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RESEARCH PAPER

A Laboratory Study on the Potentiodynamic Polarization and Transport Properties of Binary Concrete with Silica Fume and Zeolite

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ABSTRACT: The current study aims to investigate influence of w/cm ratio, cementitious materials content and supplementary cementitious materials on the transport properties of concrete and chloride-induced corrosion rate of reinforcement. To do this, several mixes are designed with and without silica fume and natural zeolite as supplementary cementitious materials, w/cm of 0.4 and 0.5, and cementitious materials contents of 325 and 400 kg/m^3. These mixes are subjected to evaluation of compressive strength, transport properties (i.e. absorption, water penetration depth and rapid chloride penetration test), and corrosion rate measurement through Potentiodynamic test and electrochemical measurements. The results of this study reveal that there is not strong correlation between corrosion rate of reinforcement and the measured strength and transport properties. The corrosion rate of reinforcement significantly decreased through reduction of water-to-cementitious materials ratio and use of supplementary cementitious materials; of which w/cm showed a more considerable influence. Increase in cement content, however, increased the transportation of water and chloride into the concrete and thus increased the corrosion rate of reinforcement.

Keywords: Concrete, Corrosion, Silica Fume, Transport Properties, Zeolite.

1. Introduction

Concrete is known to be an extensively utilized material due to its adaptability, appropriate durability and mechanical properties (Tang et al., 2015), however, this material degrade when confronted the environmental attacks. However, the most important failure of reinforced concrete structures is related to the chloride-induced corrosion of reinforcements (Montemor et al., 2003; Hooton, 2019; Glass and Buenfeld, 2000; Manera et al. 2008; Cao et al., 2019; Rodrigues et al., 2021; Tangtakabi et al., 2021). Many defects due to reinforcement corrosion have been reported in concrete bridges, marine piers, and other strategic reinforced concrete structures exposed to chloride ions (Tarighat and Jalalifar, 2014; Cavaco et al.,

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2017; Navarro et al., 2018; ACI 222R, 2019).

Penetration of chloride ions due to the de-icing salts, marine environments, and chloride ions in concrete constituents such as aggregates or water are of the major causes of corrosion (Kirkpatrick et al., 2002; Lindquist et al., 2006; Chen et al., 2021; Qu, et al. 2021).

The corrosion of concrete structures and related repairs leads to huge costs. Enormous annual costs are spent on renovation, repairs, and traffic delays due to corrosion on reinforced concrete bridges in North America (Kirkpatrick et al., 2002; Lindquist et al., 2006; Liang and Wang, 2020).

Available statistics showed that 25 to 40 percent of concrete bridges in Norway, US and UK, corrode annually and needed for repair programs with costly budgets (Webster, 2000). In south costal line of Iran the most concrete structures suffer the corrosion problems.

A number of these structures have essentially become nonfunctional due to chloride-induced corrosion of reinforcements. As such, investigating corrosion of reinforcement in concrete, recognizing parameters affecting the corrosion rate, and finding solutions to improve corrosion resistance of reinforced concrete structures have not been more urgent (Sanchez et al., 2017; Oliveira and Cascudo, 2018).

While several factors influence properties of concrete and thus the protection that concrete provides for the reinforcement, it is well defined in the literature that w/cm ratio, cement content, and supplementary cementitious materials (SCMs) like silica fume, fly ash, slag are the governing factors that can affect physical, mechanical and durability (Malhotra and Mehta, 1996; Gu et al., 2000; Madani et al. 2016; Samimi et al., 2017; Nguyen et al., 2020). SCMs can lead to reduction in chloride-ion penetration into concrete (Mangat and Molloy, 1991; Choia et al., 2006; Boğaa and Topçub, 2012; Ahmadi et al., 2014; Tang et al., 2015). For this reason, a superior corrosion resistance of the steel reinforcement in these concretes is expected (Glass and Buenfeld, 2000). The content of SCM is also important parameter which can improve the mechanical and durability properties of concrete (Choia et al., 2006; Boğaa and Topçub, 2012).

