

The Effect of Sulfates in Groundwater on Some Mechanical Properties of Self-Compacting Concrete

Asst. Prof. Dr. Ghalib M. Habeeb
University of Babylon
College of Engineering

Asst. Lecturer Alaa M. Hadi
University of Karbala
College of Engineering

الخلاصة

ان الهدف الرئيسي من هذا البحث هو تقييم اداء الخرسانة ذاتية الرص تحت ظروف ملحية قاسية تحتوي على كبريتات وكلوريدات بتراكيز مماثلة لتلك الموجودة في التربة او المياه الجوفية في المناطق الجنوبية من العراق. في هذا البحث تم استعمال اربعة انواع رئيسية من الخرسانة ذاتية الرص وهي: خرسانة ذاتية الرص خالية من اي مضاف معدني، خرسانة ذاتية الرص حاوية على 10% ميتاكاولين عالي الفعالية، خرسانة ذاتية الرص حاوية على 30% مسحوق الحجر الجيري و خرسانة ذاتية الرص حاوية على 10% ميتاكاولين عالي الفعالية و 30% مسحوق الحجر الجيري. لقياس خصائص الرص الذاتي لتلك الانواع من الخرسانة عدة طرق مختبرية تم استخدامها مثل انسياب الهطول، القمع على شكل الحرف V، الصندوق على شكل الحرف L و الصندوق على شكل الحرف U وقد بينت نتائج هذه الفحوصات بأن متطلبات الرص الذاتي قد تحققت لجميع الخلطات الخرسانية. اجريت فحوص مقاومة الانضغاط، مقاومة الشد الانفلاقي، معامل المرونة الستاتيكي، التغير بالوزن، التغير بالطول وسرعة الموجات فوق الصوتية باعمار 28, 60, 90, 120 و 180 يوم. اظهرت النتائج بانه تحت تأثير المحاليل القاسية معدل تحسن في الخصائص الميكانيكية للنماذج يقل مع ازدياد العمر مقارنة مع معدل التحسن في الخصائص الميكانيكية لنماذج تم معالجتها بالماء. كما بينت النتائج ايضا ان الخرسانة ذاتية الرص الحاوية على ميتاكاولين عالي الفعالية ابدت مقاومة افضل لمهاجمة الكبريتات الخارجية من الخلطات الخرسانية الاخرى.

Abstract

The main aim of this research is to evaluate the performance of self-compacting concrete under severe saline conditions contain sulfates and chlorides at concentrations similar to those existing in soil and groundwater of the southern parts of Iraq. In this work, four basic categories of self-compacting concrete are used: SCC without any mineral admixture, SCC incorporating 10% high reactivity metakaolin, SCC incorporating 30% limestone powder and SCC incorporating 10% high reactivity metakaolin plus 30% limestone powder. To determine self-compatibility features for those types of concrete, different test methods are adopted such as: slump flow, V-funnel, L-box and U-box. The results of this tests show the self-compatibility requirements were fulfilled for all mixes. Compressive, splitting tensile strength, static modulus of elasticity, weight change, length change and ultrasonic pulse velocity were investigated for all types of self-compacting concrete at 28, 60, 90, 120 and 180 days age. Results show that under the action of aggressive solution, the rate of improvement in mechanical properties of the specimens were decreased with age increase compared with rate of improvement in mechanical properties of the specimens cured in tap water. The results also indicated that HRM-SCC demonstrates more resistant to external sulfate attack than other types of SCC mixes.

1. Introduction

Self-compacting concrete (SCC) is one of "the most revolution development" in concrete research, this concrete is able to flow and to fill the most restricted places of the formwork without vibration^[1]. Such concrete should have a relatively low yield value to ensure high flow ability, a moderate viscosity to resist segregation and bleeding and must maintain its homogeneity during transportation, placing and curing to ensure adequate structural performance and long-term durability^[2]. Therefore, SCC mixes always contain a powerful superplasticizer and often use a large quantity of powder materials and/ or viscosity-modifying admixtures. The superplasticizer is

necessary for producing a highly fluid concrete mix while the powder materials or viscosity agents are required to maintain sufficient viscosity of the mix^[3]. The high workability of SCC results in a well compacted microstructure with reduced porosity in mortar matrix and interfacial zone, and thus improves the electrical resistivity and transport properties of concrete. This is the key to enhanced durability performance of SCC exposed to aggressive environments^[4]. Deterioration of concrete caused by aggressive environments can be the result of contact with gases or solution of many chemicals, but in the ground it is generally due to sulfate salts. Sulfate attack causes concrete deterioration by chemical and/ or physical reactions. In this phenomenon, sulfate ions penetrating from groundwater in concrete react mainly with aluminate phase of cement. As a result, gypsum and an ettringite type salt are produced that cause concrete deterioration due to expansion and disruption^[5].

