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Estimating of long term concrete magnesium sulfate resistance up to 450 days depending on cement impact and water cement ratio

Ahmed M. Diab[#1], Hafez E. Elyamany[*2], Abd Elmoaty M. Abd Elmoaty[#3], Ali H. Shalan[*4]
[#]*Structural Engineering Department, Faculty of Engineering, Alexandria University, Egypt*

Abstract—Sulfate attack is a complex form of deterioration that has damaged concrete structures throughout the world. Sulfate attack is particularly complex because the source of sulfates can be external or internal. The sulfate resistance of concretes containing different cement contents, water cement ratios, and C_3A percentages is investigated in which concrete specimens were subjected to magnesium sulfate solution up to 450 days. Three cement contents as 350, 400, and 450 kg/m^3 were used at different three water cement ratios (0.40, 0.50, 0.60) and three C_3A percentages (4.24%, 6.87%, 10.84%). Concrete sulfate resistance was estimated based on measurement of four different mechanical properties; cube compressive strength, tensile strength, modulus of elasticity, and linear expansion strain. These mechanical properties were measured after different sulfate attack periods; 28, 60, 100, 200, and 350 days. Results of this study show that cement content increasing improved concrete sulfate resistance when the concrete is subjected to sulfate attack. Moreover, concrete with high water cement ratios, and C_3A percentages showed low sulfate resistance. Concrete with low water cement ratios, and C_3A percentages provides an good performance for sulfate resistance.

Keywords: sulfate attack, C_3A percentage, magnesium sulfate, strength loss

I. INTRODUCTION

'Sulfate attack' was defined by Mehta as 'the deterioration of concrete as a result of physical-chemical interactions between the minerals in hydrated Portland cement paste and sulfate from environment' [1]. The interactions cause expansion, cracking, spalling or even disintegration of concrete. It may be noted by Neville that external sulfate attack, sometimes referred to as the "classical form of sulfate attack" is quite complex and still not fully understood [2]. The complexity of sulfate attack begins first with the variety of sulfates that can damage concrete. The most common sulfates that interact with concrete are calcium, sodium, and magnesium sulfate, which are listed in order of their aggressiveness [3]. Each of these sulfate forms are discussed separately in many references, but magnesium sulfates should bear in mind that it is common to find present in groundwater or soil [4].

Magnesium sulfate is the most complex of the three types of sulfates. It can react with all hydrated cement products and is generally considered to be the most damaging form of sulfate. Magnesium sulfate will react with calcium silicate to form gypsum plus magnesium hydroxid and a silica gel. This formation of magnesium hydroxide (brucite) is known to form a barrier which may provide protection to the concrete and it also tends to internally affect pore solution pH. Brucite formation does have its downfall in that it needs a high amount of calcium hydroxide to form. Once the CH is depleted, the magnesium sulfate will seek more calcium. In this case, decalcification of the C-S-H will occur, due to a removal of calcium as mentioned by Gollop and Taylor [5].

Several factors affect the resistance of concrete to sulfate attack. These factors include the chemistry of the cementitious material, and the permeability of the concrete. Based on the environment established by these factors, the engineer must control sulfate attack by controlling these factors – the properties of concrete. This section reviews couple of major concrete properties that influence concrete sulfate resistance. These properties are the chemistry of the Portland cement, and the permeability of the concrete based on water cement ratio value. The concrete characteristic with the greatest impact on sulfate resistance is generally considered to be the chemistry of the Portland cement that has a direct impact on the chemical reactions that cause sulfate attack. The C_3A percentage controls the amount of monosulfo aluminate available to form ettringite in hardened concrete resulting in expansive internal volume changes and the damage that characterizes sulfate attack [4].

In 1949, the Portland Cement Association (PCA) published a report of long, Long time study of cement performance in concrete, that evaluated two factors influencing sulfate resistance; cement content, and C_3A content in cement [4]. The research showed that concrete made with cements having C_3A contents grater than 7.0% performed poorly while concrete with cements having C_3A contents of 7.0% or lower performed well. Further studies were conducted to distinguish between good and excellent performance of concrete as a function of the cement [5]. PCA research showed that for concrete made with rich cement contents, mixes containing cements with 5.50% C_3A as corrected for minor oxides exhibited better performance that other high cement content concrete.

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When sulfate attack was first identified in 1908 by the United States Bureau of Reclamations (USBR), the only means of controlling the attack was by producing low permeability concrete [6]. Industry low permeability concrete can be produced by reducing the water cement ratio and/or increasing the cement content. The goal of using low permeability concrete is to minimize the penetration of sulfate ions into the concrete. Keeping the sulfate ion concentration in the hardened concrete low prevents the deleterious formation of ettringite from monosulfo aluminate [7].

II. PROPERTIES OF USED MATERIALS

Three types of cement were used in this research work. These types were ordinary Portland cement (Type I), modified Portland cement (Type II), and sulfate resisting Portland cement (Type V). The chemical compositions for each type are presented in Table 1. The used sand was natural siliceous sand of 2.70 fineness modulus. Crushed pink limestone of 3/16" nominal maximum size was used. These aggregates fulfill the limits of ASTM [8]. Superplasticizer Type F according to ASTM C 494 [9] was used in concrete mixes to achieve a constant slump for concrete as 12cm ± 2. Potable water was used for mixing and curing for all concrete specimens.

TABLE 1: CHEMICAL ANALYSIS OF CEMENTS

Cement	Calcium oxide	Silicon dioxide	Sulfur trioxide	Aluminum oxide	Ferric oxide	C_3S	C_2S	C_3A	C_4AF
Type I	61.6	20.6	2.11	6.90	4.40	35.50	27.75	10.84	13.38
Type II	56	20.07	2.46	5.40	4.40	31.51	32.79	6.87	13.38
Type V	61.2	21.44	2.16	3.26	2.60	54.37	15.82	4.24	7.91

III. STUDIED PARAMETERS AND TESTS

Twenty-seven concrete mixes was used to detect the magnesium sulfate ions concentration that diffuses in concrete up to 450 days. Table 2 shows the mix proportions of the verification experimental program that will be performed. In this stage, the considered parameters were:

a- Cement Type: Three cement types with 4.24, 6.87, and 10.84% C_3A percentage were used.

b- Cement content: Three cement contents were considered as 350, 400 and 450 kg/m^3.

c- Water cement ratio: Three water cement ratio (0.40, 0.50, and 0.60) were used for all cement contents.

Concrete specimens were subjected to 5.0% magnesium sulfate solution concentration after curing age. The sulfate solution was replaced every 3 weeks to keep constant pH value. A compressive strength test was also carried out to evaluate the effect of magnesium sulfate attack after 28, 60, 100, 200, and 350 days using three cubes of 70.7×70.7×70.7 mm for each age. A splitting tensile strength test was also carried out to evaluate the effect of magnesium sulfate attack according to ASTM C 496M-11 [10]. The tensile strength is determined after 28, 60, 100, 200, and 350 days of magnesium sulfate attack using three cylinders of 100 mm diameter and 200 mm length for each age. The static modulus of elasticity test was carried out along the time of magnesium sulfate attack at ages 28, 60, 100, 200 and 350 days according to ASTM C 469-02 [11]. Three cylinder specimens of 100 mm diameter and 200 mm length were used for each age. Length change according to ASTM C157-80, [12] was carried out to evaluate the expansion of cement paste and concrete due to magnesium sulfate attack. The length change was measured along the time of immersion in 5.0% magnesium sulfate attack up to 450 days. Two prisms of 70.0×70.0×285 mm dimension for concrete specimens were considered.

TABLE 2: MIX PROPORTIONS FOR MAGNESIUM SULFATE IONS DIFFUSION IN CONCRETE

Mix No.	C1	C2	C3	C4	C5	C6	C7	C8	C9
Cement Content	350 (Kg/m^3)			350 (Kg/m^3)			350 (Kg/m^3)		
W/C	0.40			0.50			0.60		
C_3A (%)	4.24	6.87	10.84	4.24	6.87	10.84	4.24	6.87	10.84
Mix No.	C10	C11	C12	C13	C14	C15	C16	C17	C18
Cement Content	400 (Kg/m^3)			400 (Kg/m^3)			400 (Kg/m^3)		
W/C	0.40			0.50			0.60		
C_3A (%)	4.24	6.87	10.84	4.24	6.87	10.84	4.24	6.87	10.84
Mix No.	C19	C20	C21	C22	C23	C24	C25	C26	C27
Cement Content	450 (Kg/m^3)			450 (Kg/m^3)			450 (Kg/m^3)		
W/C	0.40			0.50			0.60		
C_3A (%)	4.24	6.87	10.84	4.24	6.87	10.84	4.24	6.87	10.84

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IV. TESTS RESULTS AND DISCUSSION

The concrete resistance against sulfate attack is affected by concrete composition; cement content, water cement ratio, and C_3A percentage. This resistance of concrete is evaluated herein by different methods; compressive strength test, tensile strength test, static modulus of elasticity, and linear expansion. The tests were performed during sulfate attack at a certain time of all mixes. Concrete specimens were tested after 28, 60, 100, 200, and 350 days of magnesium sulfate exposure. The results of these tests are presented in Table 3, 4, and 5.