In pursuit of the above mentioned need for investigate the effective parameters on corrosion of reinforcement; this paper evaluates the influence of w/cm ratio, cementitious materials content and silica fume and natural zeolite on corrosion rate of reinforcement.

2. Experimental Detail

2.1. Materials

Type I Portland cement as a plain binder, silica fume and natural zeolite as SCM (secondary binders), fine and coarse aggregates, High Range Water Reducer (HRWR), and tap water. The properties of the used binders are presented in Tables 1-3. The used silica fume contained 87% silica with few percentages of calcium oxide, alumina, iron oxide and magnesium oxide. Natural zeolite confirms the requirement of ASTM C 618.

Table 1. Chemical composition of cementitious materials

Chemical analysis (%)	Portland cement-Type I	Silica fume	Natural zeolite
Calcium oxide (CaO)	63.00	2.24	1.68
Silica (SiO_2)	21.95	87.26	67.79
Alumina (Al_2O_3)	4.35	1.5	13.66
Iron oxide (Fe_2O_3)	3.80	3.80	1.44
Magnesium oxide (MgO)	2.00	2.00	1.2
Sodium oxide (Na_2O)	0.30	--	2.04
Potassium oxide (K_2O)	0.77	--	1.42
Sulfur trioxide (SO_3)	2.43	0.11	0.52

Table 2. Mechanical and physical properties of Portland cement

Compound/Property (Unit)	Value
Tricalcium silicate (C_3S) (%)	48.07
Dicalcium silicate (C_2S) (%)	26.67
Tricalcium aluminate (C_3A) (%)	2.43
2 day compressive strength (MPa)	10.80
3 day compressive strength (MPa)	18.75
7 day compressive strength (MPa)	21.15
28 day compressive strength (MPa)	34.30
Initial setting time (min)	181
Final setting time (min)	268
Specific surface (m^2/kg)	315
Specific gravity (g/cm^3)	3.15
Loss on ignition (%)	1.71
Insoluble residue (%)	0.68
Autoclave expansion (%)	0.40

Table 3. Chemical and physical properties of natural zeolite according to ASTM C618

Requirements		Class N, Natural pozzolan, ASTM C618	Natural zeolite (clinoptilolite)
Chemical requirements	$SiO_2+Al_2O_3+Fe_2O_3$ (%)	min, 70.0	82.89
	Sulfur trioxide (SO_3) (%)	max, 4.0	0.52
	Moisture content (%)	max, 3.0	2.9
	Loss on ignition (%)	max, 10.0	9.85
Physical requirements	Amount retained when wet-sieved on 45 μm sieve (%)	max, 34	28
	[1]Strength activity index, at 7 days (percent of control)	min, 75	120
	[1] Strength activity index, at 28 days (percent of control)	min, 75	127
	Water requirement (percent of control)	max, 115	114
	Autoclave expansion or contraction (%)	max, 0.8	0.02
[2] Pozzolanic activity (%)	8 days	-	45.8
	30 days	-	54.3

[1] Note that, the strength activity index was determined based on ASTM C311 by replacing 20% of Portland cement with natural zeolite; [2] Pozzolanic activity was measured through thermo-gravimetric analysis by combining 50% natural zeolite with 50% $Ca(OH)_2$ powder.

The higher Pozzolanic activity of silica fume can be related to its lower particle size (see Figure 1 for particle size distribution of cementitious materials) and higher content of reactive silica (shown in Table 3).

The properties of utilized aggregates is presented in Table 4. A HRWR polycarboxylate-based was also used to maintain a constant slump of 65 ± 15 mm for all the studied concrete mixes.

