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

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• 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.

#### ARTICLE INFO

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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.

	Туре І	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 <sub>3</sub> 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 2Mix proportions of used concrete mixes.

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     0.6     350     175     885     885     11.851     1.750       4     Type I     0.50     Na     0.6     350     175     885     885     11.418     1.750       6     Type I     0.50     Mg     0.2     350     175     885     885     12.871     1.750       8     Type I     0.50     Mg     0.6     350     175     885     885     54.428     1.750       9     Type I     0.50     Ca     0.2     350     175     885     885     12.837     1.750       11     Type I     0.50     Ca     0.6     350     175     885     885     12.867     1.750	Mix No.	Cement Type	W/C	Sulfate Cation	Sulfate % SO <sub>3</sub>	Cement (kg)	Water (kg)	Sand (kg)	Coarse Agg. (kg)	Weight of sulfate (kg)	Admixture
2     Type I     0.50     Na     0.2     350     175     885     885     6.284     1.750       3     Type I     0.50     Na     0.66     350     175     885     885     1.2657     1.750       5     Type I     0.50     Na     1.0     350     175     885     885     31.418     1.750       6     Type I     0.50     Mg     0.4     350     175     885     885     31.418     1.750       7     Type I     0.50     Mg     0.4     350     175     885     885     34.428     1.750       8     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     12.833     1.750       11     Type I     0.50     Ca     0.6     350     175     885     885     0.0     1.750 <td>1</td> <td>Type I</td> <td>0.50</td> <td>_</td> <td>0.0</td> <td>350</td> <td>175</td> <td>885</td> <td>885</td> <td>0.0</td> <td>1.750</td>	1	Type I	0.50	_	0.0	350	175	885	885	0.0	1.750
3     Type I     0.50     Na     0.4     350     175     885     885     1.2.567     1.750       5     Type I     0.50     Na     1.0     350     175     885     885     18.851     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     Ca     0.2     350     175     885     885     12.833     1.750       11     Type I     0.50     Ca     0.6     350     175     885     885     12.833     1.750       13     Type I     0.50     Ca     0.6     350     175     885     885     12.081     1.750	2	Type I	0.50	Na	0.2	350	175	885	885	6.284	1.750
4     Type I     0.50     Na     0.6     350     175     885     885     11.851     1.750       5     Type I     0.50     Mg     0.2     350     175     885     885     10.886     1.750       7     Type I     0.50     Mg     0.6     350     175     885     885     1.0286     1.750       8     Type I     0.50     Mg     0.6     350     175     885     885     3.2657     1.750       9     Type I     0.50     Ca     0.2     350     175     885     885     5.4428     1.750       10     Type I     0.50     Ca     0.4     350     175     885     885     12.833     1.750       11     Type I     0.50     Ca     0.4     350     175     885     885     12.049     1.750       13     Type V     0.50     -     0.0     350     175     885     885     12.667     1.750	3	Type I	0.50	Na	0.4	350	175	885	885	12.567	1.750
5     Type I     0.50     Na     1.0     350     175     885     885     31.418     1.750       6     Type I     0.50     Mg     0.4     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     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     0.6     350     175     885     885     12.833     1.750       13     Type I     0.50     Ca     0.6     350     175     885     885     0.0     1.750       14     Type V     0.50     Na     0.4     350     175     885     885     12.667     1.750 </td <td>4</td> <td>Type I</td> <td>0.50</td> <td>Na</td> <td>0.6</td> <td>350</td> <td>175</td> <td>885</td> <td>885</td> <td>18.851</td> <td>1.750</td>	4	Type I	0.50	Na	0.6	350	175	885	885	18.851	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       9     Type I     0.50     Mg     0.6     350     175     885     885     32.657     1.750       9     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     1.2833     1.750       12     Type I     0.50     Ca     0.6     350     175     885     885     1.2833     1.750       13     Type V     0.50     Ca     0.6     350     175     885     885     0.0     1.750       14     Type V     0.50     Na     0.4     350     175     885     885     1.771     1.750 <td>5</td> <td>Туре І</td> <td>0.50</td> <td>Na</td> <td>1.0</td> <td>350</td> <td>175</td> <td>885</td> <td>885</td> <td>31.418</td> <td>1.750</td>	5	Туре І	0.50	Na	1.0	350	175	885	885	31.418	1.750