TABLE 3
CUBE COMPRESSIVE STRENGTH FOR CONCRETE AT DIFFERENT EXPOSURE AGES

Mix	Cement Content (Kg/m^3)	w/c	C_3A (%)	Cube Compressive Strength at Different Exposure Ages (MPa)				
				28 days	60 days	100 days	200 days	350 days
C1	350	0.40	4.24	47.72	45.44	44.07	42.12	40.84
C2			6.87	37.73	35.68	34.64	32.96	31.71
C3			10.84	31.49	29.45	28.44	26.80	25.07
C4		0.50	4.24	38.00	36.00	35.00	33.00	31.72
C5			6.87	32.00	30.00	29.00	27.00	26.00
C6			10.84	29.00	27.00	26.00	24.00	23.00
C7		0.60	4.24	35.35	33.20	31.11	29.53	28.24
C8			6.87	27.89	25.95	24.17	23.03	21.40
C9			10.84	25.69	23.73	21.94	20.40	18.41
C10	400	0.40	4.24	54.00	52.00	51.00	48.50	47.00
C11			6.87	46.00	44.00	43.00	41.50	40.00
C12			10.84	38.00	36.00	35.00	33.50	32.00
C13		0.50	4.24	43.00	41.20	40.50	38.00	36.50
C14			6.87	39.01	37.00	36.00	34.00	32.80
C15			10.84	35.00	33.00	32.00	30.00	29.35
C16		0.60	4.24	40.00	38.00	36.00	34.00	32.50
C17			6.87	34.00	32.00	30.00	29.00	27.00
C18			10.84	31.00	29.00	27.00	25.50	23.50
C19	450	0.40	4.24	67.81	66.89	64.85	62.54	60.52
C20			6.87	57.78	57.08	54.94	53.10	51.83
C21			4.24	43.43	42.55	40.47	39.08	37.07
C22		0.50	6.87	54.00	53.00	51.50	49.00	47.00
C23			10.84	49.00	48.00	46.00	43.50	42.50
C24			6.87	40.00	39.00	37.00	35.00	34.00
C25		0.60	4.24	50.23	48.88	45.78	43.84	41.85
C26			6.87	42.71	41.51	38.33	37.10	34.98
C27			10.84	35.43	34.27	31.22	29.75	27.22

TABLE 4
TENSILE STRENGTH FOR CONCRETE AT DIFFERENT EXPOSURE AGES

Mix	Cement Content (Kg/m^3)	w/c	C_3A (%)	Tensile Strength (MPa)				
				28 days	60 days	100 days	200 days	350 days
C4	350	0.50	4.24	4.30	3.90	3.60	3.40	3.20
C5			6.87	3.60	3.20	2.90	2.80	2.60
C6			10.84	3.20	2.80	2.50	2.40	2.25
C10	400	0.40	4.24	5.20	5.00	4.80	4.50	4.30
C11			6.87	4.70	4.50	4.30	4.10	3.80
C12			10.84	4.20	3.90	3.70	3.50	3.30
C13		0.50	4.24	4.84	4.50	4.25	4.00	3.89

C14			6.87	4.00	3.60	3.37	3.22	3.10
C15			10.84	3.70	3.20	3.00	2.85	2.70
C16			4.24	4.40	4.00	3.70	3.40	3.20
C17		0.60	6.87	3.60	3.10	2.90	2.70	2.58
C18			10.84	3.20	2.70	2.50	2.30	2.25
C25			4.24	5.60	5.30	5.10	4.80	4.60
C26	450	0.60	6.87	4.80	4.40	4.20	4.00	3.80
C27			10.84	4.20	3.90	3.60	3.40	3.20

TABLE 5

MODULUS OF ELASTICITY FOR CONCRETE AT DIFFERENT EXPOSURE AGES

Mix	Cement Content (Kg/m^3)	w/c	C_3A (%)	Modulus pf Elasticity (GPa)				
				28 days	60 days	100 days	200 days	350 days
C4			4.24	37.00	36.00	35.00	34.00	33.00
C5	350	0.50	6.87	36.00	34.50	32.50	31.00	30.80
C6			10.84	35.00	33.00	32.00	31.00	30.00
C10			4.24	44.00	43.50	43.00	42.40	42.00
C11		0.40	6.87	42.50	41.50	41.00	40.00	39.50
C12			10.84	41.00	40.00	39.00	38.50	38.00
C13			4.24	40.00	39.50	38.70	38.00	37.00
C14	400	0.50	6.87	38.40	37.00	35.50	34.00	33.10
C15			10.84	37.00	35.70	34.00	32.94	32.00
C16			4.24	38.00	37.00	36.00	35.00	34.00
C17		0.60	6.87	36.00	34.50	33.50	31.50	30.80
C18			10.84	35.00	33.00	32.00	30.50	29.80
C25			4.24	44.50	44.00	43.50	43.00	42.00
C26	450	0.60	6.87	43.50	42.50	42.00	41.00	40.00
C27			10.84	42.50	41.50	40.50	39.50	38.50

A. Effect of Cement Content

The effect of cement content on different concrete mechanical properties due to magnesium sulfate attack is presented in this section. The mechanical properties include cube compressive strength, tensile strength, modulus of elasticity, and linear expansion. These results for concrete mechanical properties are presented in Figures 1, 2, 3, 4, 5 and 6. Figure 3 shows the effect of cement content on concrete compressive strength loss due to sulfate attack for different water cement ratios, and different C_3A contents at 28, 60, 100, 200, and 350 days of magnesium sulfate exposure. From this figure, it is clear that the increase in cement content has a positive effect on concrete magnesium sulfate resistance. As an example, for concrete mixes made with 4.24% C_3A percentage as shown in Figure 3-a, the cube compressive strength loss for concrete mixes with 0.50 w/cm ratio at 200 days is about 13.16%, 11.63% and 9.26% for concrete mixes with 350, 400 and 450 kg/m^3 cement content compared with that of 28 days cube compressive strength. Also, the cube compressive strength loss at 350 days reaches about 16.53%, 15.12%, and 12.96% for concrete mixes with 350, 400 and 450 kg/m^3 cement content, respectively. The same positive effect of cement content on concrete magnesium sulfate attack is also obvious in splitting tensile strength, modulus of elasticity, linear expansion strain results, where the increase of cement content decreases the losses in tensile strength and modulus of elasticity. Also the increase in cement content decreases the measured linear expansion strain. Figure 4, 5, and 6 show the effect of cement content on tensile strength loss, modulus of elasticity loss, and expansion strain respectively due to sulfate attack for different water cement ratio of 0.50, and different C_3A contents at 28, 60, 100, 200, and 350 days of magnesium sulfate exposure. For instance, for concrete mixes made with 6.87% C_3A percentage as shown in Figure 4-b, the tensile strength loss for concrete mixes with 0.50 w/cm ratio at 100 days is about 19.44%, 15.68% and 12.50% for concrete mixes with 350, 400 and 450 kg/m^3 cement content, respectively. For concrete mixes made with 10.84% C_3A percentage as shown in Figure 5-c, the modulus of elasticity loss for concrete mixes with 0.50 w/cm ratio at 200 days is about 11.42%, 10.97% and 7.06% for concrete mixes with 350, 400 and 450 kg/m^3 cement content.

The great effect of cement content increasing on linear expansion strain can be shown in Figure 6. From these test results, the use of

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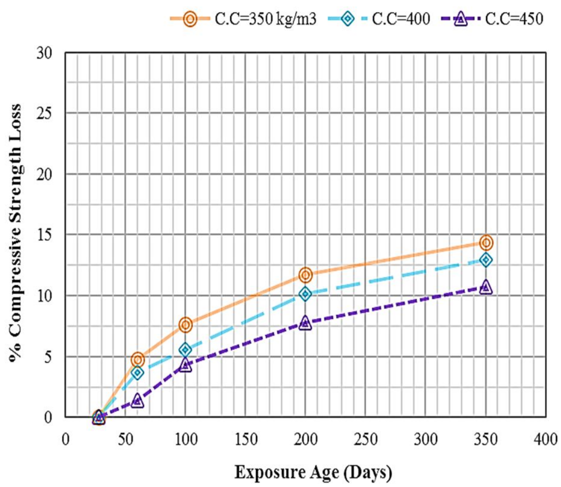
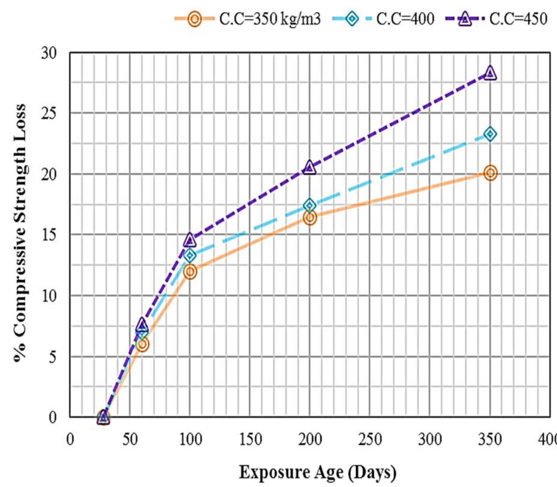
high cement content reduces the corresponding expansion strain for concrete. Also, it can be seen that, at the curves beginning, the measured expansion strain is almost the same for concrete mixes with 350, 400 and 450 kg/m^3 cement content, respectively. On the other hand, at the later ages of magnesium sulfate attack, the difference between concrete mixes with low cement content and concrete mixes with higher cement content is clear. This trend is almost the same for concrete mixes made with different C_3A percentages as shown in previous figures. For concrete mixes made with 10.84% C_3A percentage as shown in Figure 6-c, the linear expansion strain for concrete mixes with 0.50 w/cm ratio at 200 days is about 7.37x10^{-4}, 5.58x10^{-4} and 4.48x10^{-4} for concrete mixes with 350, 400 and 450 kg/m^3 cement content. The linear expansion strain at 450 days reaches about 11.40x10^{-4}, 8.40x10^{-4}, and 6.40x10^{-4} for concrete mixes with 350, 400 and 450 kg/m^3 cement content. As mentioned above, the increase of cement content has a great effect on the enhancement of concrete sulfate resistance. This good resistance of high cement content to magnesium sulfate attack is concluded and presented by Al-Amodi, Al-dulaijan and Zelic [13, 14, 15]. This conclusion was explained and demonstrated by Samson and Tixier, the increase of cement content causes a great decrease in concrete porosity and discontinuity on pores and capillary paths [16]. This reduction on porosity prevents the diffusion of sulfate ions into concrete, which reflects on improvement on concrete sulfate resistance [17].