2.2. Mixture Proportions

Table 5 summarizes mixture proportions of the selected concretes. As this study was aimed to assess the effects of influential parameters on the corrosion rate of reinforcement in mixtures, the designed concretes included concrete mixtures with w/cm of 0.4 and 0.5, cementitious materials content of 325 and 400 kg/m^3, and two sources of supplementary cementitious materials, i.e. silica fume and natural zeolite. Table 5 is divided into two groups of mixes: 1) normal concrete mixes having normal cement as a sole binder, and 2) mixes containing Portland cement as the primary binder and SCMs as the secondary binder; which labeled as binary mixes. Normal mix NC.5-325 was assigned as the reference mix containing 325 kg/m^3 Portland cement and w/cm of 0.5. Normal concrete mixes NC.4-325, NC.5-400, and NC.4-400 were designed without use of SCMs to evaluate the influence of cementitious material content and w/cm on the corrosion rate. Binary mixes SC.5-325, SC.4-325, SC.5-400 and SC.4-400 were designed similar to normal mixes, but by replacing 7.5% with silica fume. Binary mixes NZL.5-325 and NZH.5-325 contained 15 and 30% natural zeolite.

As mentioned earlier, different amounts of HRWR was used to keep the constant flow for all the selected mixes. In Table 5, reducing w/cm or replacing cement with SCMs increased the demand for HRWR. Increases in the cementitious materials content, however, decreased the used amount of HRWR which could be related to the higher amount of water in the mix when cementitious materials content increases for a constant w/cm.

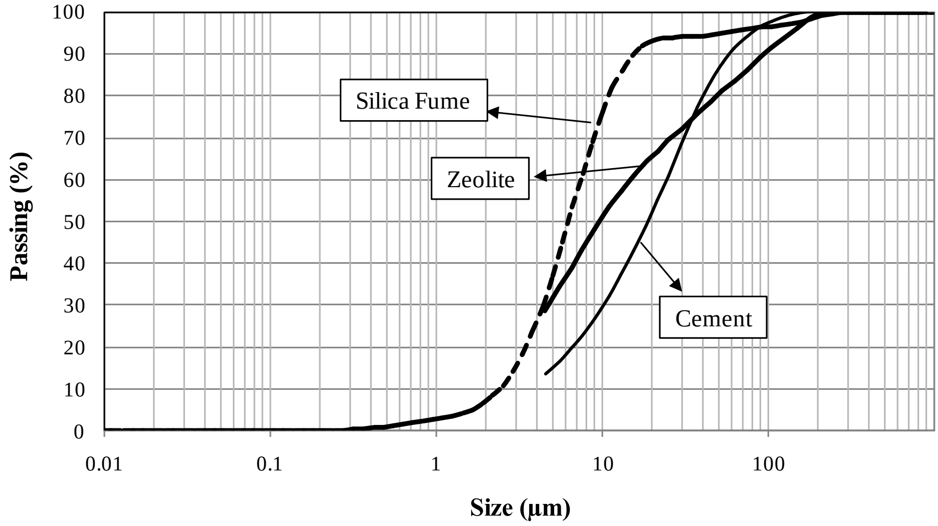

Fig. 1. Particle size distribution of cementitious materials

Table 4. Aggregate properties

Aggregate type	Specific gravity	Absorption (%)	Passing sieve #200 (75 μm) (%)
Fine aggregates (0 - 4.75 mm)	2.46	2.50	2.37
Coarse aggregates (4.75 - 19 mm)	2.56	2.17	--

Table 5. Mixture proportions of the selected concretes

Mix ID	Cement (kg/m^3)	Silica fume (kg/m^3)	Natural zeolite (kg/m^3)	w/cm	Water (kg/m^3)	Fine aggregate (kg/m^3)	Coarse aggregate (kg/m^3)	HRWR (% of cementitious materials content)
Normal mixes								
NC.5-325 (Reference)	325	0	0	0.50	162.5	885.4	901.2	0.261
NC.4-325	325	0	0	0.40	130	918.3	933.9	0.426
NC.5-400	400	0	0	0.5	200	953.3	786	0.071
NC.4-400	400	0	0	0.4	160	953.3	786	--
Binary mixes								
SC.5-325	300.6	24.4	0	0.50	162.5	885.4	901.2	0.502
SC.4-325	300.6	24.4	0	0.40	130	915.5	930.8	0.824
SC.5-400	370	30	0	0.5	200	953.3	786	0.357
SC.4-400	370	30	0	0.4	160	953.3	786	0.424
NZL.5-325	276.3	0	48.7	0.5	162.5	877	877	0.433
NZH.5-325	227.5	0	97.5	0.5	162.5	870	870	1.146

-- : No data recorded.