7     Type I     0.50     Mg     0.4     350     175     885     885     21.71     1.750       8     Type I     0.50     Mg     0.6     350     175     885     885     32.657     1.750       9     Type I     0.50     Ca     0.2     350     175     885     885     54.428     1.750       10     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     12.833     1.750       13     Type V     0.50     Ca     1.0     350     175     885     885     32.081     1.750       14     Type V     0.50     -     0.0     350     175     885     885     12.567     1.750       15     Type V     0.50     Na     1.0     350     175     885     885     12.483     1.750	6	Туре І	0.50	Mg	0.2	350	175	885	885	10.886	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     12.833     1.750       11     Type I     0.50     Ca     0.6     350     175     885     885     12.833     1.750       13     Type I     0.50     Ca     0.6     350     175     885     885     32.081     1.750       14     Type V     0.50     Ca     0.0     350     175     885     885     0.0     1.750       15     Type V     0.50     Na     0.4     350     175     885     885     31.418     1.750       16     Type V     0.50     Ma     1.0     350     175     885     885     54.428     1.750	7	Туре І	0.50	Mg	0.4	350	175	885	885	21.771	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     0.6     350     175     885     885     12.833     1.750       12     Type I     0.50     Ca     0.6     350     175     885     885     12.833     1.750       13     Type I     0.50     Ca     0.0     350     175     885     885     0.0     1.750       14     Type V     0.50     A     0.0     350     175     885     885     0.0     1.750       15     Type V     0.50     Na     0.4     350     175     885     885     12.471     1.750       16     Type V     0.50     Mg     0.4     350     175     885     885     12.471     1.750 <td>8</td> <td>Туре І</td> <td>0.50</td> <td>Mg</td> <td>0.6</td> <td>350</td> <td>175</td> <td>885</td> <td>885</td> <td>32.657</td> <td>1.750</td>	8	Туре І	0.50	Mg	0.6	350	175	885	885	32.657	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     Na     0.4     350     175     885     885     1.1418     1.750       15     Type V     0.50     Na     1.0     350     175     885     885     31.418     1.750       17     Type V     0.50     Ga     0.4     350     175	9	Туре І	0.50	Mg	1.0	350	175	885	885	54.428	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     19.249     1.750       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     12.67     1.750       16     Type V     0.50     Na     0.4     350     175     885     885     12.833     1.750       17     Type V     0.50     Mg     1.0     350     175     885     885     12.833     1.750       18     Type V     0.50     Ca     0.4     350     175     885     885     32.081     1.750	10	Туре І	0.50	Ca	0.2	350	175	885	885	6.416	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     31.418     1.750       16     Type V     0.50     Mg     0.4     350     175     885     885     21.771     1.750       18     Type V     0.50     Ca     0.4     350     175     885     885     32.081     1.750       19     Type V     0.50     Ca     1.0     350     175 <t< td=""><td>11</td><td>Туре І</td><td>0.50</td><td>Ca</td><td>0.4</td><td>350</td><td>175</td><td>885</td><td>885</td><td>12.833</td><td>1.750</td></t<>	11	Туре І	0.50	Ca	0.4	350	175	885	885	12.833	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     31.418     1.750       16     Type V     0.50     Ma     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     Ca     0.4     350     175     