a- C_3A = 4.24%



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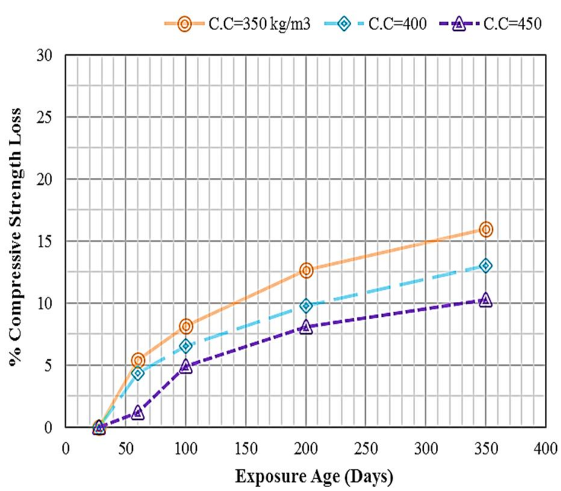
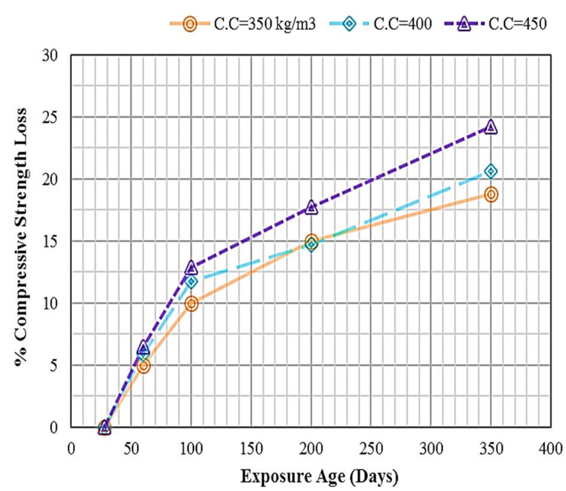


b- C_3A = 6.87%



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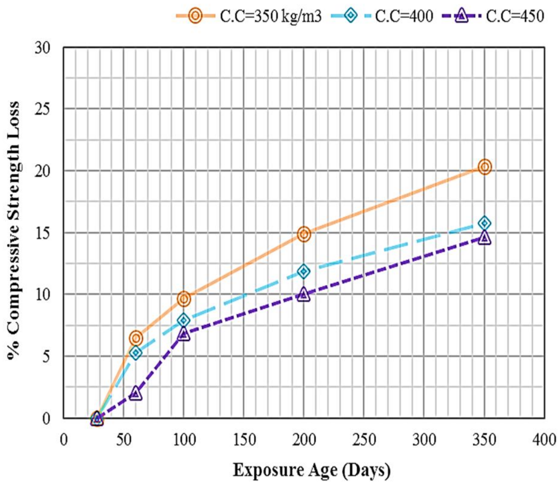
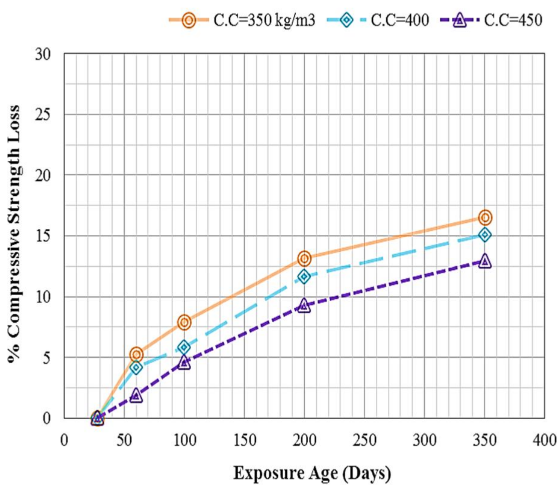
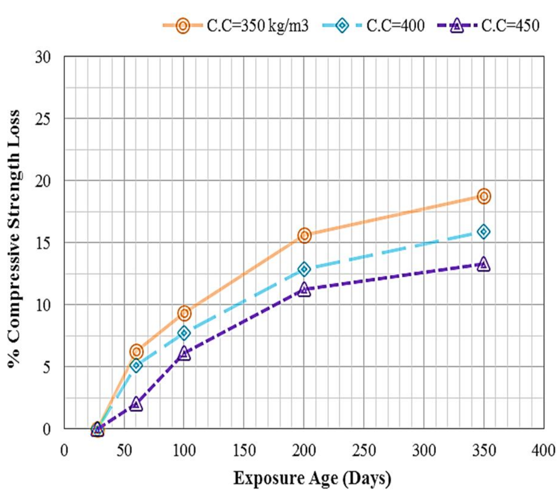


c- C_3A = 10.84%

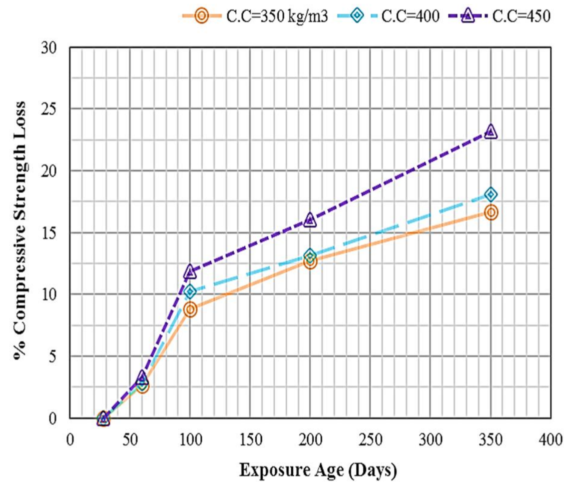
Fig. 1. Effect of cement content on cube compressive strength loss at different ages for concrete with 0.40 water cement ratio



a- C_3A = 4.24%

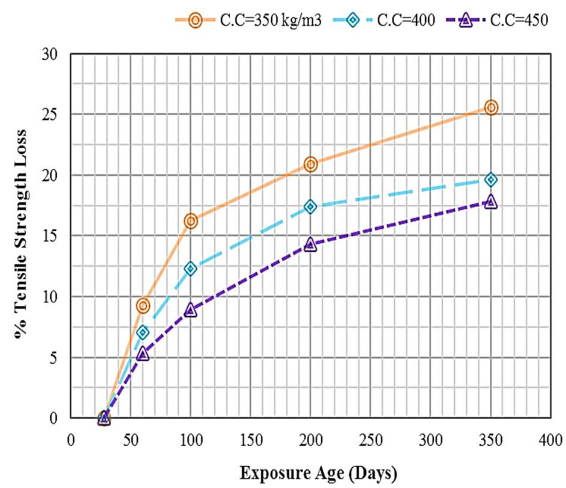


b- C_3A = 6.87%

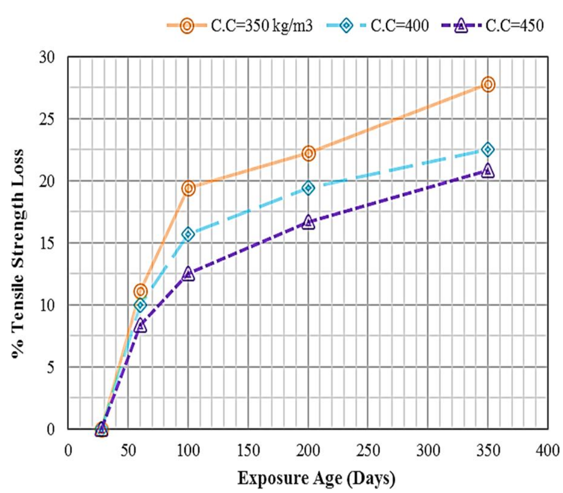


c- C_3A = 10.84%

Fig. 2. Effect of cement content on tensile strength and strength loss at different ages for concrete with 0.60 water cement ratio