2.3. Corrosion Test Setup and Electrochemical Measurements

Specimens (Cylindrical) with size of 85 (diameter) × 200 (height) mm were utilized for electrochemical investigations. Two reinforcing bars (with diameter of 10 mm) included in specimens as reinforcing bars (Figure 2). For test measurement, reinforced specimens were cast and stored in wet-curing for 28 days in saturated limewater. Then, specimens were subjected to cyclic-pondings comprising two-weeks of exposure to sodium chloride solution (5% NaCl by weight) followed by two weeks in dry condition. At different ages of pondings, Potentiodynamic test was conducted to measure the corrosion rate of rears in specimens.

The setup utilized in this research, is a simulation of a “cored reinforced concrete specimen” of concrete structure element which an inspector engineer, might be gained from a real structure. In the used setup, it can be seen a “near-to-real” simulation of such petrochemical system.

3. Experimental Results

3.1. Compressive Strength

Table 6 summarizes the compressive strength test results of the selected mixes at the age of 28 and 90 days (150 × 300 mm cylindrical specimens). The compressive strength increased when w/cm decreased, cementitious materials content increased, or a portion of PC was replaced with silica fume. The improvements due to increases in cementitious materials content was less significant compared to those observed by use of silica fume and reduction in w/cm. Use of natural zeolite, however, resulted in slight decreases in the compressive strength; particularly at the age of 28 days.

For mixtures without SCM, except NC.4-325, almost 85% of 90-day compressive strength was achieved in 28 days. For SC concrete, except SC.4-325, almost 95% of 90-day compressive strength was gained in 28 days. For NZH.5-325, 70% of 90-day compressive strength was developed at 28 days highlighting late pozzolanic reactivity of natural zeolite (Shekarchi et al., 2012). Low dosage natural zeolite worked like the regular concrete without SCM.

Decreases in w/cm from 0.5 to 0.4 led to 42.9 and 28.5% improvements in 28-day compressive strength of normal concrete having 325 and 400 kg/m^3 of Portland cement, respectively. These enhancements were respectively 31.2 and 25.2 % at the age of 90 days. The improvements due to the reduction in w/cm were lower for silica fume contained concretes. When w/cm reduced from 0.5 to 0.4, the compressive strength of silica fume contained concrete improved averagely 22% and 10% for mixes having cementitious materials content of 325 and 400 kg/m^3, respectively.

