



Four-years carbonation and chloride induced steel corrosion of sulfate-contaminated aggregates concrete

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HIGHLIGHTS

- Effect of using sulfate contaminated aggregate on corrosion resistance were studied.
- The work extended to four years.
- Sulfate cation and content significantly affected on corrosion resistance.
- Porosity/compressive strength–corrosion resistance relations were established.

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ABSTRACT

This paper presents an experimental work of a four-years study on the corrosion resistance of concrete made of sulfate contaminated aggregates. The study involved both carbonation and chloride induced corrosion. The studied parameters include effects of sulfate cation (sodium, calcium and magnesium sulfates) and sulfate content in addition to water-to-cement ratio, cement content and cement type. Concrete porosity and concrete compressive strength were used to analyze the corrosion resistance. From the test results, for carbonation induced corrosion, the four-years carbonation depth influenced by sulfate content and cation where magnesium sulfate yielded highest carbonation depth compared with those of studied cations. Using low water cement ratio, high cement content and use of Type V cement reduced the four-years carbonation depth. Also, carbonation rate was almost proportional with concrete porosity and concrete compressive strength. The porosity–carbonation rate and concrete compressive strength were sulfate cation and sulfate content dependent. For chloride induced corrosion in terms of steel reinforcement weight loss, the use of sulfate contaminated aggregate negatively affected the chloride induced corrosion. Low water cement ratio, high cement content and use of Type V Portland cement decreased the steel weight loss. Finally, there was a direct relation between concrete porosity/concrete compressive strength and steel weight loss but these relations were sulfate content and sulfate cation independent.

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1. Introduction and research significance

During the service life of reinforced concrete structures, they are subject to several different aggressive agents. These agents include sulfates, chlorides, seawater, wetting and drying and freezing and thawing. Many researches were conducted to study the effect of different previous conditions on the performance of concrete itself or on reinforced concrete elements [1–10].

Sulfate ions in solution state from the surrounding soil or water are considered very harmful substances as results of the expansive chemical products, gypsum and ettringite, which causing cracking and more sulfate ingress. The nature of chemical products depends

of the cation of sulfate ions. Sodium, magnesium, calcium and potassium are considered the most common sulfate cations. The sulfate-related expansions in concrete are associated with ettringite and gypsum formation. This expansion causes cracking, stiffness loss and strength loss [11].

Corrosion of reinforced steel in concrete structures is considered the most significant deterioration process affecting on the safety of concrete structures [12]. Reinforcement in concrete structures is protected against corrosion when embedder into alkaline (12–12.5 pH) and free chloride concrete. The corrosion of steel reinforcement may be initiated due to the carbonation (loss of alkalinity) of concrete reaching the level of steel reinforcement (carbonation-induced corrosion) or may be due to the ingress of chlorides at a certain threshold level (chloride-induced corrosion) [1,11,13].

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Table 1
Chemical composition of used cement.

	Type I	Type V
Silicon dioxide (%)	18.9	20.2
Aluminum Oxide (%)	5.1	3.4
Ferric Oxide (%)	3.1	5.3
Calcium Oxide (%)	63.3	62.9
Magnesium Oxide (%)	2.1	2.7
Sulfur Trioxide (%)	3.2	2.1
C ₃ A (%)	8.27	0.17

Concrete carbonation is a chemical reaction between penetrated carbon dioxide and calcium hydroxide (alkaline cement hydration product). This reaction reduces the concrete alkalinity and thus will destroy the passive film initially-formed around steel bars. This process leads to initiate the steel corrosion [14,15].

Chloride-induced corrosion is considered the most serious type of concrete structure deterioration. Corrosion is an electrochemical reaction occurs when there is a difference in electrical potential along the steel in concrete. This electrochemical reaction forms an electrochemical cell consisting of anode, cathode and electrolyte. Sequent reactions occur at the anode and cathode and thus convert the metallic iron to rust. [1,11]. The presence of chloride

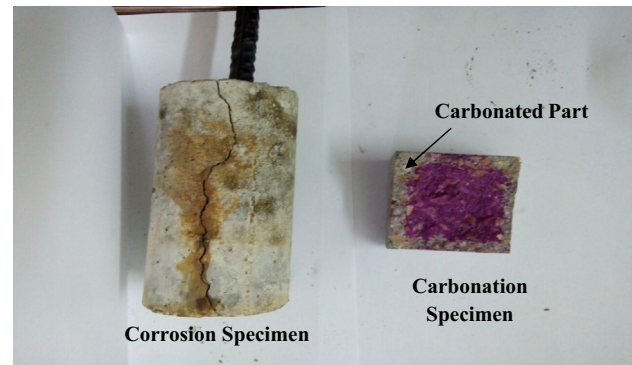


Fig. 1. Carbonation and corrosion specimens.

ions activates the surface of steel to form anode. Also, the presence of chloride ions increases the Cl^-/OH^- molar ratio which may reach to a value that able to destroy the steel bar surrounding passive film [1,11–13].