a- C_3A = 4.24%



b- C_3A = 6.87%

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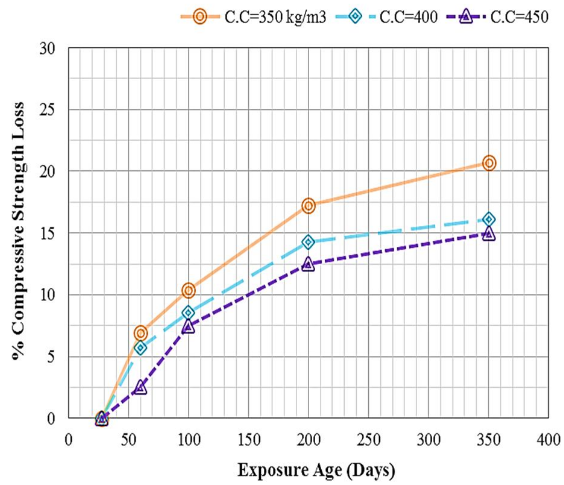
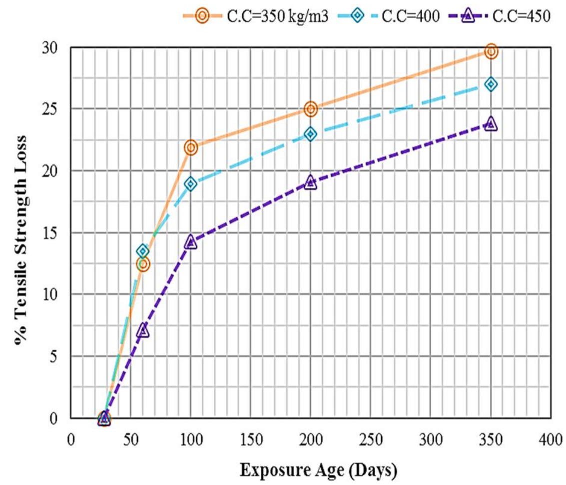


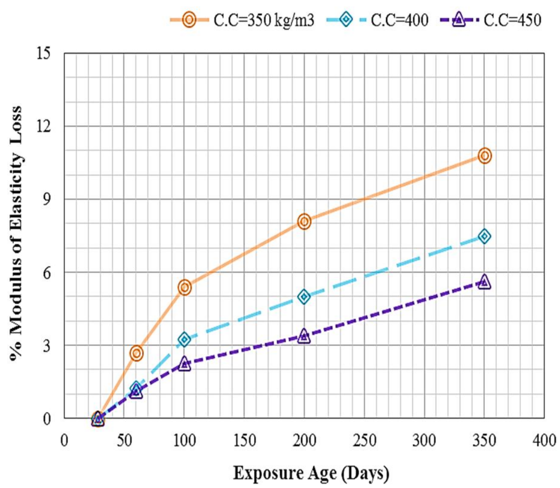
c- C_3A = 10.84%

Fig. 3. Effect of cement content on cube compressive strength loss at different ages for concrete with 0.50 water cement ratio



c- C_3A = 10.84%

Fig. 4. Effect of cement content on tensile strength and strength loss at different ages for concrete with 0.50 water cement ratio



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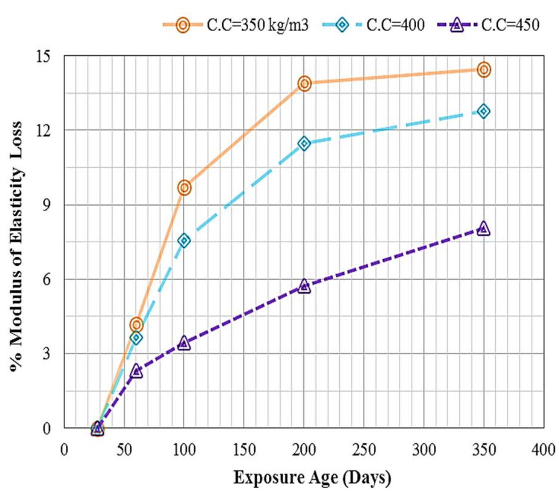
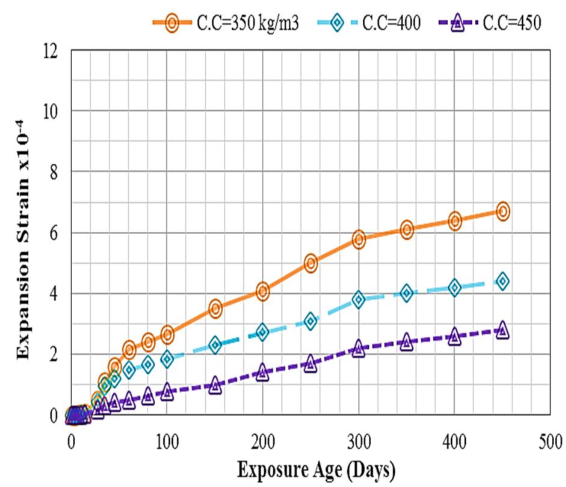


b- C_3A = 6.87%



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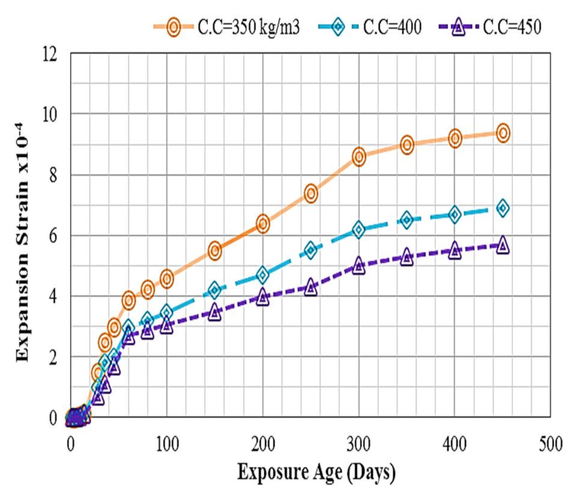
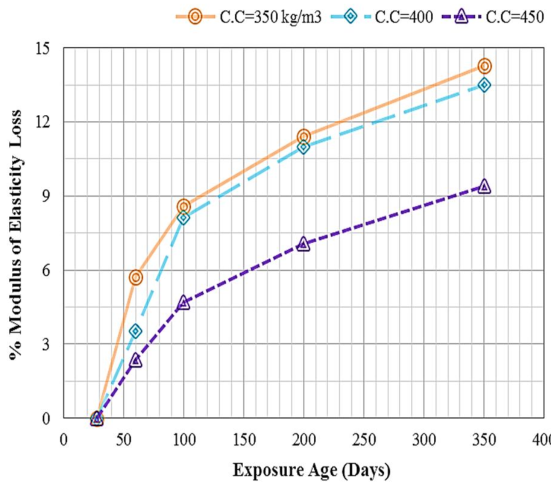
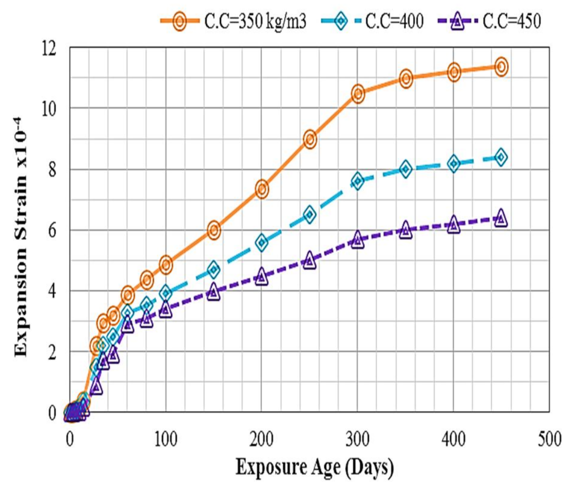


b- C_3A = 6.87%



c- C_3A = 10.84%

Fig. 5. Effect of cement content on modulus of elasticity loss at different ages for concrete with 0.50 water cement ratio



c- C_3A = 10.84%

Fig. 6. Effect of cement content on linear expansion strain at different ages for concrete with 0.50 water cement ratio

Most international codes ensure the important of cement content on increasing the concrete resistance of sulfates [18]. From the previous figures, one can conclude that the concrete properties deteriorate as exposure age to sulfate solution increases. For example, at 4.24% C_3A percentage as shown in Figure 3-a, the compressive strength loss increases to 5.0%, 9.0%, and 13% as exposure age increases to 100, 200, and 350 days respectively for cement content of 450 kg/m^3. This conclusion is confirmed in tensile strength and modulus of elasticity loss. The tensile strength loss reaches to 9.0%, 14.0%, 18.0% as exposure age increases to 100, 200, and 350 days respectively at the same cement content. The exposure age affects slightly on modulus of elasticity loss as shown in Figure 5-b, so the modulus of elasticity loss reaches to 2.0%, 4.0%, and 6.0% as exposure age increases to 100, 200, and 350 days respectively of cement content of 450 kg/m^3. It can be noticed that expansion strain increases gradually as exposure age increases because of gypsums and ettringite formation. For instance, expansion strain increases to 0.80x10^{-4}, 1.50x10^{-4}, and 2.80x10^{-4} as exposure age increases to 100, 200, and 450 days respectively.