This paper includes an attempt to produce self-compacting concrete incorporating high range water reducing agent (HRWRA) and local cheap materials such as limestone powder (LSP) and high reactivity metakaolin (HRM), and then investigate the effect of these mineral and chemical admixtures on the strength and durability performance of self-compacting concrete exposed to aggressive solution.

2. Experimental Program

2-1: Materials

2-1-1: Cement

The cement used in this study is ordinary Portland cement type I. This cement is tested and checked according to Iraqi standard specification (IQS No.5:1984)^[6]. The chemical and physical properties of this cement are illustrated in Tables 1 and 2, respectively.

Table 1: Chemical composition and main compounds of cement*

<i>Compound composition</i>	<i>Chemical composition</i>	<i>Percentage by weight</i>	<i>Limits of (IQS NO.5 /1984)</i>
Lime	CaO	62.28	/
Silica	SiO ₂	20.82	/
Alumina	Al ₂ O ₃	4.34	/
Iron oxide	Fe ₂ O ₃	4.20	/
Sulfate	SO ₃	2.45	≤ 2.5 %
Magnesia	MgO	3.15	≤ 5 %
Free lime	Free CaO	1.4	/
Loss on ignition	L.O.I.	2.33	≤ 4 %
Insoluble residue	I.R.	1.26	≤ 1.5 %
Lime saturation factor	L.S.F.	0.89	0.66 – 1.02
<i>Main compounds (Boque's equs.)</i>		<i>Percent by weight of cement</i>	
Tricalcium silicate (C ₃ S)		47.39	
Dicalcium (C ₂ S)		24.21	
Tricalcium aluminate (C ₃ A)		4.40	
Tetracalcium aluminoferrite (C ₄ AF)		12.77	

*Chemical tests were conducted by the environmental laboratory of University of Babylon

Table 2: Physical properties of cement*

<i>Physical properties</i>	<i>Test results</i>	<i>Limits of (IQS NO.5 /1984)</i>
Setting time (Vicat's Method)		
Initial, min	170	≥ 45 min
Final, min	225	≤ 600 min
Fineness (Blaine Method) ,m ² /kg	328	≥230 m ² /kg
Compressive strength, MPa		
3 days	21.5	≥ 15, MPa
7 days	31.2	≥23, MPa

*Physical tests were conducted by the constructional materials laboratory of University of Babylon

2-1-2: Sand

Locally available natural sand with 4.75mm maximum size was used in presented work. It's grading was within the limits of the Iraqi specification (IQS No.45:1984)^[7]. Tables 3 and 4 show the grading and physical properties of this fine aggregate, respectively.

2-1-3: Gravel

Natural rounded gravel of maximum size 14 mm was used in presented work. Table 5 shows the grading of this aggregate, which conforms to the Iraqi specification (IQS No.45:1984). The specific gravity, sulfate content and absorption of coarse aggregate are illustrated in Table 6.

Table 3: Grading of fine aggregate

<i>Sieve size (mm)</i>	<i>Cumulative passing%</i>	<i>Limits of Iraqi specification No.45/1984 /zone (2)</i>
10	100	100
4.75	97	90-100
2.36	88	75-100
1.18	77	55-90
0.6	59	35-59
0.3	22	8-30
0.15	5	0-10

Table 4: Physical properties of fine aggregate*

<i>Physical properties</i>	<i>Test result</i>	<i>Limits of Iraqi specification No.45/1984</i>
Specific gravity	2.6	/
Sulfate content	0.44%	≤ 0.5 %
Absorption	2.1%	/
Dry-Loose density (kg/m ³)	1595	/
Fineness modulus	2.52	/