885     885     32.081     1.750       20     Type V     0.50     Ca     0.4     350     175 <t< td=""><td>12</td><td>Туре І</td><td>0.50</td><td>Ca</td><td>0.6</td><td>350</td><td>175</td><td>885</td><td>885</td><td>19.249</td><td>1.750</td></t<>	12	Туре І	0.50	Ca	0.6	350	175	885	885	19.249	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     1.2567     1.750       16     Type V     0.50     Mg     0.4     350     175     885     885     31.418     1.750       17     Type V     0.50     Mg     1.0     350     175     885     885     21.771     1.750       18     Type V     0.50     Ca     0.4     350     175     885     885     32.081     1.750       20     Type V     0.50     Ca     0.0     450     225     820     800     0.0     2.250       21     Type I     0.50     Na     0.4     450     225     8	13	Туре І	0.50	Ca	1.0	350	175	885	885	32.081	1.750
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     Mg     0.4     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     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     Na     0.4     450     225 <t< td=""><td>Mix No.</td><td>Cement Type</td><td>W/C</td><td>Sulfate Cation</td><td>Sulfate %</td><td>Cement (kg)</td><td>Water (kg)</td><td>Sand (kg)</td><td>Coarse Agg. (kg)</td><td>Weight of sulfate (kg)</td><td>Admixture</td></t<>	Mix No.	Cement Type	W/C	Sulfate Cation	Sulfate %	Cement (kg)	Water (kg)	Sand (kg)	Coarse Agg. (kg)	Weight of sulfate (kg)	Admixture
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     21.771     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       21     Type V     0.50     Ca     0.4     450     225     820     820     0.0     2.250       22     Type I     0.50     Na     1.0     450     225     820     820     20.172     2.250	14	Type V	0.50	-	0.0	350	175	885	885	0.0	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       20     Type V     0.50     Ca     1.0     350     175     885     885     32.081     1.750       21     Type V     0.50     Ca     1.0     450     225     820     820     11.644     2.250       22     Type I     0.50     Mg     1.0     450     225     820     820     20.172     2.250 <td>15</td> <td>Type V</td> <td>0.50</td> <td>Na</td> <td>0.4</td> <td>350</td> <td>175</td> <td>885</td> <td>885</td> <td>12.567</td> <td>1.750</td>	15	Type V	0.50	Na	0.4	350	175	885	885	12.567	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     11.644     2.250       23     Type I     0.50     Na     1.0     450     225     820     820     20.172     2.250       24     Type I     0.50     Mg     1.0     450     225	16	Type V	0.50	Na	1.0	350	175	885	885	31.418	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       20     Type V     0.50     Ca     1.0     350     175     885     885     32.081     1.750       20     Type V     0.50     Ca     1.0     350     175     885     885     32.081     1.750       20     Type V     0.50     Ca     0.0     450     225     820     820     0.0     2.250       22     Type I     0.50     Na     1.0     450     225     820     820     20.172     2.250       24     Type I     0.50     Mg     1.0     450     225     820     820     50.430     2.250	17	Type V	0.50	Mg	0.4	350	175	885	885	21.771	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       23     Type I     0.50     Na     0.4     450     225     820     820     20.172     2.250       24     Type I     0.50     Mg     0.4     450     225     820     820     20.172     2.250       25     Type I     0.50     Mg     0.4     450     225     820     820     20.172     2.250       26     Type I     0.50     Ca     0.4     450     225 <t< td=""><td>18</td><td>Type V</td><td>0.50</td><td>Mg</td><td>1.0</td><td>350</td><td>175</td><td>885</td><td>885</td><td>54.428</td><td>1.750</td></t<>	18	Type V	0.50	Mg	1.0	350	175	885	885	54.428	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     20.116     2.250       23     Type I     0.50     Na     1.0     450     225     820     820     20.172     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     211.890     2.250       26     Type I     0.50     Ca     1.0     450     225     <	19	Type V	0.50	Ca	0.4	350	175	885	885	12.833	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     20.172     2.250       26     Type I     0.50     Ca     0.4     450     225     820     820     29.725     2.250       27     Type I     0.50     Ca     1.0     450     225 <t< td=""><td>20</td><td>Type V</td><td>0.50</td><td>Ca</td><td>1.0</td><td>350</td><td>175</td><td>885</td><td>885</td><td>32.081</td><td>1.750</td></t<>	20	Type V	0.50	Ca	1.0	350	175	885	885	32.081	1.750