B. Effect of Water Cement Ratio

The effect of water cement ratio on different concrete mechanical properties due to magnesium sulfate attack is presented in this section. The mechanical properties include cube compressive strength, tensile strength, modulus of elasticity, and linear expansion. These results for concrete mechanical properties are presented in Figures 7, 8, 9 and 10. Figure 7 show the effect of water cement ratio on concrete compressive strength loss due to sulfate attack for different cement contents, and different C_3A contents at 28, 60, 100, 200, and 350 days of magnesium sulfate exposure. From this figure, it is clear that the increase in water cement ratio has a negative effect on concrete magnesium sulfate resistance. As an example, for concrete mixes made with 4.24% C_3A percentage as shown in Figure 7-a, the cube compressive strength loss for concrete mixes with cement content of 400 kg/m^3 at 200 days is about 10.0%, 11.50% and 15.0% for concrete mixes with 0.40, 0.50, and 0.50 water cement ratio, respectively. Also, the cube compressive strength loss at 350 days reaches about 13.0%, 15.0%, and 18.50% for concrete mixes with 0.40, 0.50, and 0.50 water cement ratio. The same negative effect of water cement ratio on concrete magnesium sulfate attack is also obvious in splitting tensile strength, modulus of elasticity, linear expansion strain results, where the increase of water cement ratio decreases the losses in tensile strength and modulus of elasticity. Also the increase in water cement ratio increases the measured linear expansion strain. Figure 8, 9, and 10 show the effect of water cement ratio on tensile strength loss, modulus of elasticity loss, and expansion strain respectively due to sulfate attack for different cement contents, and different C_3A contents at 28, 60, 100, 200, and 350 days of magnesium sulfate exposure. For instance, for concrete mixes made with 6.87% C_3A percentage as shown in Figure 8-b, the tensile strength loss for concrete mixes with cement content of 400 kg/m^3 at 200 days is about 10.0%, 13.0% and 15.0% for concrete mixes with 0.40, 0.50, and 0.50 water cement ratio. For concrete mixes made with 10.84% C_3A percentage as shown in Figure 9-c, the modulus of elasticity loss for concrete mixes with cement content of 400 kg/m^3 at 200 days is about 6.0%, 11.0% and 13.0% for concrete mixes with 0.40, 0.50, and 0.50 water cement ratio.

The bad effect of water cement ratio increasing on linear expansion strain can be shown in Figure 10. From these test results, the

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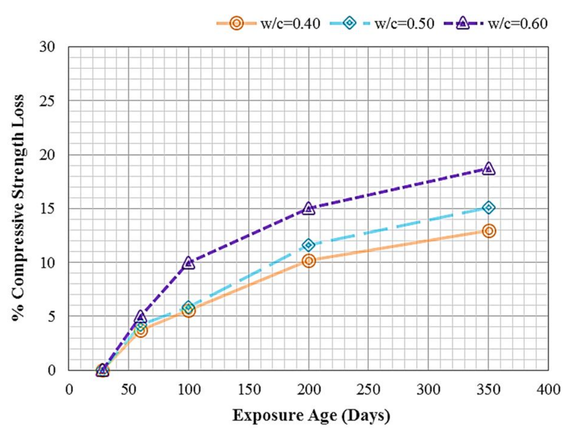
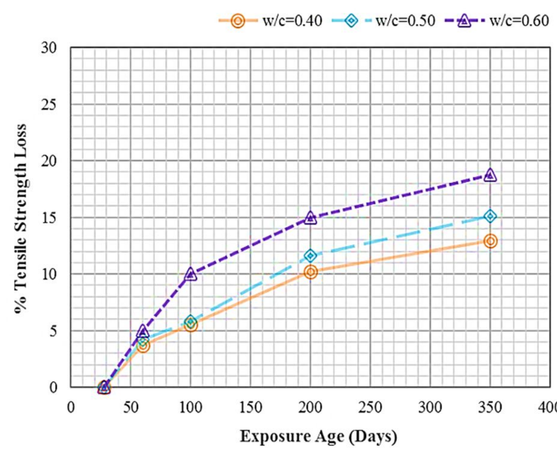
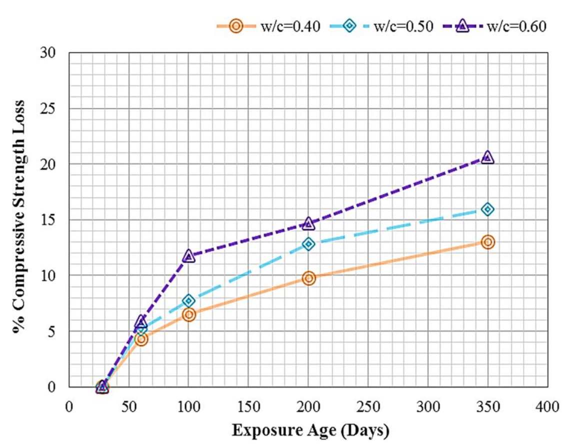
use of high water cement ratio increases the corresponding expansion strain for concrete. Also, it can be seen that, at the curves beginning, the measured expansion strain is almost the same for concrete mixes with 0.40, 0.50, and 0.50 water cement ratio up to 28 days. On the other hand, at the later ages of magnesium sulfate attack, the difference between concrete mixes with low water cement ratio and concrete mixes with higher water cement ratio is clear. This trend is almost the same for concrete mixes made with different C_3A percentages as shown in previous figures. For concrete mixes made with 6.87% C_3A percentage as shown in Figure 10-b, the linear expansion strain for concrete mixes with cement content of 400 kg/m^3 at 200 days is about $3.40x10^{-4}$, $4.69x10^{-4}$ and $6.80x10^{-4}$ for concrete mixes with 0.40, 0.50, and 0.50 water cement ratio, respectively. The linear expansion strain at 450 days reaches about $4.93x10^{-4}$, $6.90x10^{-4}$, and $9.4x10^{-4}$ for concrete mixes with 0.40, 0.50, and 0.50 water cement ratio respectively. As mentioned above, the increase of water cement ratio has a negative effect on the concrete sulfate resistance. This bad resistance of high water cement ratio to magnesium sulfate attack was concluded and presented by Al-Amodi, Al-dulaijan and Zelic [13, 14, 15]. This conclusion was explained and modeled by Power. The increase of water cement ratio causes a great increase in concrete porosity and water permeability [19]. This increase of porosity increases the diffusion coefficient of sulfate ions into concrete, which reflects on deterioration of concrete sulfate resistance [20, 21]. ACI 201 concluded that the concrete permeability has significant effect not only for resistance of concrete to sulfates but also for all chemical attack. [22]. The w/cm ratio is the most effective factor where decreasing w/cm ratio decreases the coefficient of permeability and this leads to decrease the durability of cement pastes [7, 19]. The great effect of water cement ratio increasing on expansion strain increasing can be concluded by the explanation of linear expansion strain generation. Expansion strain is generated by the formation of high volume gypsum and ettringite crystals along the walls of capillary and gel pores [23]. In this way, the positive capillary pressure causes the cement matrix to expand. The first effect of water cement ratio decreasing is due to the increasing number of small sized pores, and so the area of pore walls increases as well, lowering the total capillary pressure in the system during retreat of the water film. The second effect is the increasing of cement matrix strength which preventing the cement matrix to expand [24, 25].

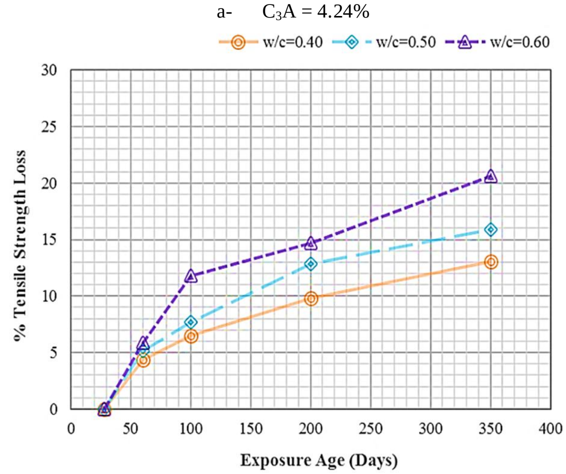




a- C_3A = 4.24%

a- C_3A = 4.24%





b- C_3A = 6.87%

b- C_3A = 6.87%

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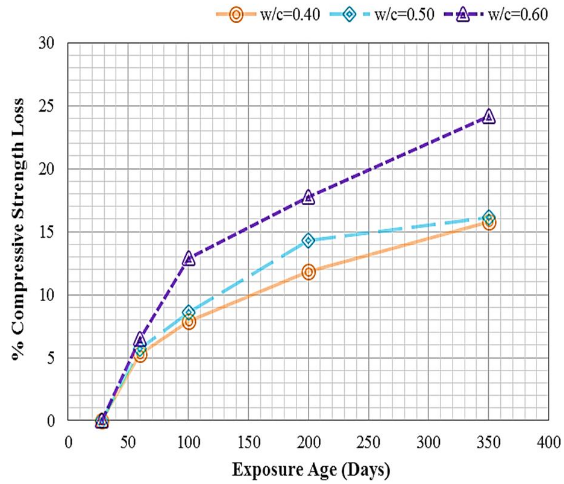
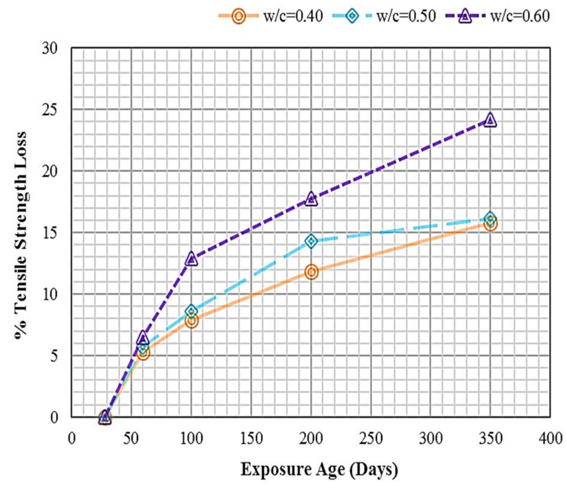