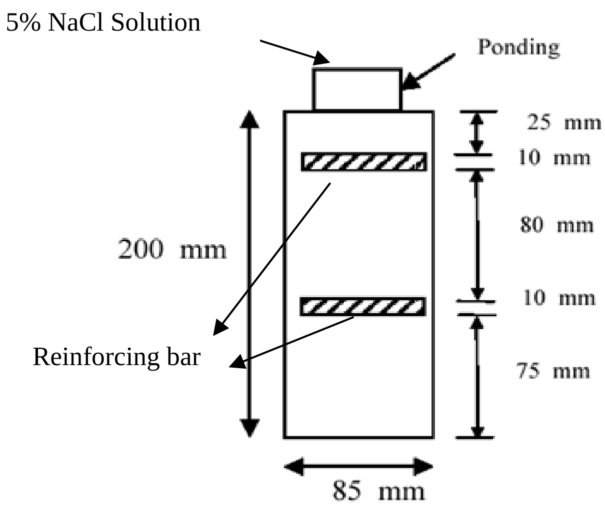

Fig. 2. Schematic of ponding test setup for reinforced concrete specimens

Table 6. Compressive strength and transport properties

Mix ID	Compressive strength (MPa)		Water penetration depth (mm)		24 h-Water absorption (%)		Chloride ion penetration (C)	
	28 days	90 days	28 days	90 days	28 days	90 days	28 days	90 days
Normal mixes								
NC.5-325 (Ref)	23.8	28.2	17.3	15.7	7.5	7.0	7863	6848
NC.4-325	34.0	37.0	15.8	13.1	4.5	4.9	2484	1624
NC.5-400	27.0	31.7	15.7	13.3	8.2	6.8	7120	7521
NC.4-400	34.7	39.7	13.3	12.5	6.6	6.7	7174	5494
Binary mixes								
SC.5-325	35.5	36.4	15.6	12.7	7.2	6.0	1757	1043
SC.4-325	40.1	47.8	12.7	11.3	4.2	4.7	1024	718
SC.5-400	42.7	44.8	11.6	11.0	6.7	6.7	1534	1541
SC.4-400	46.3	49.6	12.0	11.3	5.1	6.1	1093	1157
NZL.5-325	23.1	27.4	13.5	11.5	8.0	8.0	1914	958
NZH.5-325	18.1	26.2	9.5	10.5	7.8	7.6	572	408

The mentioned improvements were average of improvements in 28 and 90 days. An increase in cementitious materials contents from 325 to 400 kg/m^3 resulted in averagely 13 and 22% increases in compressive strength of normal and silica fume contained concrete having w/cm of 0.5, respectively. These enhancements were averagely 5 and 10% for w/cm of 0.4, respectively.

Use of silica fume as a supplementary cementitious material led to significant improvements in the compressive strength of the selected concretes. On contrary, use of natural zeolite resulted in a slight decrease in compressive strength at the age of 28 days. Silica fume contained concretes produced averagely 54 and 26% higher 28-day compressive strength than those of normal concrete for w/cm of 0.5 and 0.4, respectively. In the case of natural zeolite contained concrete, the 28-days compressive strength of mixes containing 15 and 30% natural zeolite were 3 and 24% lower than that of reference concrete, respectively. Once curing age extended to 90 days, natural zeolite contained mixes produced similar strength to that of reference concrete. This behavior can be related to the late pozzolanic activity of natural zeolite at later ages. The 90- day compressive strength of silica fume contained concretes were 27 to 35% higher than that of normal concretes.

3.2. Transport Properties

Transport properties of the selected concretes were evaluated through measurements of water penetration depth as per BS EN 12390-8, water absorption according to BS 1881-122 and rapid chloride penetration based on ASTM C1202. Table 6 documents the results of transport properties. Generally speaking; reduction in w/cm and use of SCMs were effective in improving transport properties of the selected concretes. The observed improvements were more significant when w/cm was reduced than when a portion of cement was replaced by SCMs. Increases in cementitious materials content was only effective in improving water penetration depth of the selected concretes.

Water penetration depth was measured on 15 cm cubic specimens by applying water under pressure of 0.5 MPa for 3 days. Overall, the penetration depth was slightly decreased by reduction in w/cm, use of higher cementitious materials content and partial replacement of Portland cement with SCMs. Use of SCMs was, however, the most effective factor in improving (i.e. decreasing) water penetration depth into the concrete. The penetration depths of silica fume contained mixes were up to 26% (averagely 15.6%) lower than those of normal concrete mixes for similar w/cm and cementitious materials content. Binary mixes containing 15 and 30% natural zeolite presented averagely 24 and 39%

lower penetration depth than those of reference mix, respectively. For the cementitious materials content of 325 kg/m^3, reduction in w/cm from 0.5 to 0.4 improved water penetration depth of normal and silica fume contained concrete by averagely 14%. In the case of normal concrete having cementitious materials content of 400 kg/m^3, the reductions due to the decreases in w/cm were about 15 and 6% at the age of 28 and 90 days, respectively. For the similar cementitious materials content (i.e. 400 kg/m^3), this reduction in w/cm resulted in almost 3% increase in penetration depth of silica fume contained concretes. Increases in cementitious materials content also improved the water permeability of the selected concretes. The water penetration depth of the selected mixes improved by averagely 10% when cementitious materials content increased from 325 to 400 kg/m^3.