Most building codes as ACI 318 [16] and Egyptian code (ECP 203) [17], proposed some consideration to produce a more durable

Table 2
Mix proportions of used concrete mixes.

Mix No.	Cement Type	W/C	Sulfate Cation	Sulfate % SO_3	Cement (kg)	Water (kg)	Sand (kg)	Coarse Agg. (kg)	Weight of sulfate (kg)	Admixture
1	Type I	0.50	–	0.0	350	175	885	885	0.0	1.750
2	Type I	0.50	Na	0.2	350	175	885	885	6.284	1.750
3	Type I	0.50	Na	0.4	350	175	885	885	12.567	1.750
4	Type I	0.50	Na	0.6	350	175	885	885	18.851	1.750
5	Type I	0.50	Na	1.0	350	175	885	885	31.418	1.750
6	Type I	0.50	Mg	0.2	350	175	885	885	10.886	1.750
7	Type I	0.50	Mg	0.4	350	175	885	885	21.771	1.750
8	Type I	0.50	Mg	0.6	350	175	885	885	32.657	1.750
9	Type I	0.50	Mg	1.0	350	175	885	885	54.428	1.750
10	Type I	0.50	Ca	0.2	350	175	885	885	6.416	1.750
11	Type I	0.50	Ca	0.4	350	175	885	885	12.833	1.750
12	Type I	0.50	Ca	0.6	350	175	885	885	19.249	1.750
13	Type I	0.50	Ca	1.0	350	175	885	885	32.081	1.750
Mix No.	Cement Type	W/C	Sulfate Cation	Sulfate %	Cement (kg)	Water (kg)	Sand (kg)	Coarse Agg. (kg)	Weight of sulfate (kg)	Admixture
14	Type V	0.50	–	0.0	350	175	885	885	0.0	1.750
15	Type V	0.50	Na	0.4	350	175	885	885	12.567	1.750
16	Type V	0.50	Na	1.0	350	175	885	885	31.418	1.750
17	Type V	0.50	Mg	0.4	350	175	885	885	21.771	1.750
18	Type V	0.50	Mg	1.0	350	175	885	885	54.428	1.750
19	Type V	0.50	Ca	0.4	350	175	885	885	12.833	1.750
20	Type V	0.50	Ca	1.0	350	175	885	885	32.081	1.750
Mix No.	Cement Type	W/C	Sulfate Cation	Sulfate %	Cement (kg)	Water (kg)	Sand (kg)	Coarse Agg. (kg)	Weight of sulfate (kg)	Admixture
21	Type I	0.50	–	0.0	450	225	820	820	0.0	2.250
22	Type I	0.50	Na	0.4	450	225	820	820	11.644	2.250
23	Type I	0.50	Na	1.0	450	225	820	820	29.110	2.250
24	Type I	0.50	Mg	0.4	450	225	820	820	20.172	2.250
25	Type I	0.50	Mg	1.0	450	225	820	820	50.430	2.250
26	Type I	0.50	Ca	0.4	450	225	820	820	11.890	2.250
27	Type I	0.50	Ca	1.0	450	225	820	820	29.725	2.250
Mix No.	Cement Type	W/C	Sulfate Cation	Sulfate %	Cement (kg)	Water (kg)	Sand (kg)	Coarse Agg. (kg)	Weight of sulfate (kg)	Admixture
28	Type I	0.40	–	0.0	350	140	900	900	0.0	1.750
29	Type I	0.40	Na	0.4	350	140	900	900	12.780	1.750
30	Type I	0.40	Na	1.0	350	140	900	900	31.950	1.750
31	Type I	0.40	Mg	0.4	350	140	900	900	22.140	1.750
32	Type I	0.40	Mg	1.0	350	140	900	900	55.350	1.750
33	Type I	0.40	Ca	0.4	350	140	900	900	13.050	1.750
34	Type I	0.40	Ca	1.0	350	140	900	900	32.625	1.750

Example for calculating the required weight of sulfates (mix 5 as an example).

$\text{SO}_3 = 1.0\%$ (0.01), Weight of aggregates (coarse and fine) = 1770 kg.

Weight of $\text{SO}_3 = 1770 \times 0.01 = 17.70$ kg.

The molecular weight of sodium sulfate is 142 g/mole and molecular weight of SO_3 is 80 g/mole.

Thus, the weight of sodium sulfate = $17.70 \times (142/80) = 31.418$ kg.

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