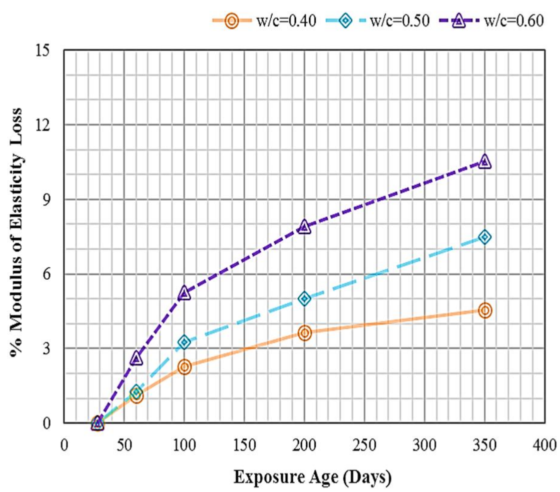
c- C_3A = 10.84%



c- C_3A = 10.84%

Fig. 7. Effect of water cement ratio on cube compressive strength loss at different ages for concrete with 400 kg/m^3 cement content

Fig. 8. Effect of water cement ratio on tensile strength loss at different ages for concrete with 400 kg/m^3 cement content



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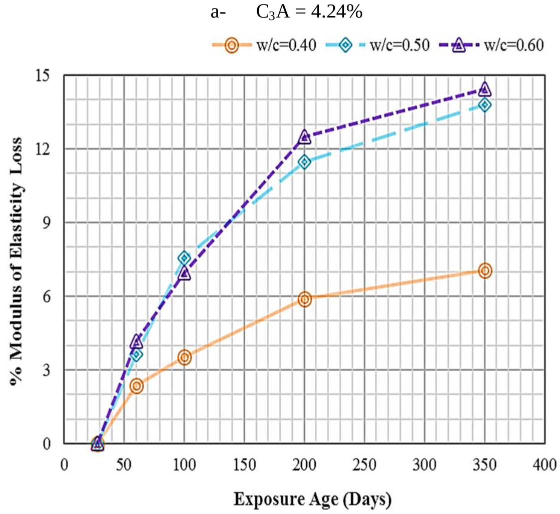
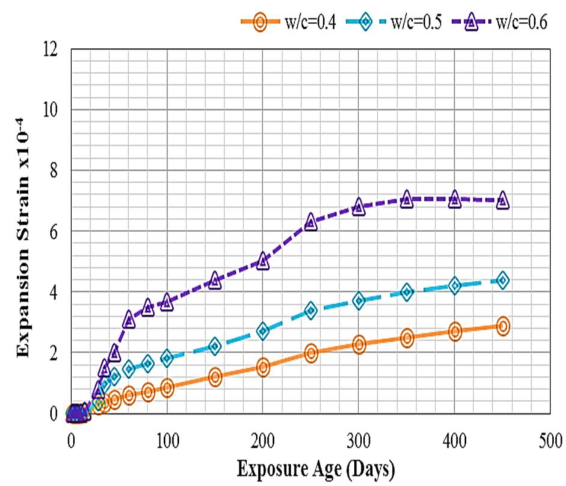
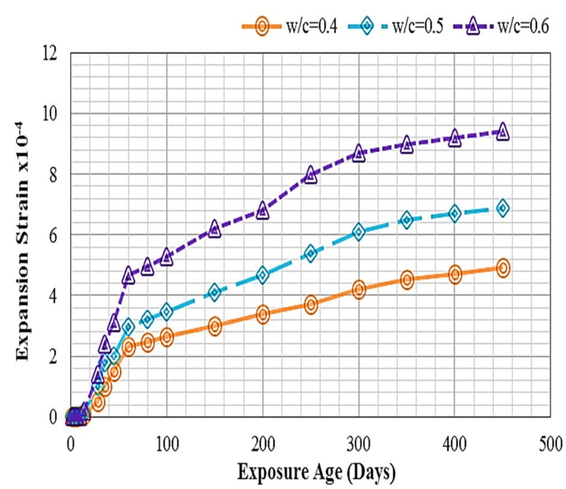


b- C_3A = 6.87%



a- C_3A = 4.24%



b- C_3A = 6.87%

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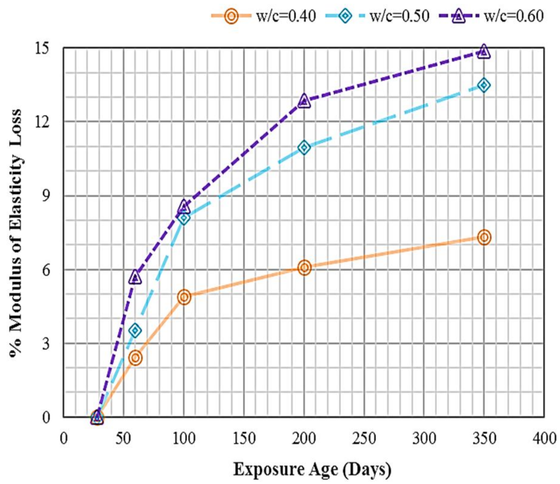
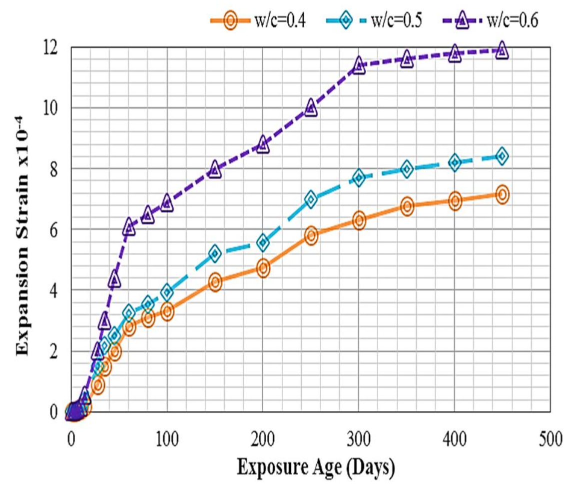


c- C_3A = 10.84%

Fig. 9. Effect of water cement ratio on modulus of elasticity loss at different ages for concrete with 400 kg/m3 cement content



c- C_3A = 10.84%

Fig. 10. Effect of water cement ratio on linear expansion strain at different ages for concrete with 400 kg/m3 cement content

C. *Effect of C_3A Content in Cement*

The effect of C_3A percentage on different concrete mechanical properties due to magnesium sulfate attack is presented in this section. The mechanical properties include cube compressive strength, tensile strength, modulus of elasticity, and linear expansion. These results for concrete mechanical properties are presented in Figures 11, 12, 13 and 14. Figure 11 show the effect of C_3A percentage on concrete compressive strength due to sulfate attack for different water cement ratios, and 400 kg/m^3 at 28, 60, 100, 200, and 350 days of magnesium sulfate exposure. From this figure, it is clear that the increase in C_3A percentage has a negative effect on concrete magnesium sulfate resistance. As an example, for concrete mixes made with 0.40 water cement ratio as shown in Figure 11-a, the cube compressive strength loss for concrete mixes with cement content of 400 kg/m^3 at 200 days is about 9.0%, 10.0% and 12.0% for concrete mixes with 4.24%, 6.87%, and 10.84% C_3A percentages, respectively.

The same negative effect of C_3A percentage on concrete magnesium sulfate attack is also obvious in splitting tensile strength, modulus of elasticity, linear expansion strain results, where the increase of C_3A percentage increases the losses in tensile strength and modulus of elasticity. Also the increase in C_3A percentage increases the measured linear expansion strain. Figure 12, 13, and 14 show the effect of C_3A percentage on tensile strength loss, modulus of elasticity loss, and expansion strain respectively due to sulfate attack for different water cement ratios at 28, 60, 100, 200, and 350 days of magnesium sulfate exposure. For instance, for concrete mixes made with 0.50 water cement ratio as shown in Figure 12-b, the tensile strength loss for concrete mixes with cement content of 400 kg/m^3 at 100 days is about 12.50%, 16.0% and 19.0% for concrete mixes with 4.24%, 6.87%, and 10.84% C_3A percentages. For concrete mixes made with 0.60 water cement ratio as shown in Figure 13-c, the modulus of elasticity loss for concrete mixes with cement content of 400 kg/m^3 at 200 days is about 7.80%, 12.60% and 13.0% for concrete mixes with 4.24%, 6.87%, and 10.84% C3A percentages respectively.