Decreases in w/cm led to more considerable improvements in water absorption of the selected concretes. On average, water absorption of normal and silica fume contained concretes decreased by averagely 33.4 and 13.2%, respectively, when w/cm was reduced from 0.5 to 0.4. Increases in cementitious materials content, however, resulted in increase in water absorption; in particular, for concretes having w/cm of 0.4. Water absorption of concretes (normal and silica fume contained mixes) having w/cm of 0.4 was increased by averagely 34% with increases in cementitious materials content. For w/cm of 0.5, water absorption did not change by the increases in cementitious materials content. Application of SCMs did not show significant effect in water absorption of the selected concretes. Water absorption of silica fume contained concretes were averagely 10% lower than that of normal concretes. On the other hand, natural zeolite contained concretes produced averagely 8% higher water absorption than that of reference concrete.

Rapid Chloride Penetration Test (RCPT) was conducted on 10 cm diameter by 5 cm height disks per ASTM C1202. The charge passed through concrete disks significantly reduced by use of SCMs. The passing charges of binary mixes containing silica fume was 56 to 85% (averagely 75%) lower than those of normal concrete. A similar reduction was observed by use of natural zeolite in percentages higher than silica fume. Mixes NZL.5-325 and NZH.5-325 had almost 80% lower RCPT value than that of reference mix. Use of higher cementitious materials content resulted in averagely 66% increases in RCPT results of the selected mixes. The increases were more magnified for mixes with w/cm of 0.4 than mixes with w/cm of 0.5, and for normal concretes than silica fume contained concretes. As RCPT is related to the movements of different ions; in particular hydroxyls (OH^-), the observed increases by use of higher cementitious materials content can be related to production of higher calcium hydroxide as a main production of Portland cement hydration. On the other hand, use of SCMs reduces RCPT passing charges through 1) consumption of hydroxyls; and 2) production of more C-S-H by reactions with calcium hydroxide leading to lower permeability. Decreases in w/cm resulted in 72 and 36% reduction in RCPT of normal and silica fume contained mixes having 325 kg/m^3 of Portland cement, respectively. Lower reductions of averagely 13 and 27% were observed when cementitious materials content of 400 kg/m^3 was used.

3.3. Corrosion Rate Measurements

Potentiodynamic polarization curves were obtained at a scan rate of 0.1667 mV/s using a four electrode arrangement shown in Figure 3. Solartron 1287 electrical interface and associated software CorrWare were utilized to control the test procedures and analyze the data (see Figure 3). A $Hg/HgSO_4$ in saturated K_2SO_4 solution (0.64 V/NHE) and platinum bar were used as reference and counter-electrodes, respectively (RE and SE in Figure 3). Reinforcing rebar as working electrode was connected to WE terminal as depicted in Figure 3.

Using the results of potentiodynamic polarization test, corrosion rate of reinforcement embedded in the selected concrete mixes were estimated. Table 7 documents the corrosion rate and corrosion current density of reinforcement at various ages of testing. The one-year reinforcement' corrosion rate for the selected mixes is also presented in Figure 4. Generally, decreases in w/cm and use of SCMs reduced the corrosion rate of the reinforcement. These improvements were more significant for w/cm than for those related to the use of SCMs. Increase in cement content, however, resulted in increases in the corrosion rate of reinforcement.

Reductions in w/cm from 0.5 to 0.4 led to significant reduction in corrosion rate of reinforcement. For normal concretes, the reduction in w/cm resulted in averagely 75, 77 and 89% reduction in 180, 270, and 365-day corrosion rates, respectively. For the same ponding ages of 180, 270 and 365 days, the improvements due to reduction in w/cm were averagely 72, 75 and 92% for silica fume contained concretes, respectively.

Use of supplementary cementitious materials, in particular silica fume, was also useful in improving (i.e. reducing) the corrosion rates. The 180, 270, and 365- day corrosion rates of reinforcement embedded in silica fume contained concrete mixes were averagely 68, 38 and 30% lower than those embedded in normal concrete mixes, respectively. Replacing 15 and 30% of cement with natural zeolite led to 63 and 90% reduction in 180-day corrosion rate, respectively. This reduction was 64% at 270 day by use of 30% natural zeolite as SCMs, while 270-day corrosion rate of NZL.5-325 was higher than that of reference concrete.