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       24     Type I     0.50     Mg     1.0     450     225     820     820     20.172     2.250       25     Type I     0.50     Ca     0.4     450     225     820     820     11.890     2.250       26     Type I     0.50     Ca     1.0     450     225     820     820     29.725     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
22     Type I     0.50     Na     0.4     450     225     820     820     1.644     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     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     1.890     2.250       27     Type I     0.50     Ca     1.0     450     225     820     820     29.725     2.250       28     Type I     0.40     -     0.0     350     140     900     900     0.0     1.750	21	Туре І	0.50	-	0.0	450	225	820	820	0.0	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   50.430   2.250     26   Type I   0.50   Ca   0.4   450   225   820   820   29.725   2.250     27   Type I   0.50   Ca   1.0   450   225   820   820   29.725   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	22	Type I	0.50	Na	0.4	450	225	820	820	11.644	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     1.750     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	23	Type I	0.50	Na	1.0	450	225	820	820	29.110	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       30     Type I     0.40     Na     1.0     350     140     900     900     31.950     1.750       31     Type I     0.40     Na     1.0     350     140     900     900     22.140     1.750       32     Type I     0.40     Mg     0.4     350     140 <t< td=""><td>24</td><td>Type I</td><td>0.50</td><td>Mg</td><td>0.4</td><td>450</td><td>225</td><td>820</td><td>820</td><td>20.172</td><td>2.250</td></t<>	24	Type I	0.50	Mg	0.4	450	225	820	820	20.172	2.250
26     Type I     0.50     Ca     0.4     450     225     820     820     1.890     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       30     Type I     0.40     Na     1.0     350     140     900     900     12.780     1.750       31     Type I     0.40     Na     1.0     350     140     900     900     22.140     1.750       32     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 <td< td=""><td>25</td><td>Туре І</td><td>0.50</td><td>Mg</td><td>1.0</td><td>450</td><td>225</td><td>820</td><td>820</td><td>50.430</td><td>2.250</td></td<>	25	Туре І	0.50	Mg	1.0	450	225	820	820	50.430	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	26	Туре І	0.50	Ca	0.4	450	225	820	820	11.890	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	27	Туре І	0.50	Ca	1.0	450	225	820	820	29.725	2.250
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	Mix No.	Cement Type	W/C	Sulfate Cation	Sulfate %	Cement (kg)	Water (kg)	Sand (kg)	Coarse Agg. (kg)	Weight of sulfate (kg)	Admixture
29Type I0.40Na0.435014090090012.7801.75030Type I0.40Na1.035014090090031.9501.75031Type I0.40Mg0.435014090090022.1401.75032Type I0.40Mg1.035014090090055.3501.750	28	Туре І	0.40	-	0.0	350	140	900	900	0.0	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	29	Туре І	0.40	Na	0.4	350	140	900	900	12.780	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	30	Туре І	0.40	Na	1.0	350	140	900	900	31.950	1.750
32 Type I 0.40 Mg 1.0 350 140 900 900 55.350 1.750	31	Туре І	0.40	Mg	0.4	350	140	900	900	22.140	1.750
	32	Туре І	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	33	Туре І	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	34	Туре І	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).

 $SO_3 = 1.0\%$  (0.01), Weight of aggregates (coarse and fine) = 1770 kg.

Weight of  $SO_3 = 1770 \times 0.01 = 17.70$  kg.

The molecular weight of sodium sulfate is 142 g/mole and molecular weight of SO<sub>3</sub> is 80 g/mole.

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

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