The bad effect of C_3A percentage increasing on linear expansion strain can be shown in Figure 14. From these test results, the use of high C_3A percentage increases the corresponding expansion strain for concrete. Also, it can be seen that, at the curves beginning, the measured expansion strain is almost the same for concrete mixes with 4.24%, 6.87%, and 10.84% C_3A percentages up to 28 days. This trend is almost the same for concrete mixes made with different water cement ratios as shown in previous figures. For concrete mixes made with 0.60 water cement ratio as shown in Figure 14-c, the linear expansion strain for concrete mixes with cement content of 400 kg/m3 at 300 days is about 6.80x10-4, 8.70x10-4 and 10.0x10-4 for concrete mixes with 4.24%, 6.87%, and 11.40% C3A percentages respectively. The linear expansion strain at 450 days reaches about 7.43x10-4, 9.40x10-4, and 11.90x10-4 for concrete mixes with 4.24%, 6.87%, and 10.84% C3A percentages respectively.

As mentioned above, the increase of C_3A percentage has a negative effect on the concrete sulfate resistance. This bad resistance of higher C_3A percentage to magnesium sulfate attack is concluded and presented by Al-Amodi, Al-dulaijan and Zelic [13, 14, 15]. This increasing of high volume crystals increases the deterioration of concrete [16]. Ouyang reported that the sulfate ions react with portlandite to form gypsum and latter reacts mainly with monosulfo aluminates to form ettringite [26]. Akpinar confirmed this observation as the low C_3A content minimizes the monosulfo aluminates content and thus the formation of ettringite, leading to much more reduced expansions [27, 28].

V. CONCLUSIONS

From the present study the following conclusions are drawn:

A. The cement content, water cement ratio, and C_3A content have important influence on concrete sulfate resistance.

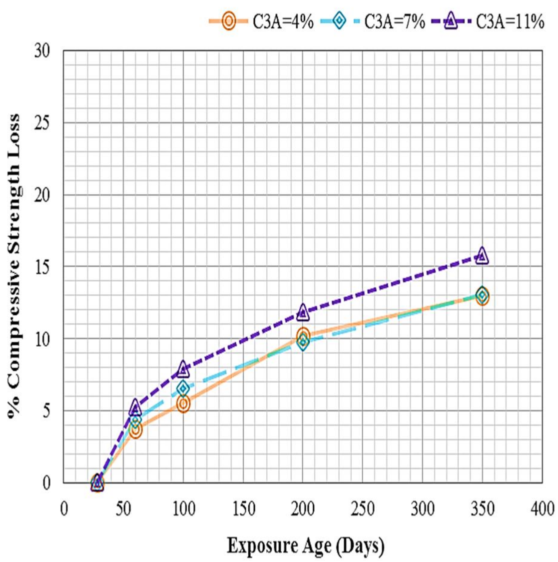
B. The increase of C_3A content and water cement ratio in concrete can significantly increase the deterioration of concrete sulfate resistance, particularly when the sulfate concentration is high and the immersion time is longer.

C. The compressive strength loss value of concrete sulfate resistance depends positively on cement content increasing and the immersion time is longer.

D. Both the water cement ratio and C_3A content increasing can significantly increase the compressive and tensile strength loss.

VI. ACKNOWLEDGMENT

This research was carried in the laboratories of the Structural Engineering Department at Alexandria University. Assistance by the lab staff on the experimental work is greatly appreciated.



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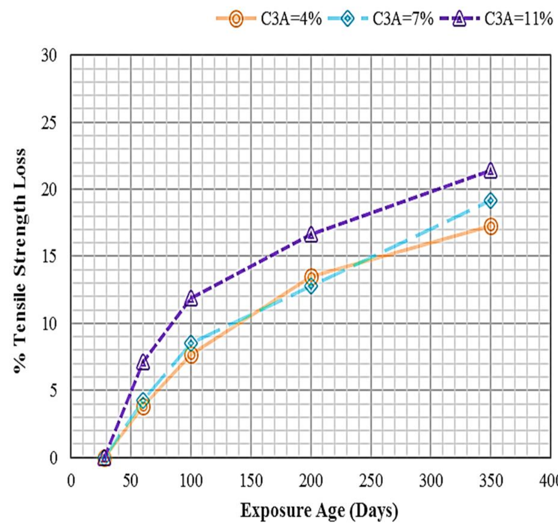

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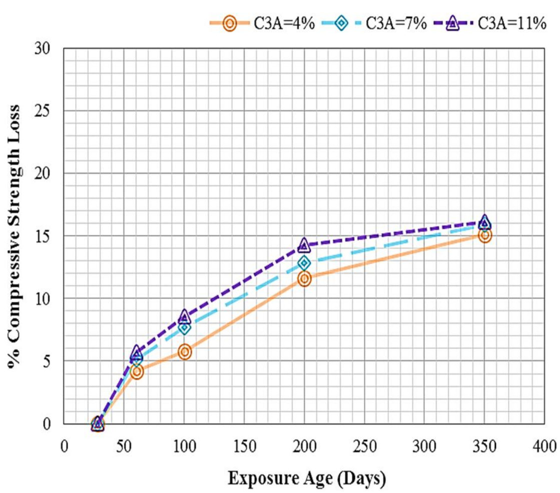
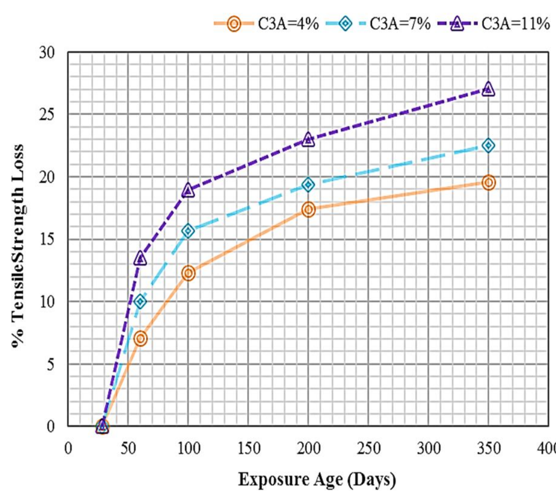


b- w/c=0.50



b- w/c=0.50

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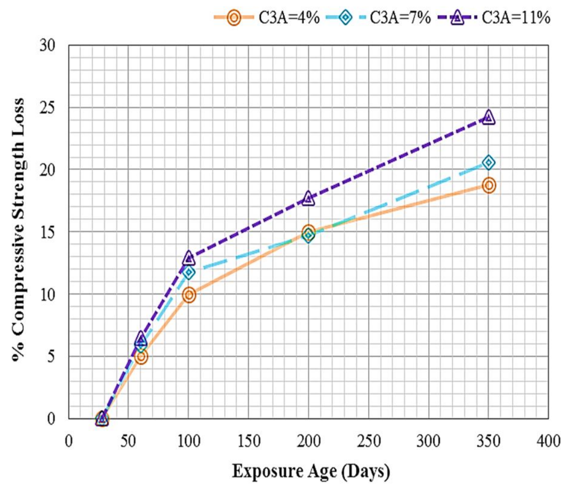
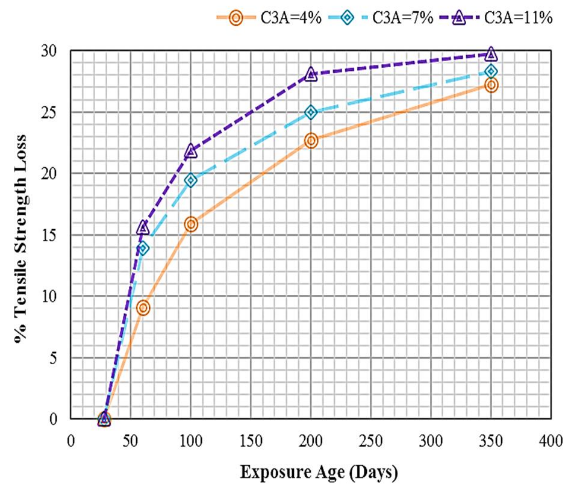


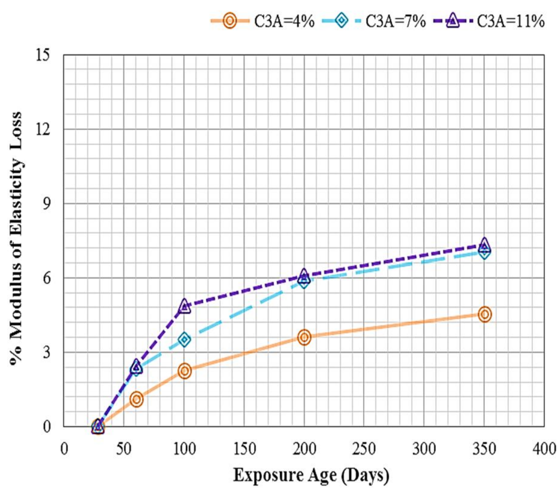
c- w/c=0.60

Fig. 11. Effect of C_3A percentage on cube compressive strength loss at different ages for concrete with 400 kg/m^3 cement content