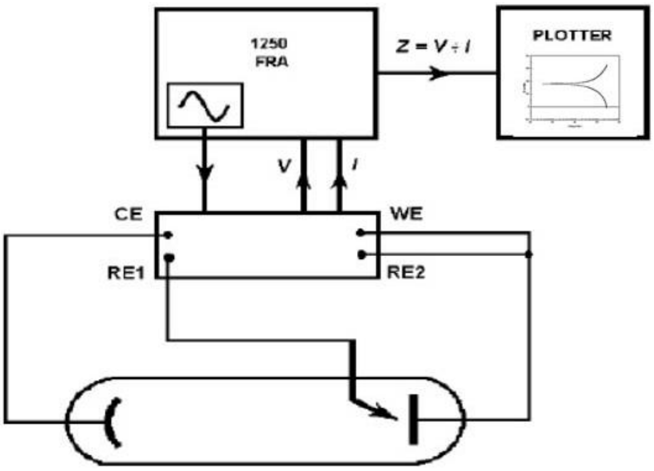

Fig. 3. Schematic of four electrode setup for electrochemical measurements

Table 7. Corrosion rate and current density based on potentiodynamic polarization test

Mix ID	**Corrosion rate (mm/yr)**			**Corrosion current density (mA/cm^2)**		
	180 days	**270 days**	**365 days**	**180 days**	**270 days**	**365 days**
Normal mixes						
NC.5-325 (Reference)	0.313	0.120	0.077	0.0270	0.0104	0.0066
NC.4-325	0.078	0.028	0.005	0.0067	0.0024	0.0004
NC.5-400	--	0.112	0.175	--	0.0097	0.0151
NC.4-400	0.169	--	0.028	0.0146	--	0.0024
Binary mixes						
SC.5-325	0.087	0.065	0.058	0.0075	0.0056	0.0050
SC.4-325	0.031	0.017	0.004	0.0027	0.0015	0.0003
SC.5-400	0.236	0.079	0.139	0.0204	0.0068	0.0120
SC.4-400	0.050	0.019	0.013	0.0043	0.0016	0.0011
NZL.5-325	0.114	0.182	--	0.0098	0.0157	--
NZH.5-325	0.032	0.043	--	0.0028	0.0037	--

Note: -- means no data recorded or failed measurement

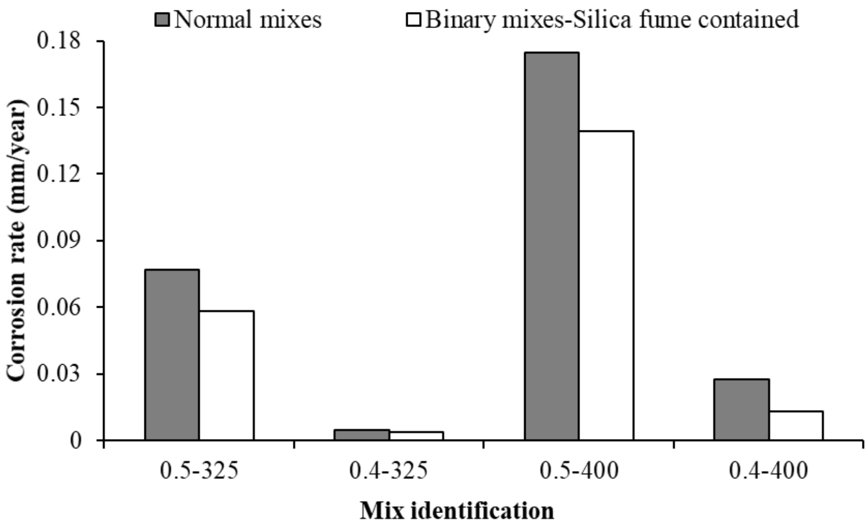

Fig. 4. One-year reinforcement' corrosion rate of the selected mixes measured by potentiodynamic polarization

Increases in cementitious materials content, however, increased the corrosion rate of reinforcement. On average, the reinforcement corrosion rate of normal and silica fume contained concrete mixes having cementitious materials content of 400 kg/m^3 were 2.8 and 2.1 times of those mixes having cementitious materials content of 325 kg/m^3, respectively. The best combination was when w/cm reduced and a portion of Portland cement was replaced with silica fume. The corrosion rates of NC.5-325 and NC.5-400 (average of 180, 270 and 365 days) were almost as 14 and 10 times of those of SC.4-325 and SC.4-400, respectively.

