCarter, J.W., Forde, M.C. and Whittington, M.W. (1981), "Resistivity characteristics of concrete", *Proceeding of Institution of civil Engineers*, Part 2, **71**, March.

Okamura, H.M. and Ouchi, M. (2003), "Self-compacting concrete", *J. Adv. Concrete Technol.*, **1**(1), 5-15.

Perraton, D., Aïtcin, P.C. and Carles-Gbergues, A. (1994), *Permeability, as seen by the researcher*, Ed. Malier, Y., High Performance Concrete: From Material to Structure, E & FN Spon, London, UK.

Qing, Y., Zenan, Z. and Deyu, K. (2007), "Influence of nano-SiO_2 addition on properties of hardened cement paste as compared with silica fume", *Construct. Build. Mater.*, **21**, 539-45.

Siddique, R. (2011), "Properties of self-compacting concrete containing class F fly ash", *Mater. Des.*, **32** (3), 1501-1507.

Ye, G., Lura, P. and van Breugel, K. (2006), "Modeling of water permeability in cementitious materials", *Mater. Struct.*, **39**, 877-885.