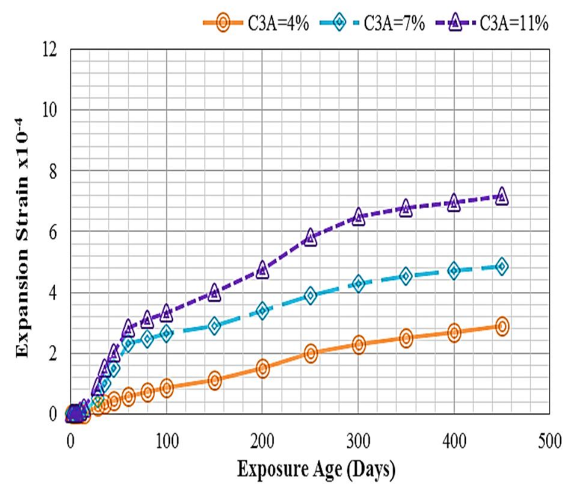


c- w/c=0.60

Fig. 12. Effect of C_3A percentage on tensile strength loss at different ages for concrete with 400 kg/m^3 cement content



a- w/c=0.40



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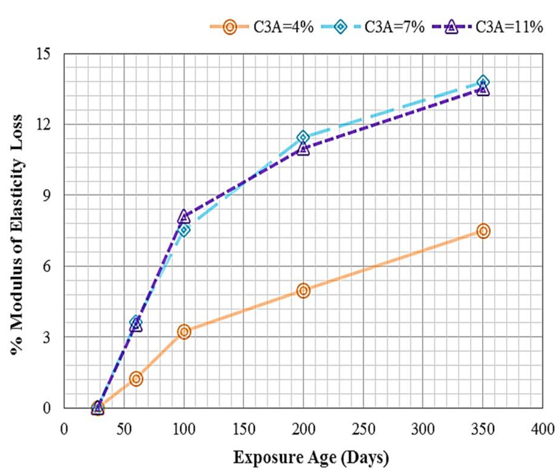
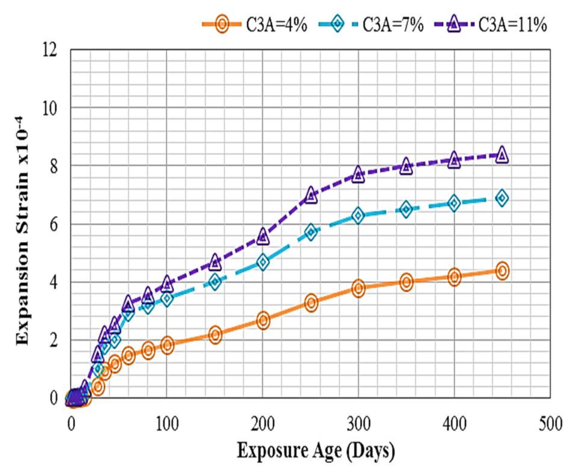


b- w/c=0.50



b- w/c=0.50

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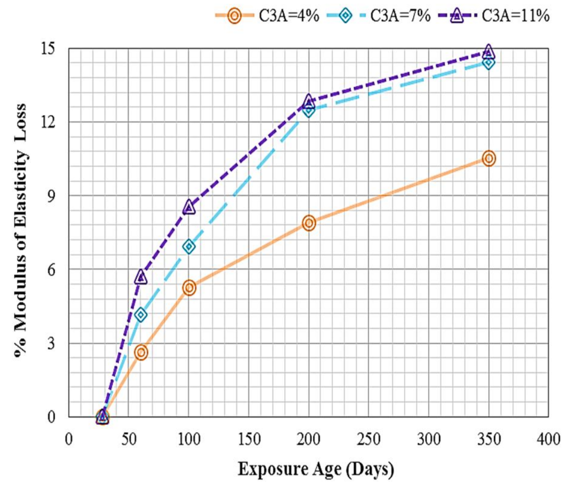
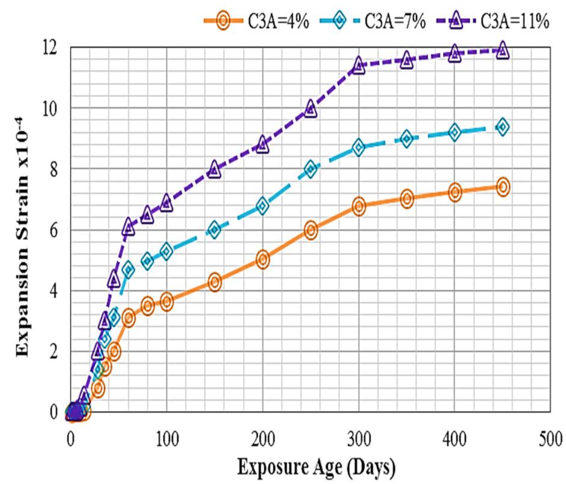


c- w/c=0.60

Fig. 13. Effect of C_3A percentage on modulus of elasticity loss at different ages for concrete with 400 kg/m^3 cement content



c- w/c=0.60

Fig. 14. Effect of C_3A percentage on linear expansion strain at different ages for concrete with 400 kg/m^3 cement content

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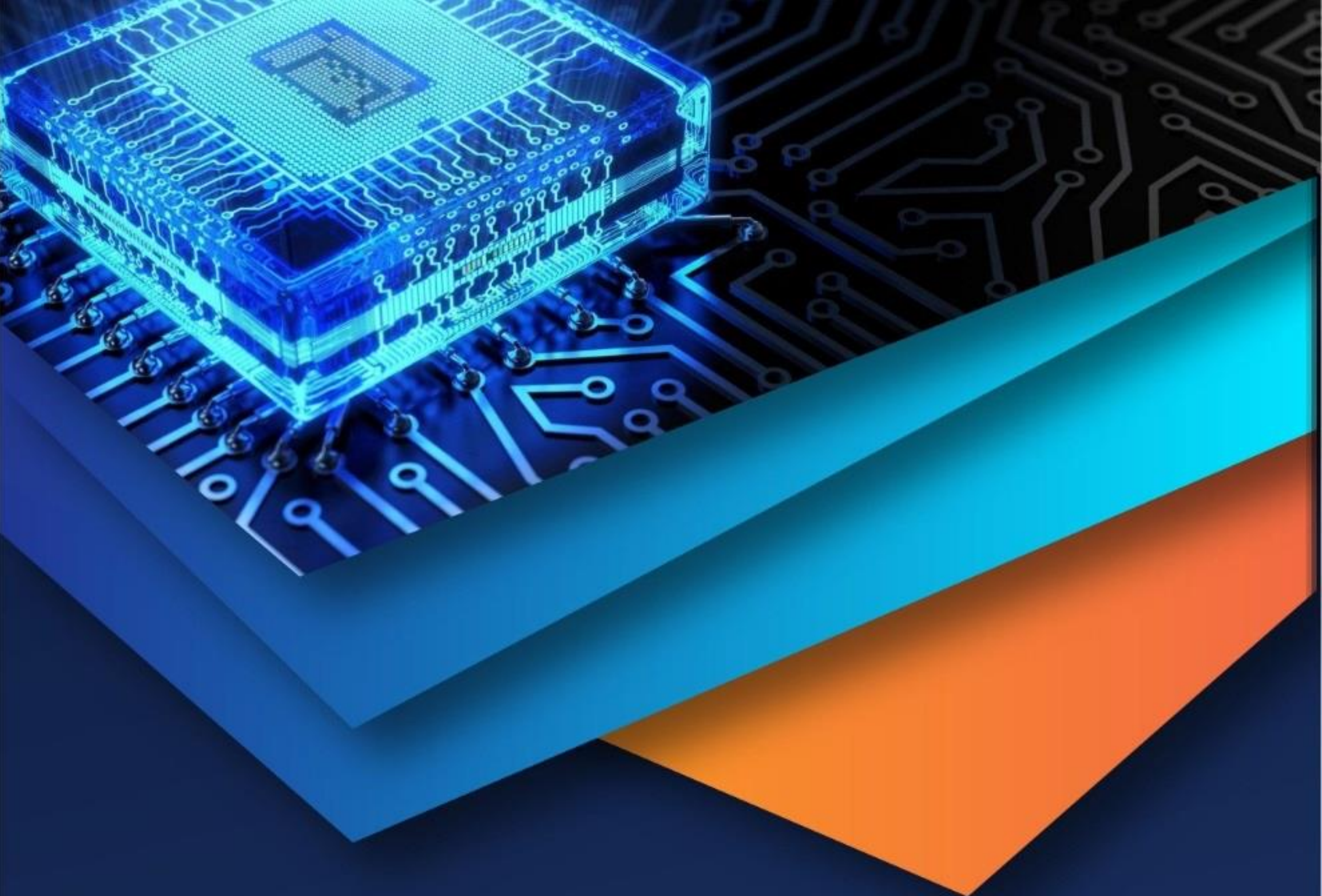

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