It is worth mentioning that effect of age of ponding on the corrosion was not discussed due to the different condition of samples at the time of testing. The reason is that concretes were in different conditions of full or empty dike at different ages; i.e. 180 days (full dike), 270 and 365 days (empty dike). As such, the difference between the trends in different ages could be related to the above-mentioned fact.

Table 8 shows the correlation factor between corrosion rate and the measured strength and transport properties. As expected there is an inverse relationship between corrosion rate and compressive strength. Although it's not a strong relationship which means that compressive strength cannot be a proper indicator for the evaluation of chloride-induced corrosion resistance of concrete. The corrosion rate of reinforcement showed direct relationship with the measured transport properties. The relationships, however, were not strong enough to be used as direct indices for prediction of corrosion rate of reinforcement in concrete. It can be particularly seen that the results of rapid chloride penetration test cannot be justified as an index for chloride-induced corrosion of reinforcement.

The direct relationship does not mean a strong correlation between rapid transport property tests and corrosion rate, but only showing that higher transport property led to higher penetration of chlorides and thus higher corrosion rate. From chemical point of view, the lower transport property is related to pozzolanic reactivity producing more C-S-H gel or silica fume acting as both pozzolans and nucleation sites which result in an improved pore system. Lower w/c also contributes physically to an improved pore system lowering the pore volume. An improved pore structure results in less chloride penetration and less chloride available at the level of reinforcement. It should be noted that while all these result in lower corrosion rate, the relationship is not strong and therefore, it is not easy to effectively predict the service life using transport property (Andrielli et al., 2018; Ramezanianpour et al., 2015).

Table 8. Correlation between corrosion rate and the measured strength and transport properties

	Compressive strength		Water penetration depth		Water absorption		Rapid chloride penetration test	
	28 days	90 days	28 days	90 days	28 days	90 days	28 days	90 days
Corrosion rate-180 days	-0.12	-0.22	0.46	0.65	0.43	0.34	0.74	0.78
Corrosion rate-270 days	-0.56	-0.64	0.33	0.32	0.76	0.73	0.48	0.42
Corrosion rate-365 days	-0.37	-0.43	0.15	0.17	0.80	0.66	0.38	0.52

4. Conclusions

The current study investigated influences of water-to-cementitious materials ratio, cementitious materials content and supplementary cementitious materials on the transport properties and corrosion rate of reinforcement in vibratory-placed concrete through testing reinforced concrete mixes having w/cm of 0.4 and 0.5, silica fume and natural zeolite as SCMs, and total cementitious materials content of 325 and 400 kg/m^3. From the observations of this study, the following conclusions can be drawn:

- Overall, w/cm ratio and supplementary cementitious materials were more influential on the transport properties of the selected mixes compared to cementitious materials content. The studied transport properties (i.e. water absorption, water penetration depth and rapid chloride penetration) considerably improved by reduction of w/cm ratio and use of supplementary cementitious materials. Increases in cementitious materials content slightly reduced the water penetration depth of the selected concretes and increased water absorption and passing charges in rapid chloride penetration test.
- The corrosion rate of reinforcement significantly decreased through reduction of w/cm ratio and use of supplementary cementitious materials. These improvements were more significant when w/cm decreased than when SCMs were included. Increase in cement content increased the corrosion rate of reinforcement.
- The corrosion rate of reinforcement showed direct relationship with the measured transport properties. The relationships, however, were not strong enough to be used as direct indices for prediction of corrosion rate of reinforcement in concrete.

5. Acknowledgment

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