*Physical tests were conducted by the constructional materials laboratory of University of Babylon

Table 5: Grading of coarse aggregate

<i>Sieve size (mm)</i>	<i>Cumulative passing%</i>	<i>Limits of Iraqi specification No.45/1984</i>
20	100	100
14	96.5	90-100
10	73.4	50-85
5	7.9	0-10
2.36	/	/

Table 6: Physical properties of coarse aggregate*

<i>Physical properties</i>	<i>Test result</i>	<i>Limits of Iraqi specification No.45/1984⁽¹⁰¹⁾</i>
Specific gravity	2.65	/
Sulfate content	0.03%	≤ 0.1 %
Absorption	0.5%	/
Dry rodded density (kg/m ³)	1635	/

*Physical tests were conducted by the constructional materials laboratory of University of Babylon

2-1-4: Superplasticizer

A chemical admixture based on modified polycarboxylic ether, which is known (Glenium 51) was used in producing SCC as a high range water reducing admixture (HRWRA). Glenium 51 is considered one of a new generation of copolymer-based superplasticizer that complies with ASTM C 494 type A and F. Typical properties of Glenium 51 are shown in Table 7.

Table 7: Typical properties of Glenium 51 *

Form	Viscous liquid
Color	Light down
Relative density	1.1 at 20°C
pH	6.6
Viscosity	128 cps at 20°C
Chloride content	Free

*Given by manufacture.

2-1-5: Limestone powder (LSP)

Finely ground limestone, has CaCO₃ as its main component. This material is locally named as Al-Gubra, which has been brought from local market and used to increase the amount of powder. The chemical composition and physical properties of LSP are shown in Tables 8 & 9, respectively.

Table 8: Chemical analysis of LSP*

<i>Oxide</i>	<i>Content %</i>
CaO	60.01
Fe ₂ O ₃	0.2
Al ₂ O ₃	0.61
SiO ₂	1.22
MgO	0.32
SO ₃	0.1
L.O.I	36.5

*Chemical analysis were conducted by the constructional materials laboratory of University of Babylon

Table 9: Physical properties of LSP*

<i>Physical properties</i>	<i>LSP</i>
Physical form	Powder
Color	White
Surface area (Blaine Method), m ² /kg	310

*Physical tests were conducted by the constructional materials laboratory in University of Babylon

2-1-6: High reactivity metakaolin (HRM)

High reactivity metakaolin (HRM) is an aluminosilicate pozzolan produced by clinking the kaolin (a fine, white, clay mineral that has been traditionally used in the manufacture of porcelain) at temperatures of (700-900) C°, locally available fine grain size kaolin clinks in laboratory using the burning kiln of clinkering ability up to 1200 C°. Kaolin is burned at 700 C° for whole one hour then left to coal down. This procedure of clinking is based on the work of many researchers especially Al-Hadithi^[8]. The chemical composition and physical properties of HRM are listed in Tables 10 and 11, respectively. The HRM used in this work conforms to the requirements of ASTM C618 Class N pozzolan as shown in Table 12.

Table 10: Chemical analysis of HRM *

<i>Oxide composition</i>	<i>Oxide content %</i>
SiO ₂	55.24
Al ₂ O ₃	37.1
Fe ₂ O ₃	1.47
CaO	1.12
MgO	0.13
SO ₃	0.07
Na ₂ O	0.15
L.O.I	3.59

*Chemical tests were conducted by the National Center for Construction Laboratories and Research (NCCLR)

Table 11: Physical properties of HRM *

<i>Physical properties</i>	<i>HRM</i>
Physical form	Powder
Color	Off-white
Specific gravity	2.64
Surface area (Blaine Method) ,m ² /kg	654

*Physical tests were conducted by the National Center for Construction Laboratories and Research (NCCLR)

Table 12: Chemical requirements of Pozzolan ASTM C618

<i>Oxide composition</i>	<i>Pozzolan class N</i>	<i>HRM</i>
SiO ₂ +Al ₂ O ₃ +Fe ₂ O ₃ , min.%	70	93.81
SO ₃ , max. %	4	0.07
Loss on ignition	max. 10	3.59

2-1-7: Water

The water used in the mix design was potable water from the water-supply network system; so, it was free from suspended solids and organic materials, which might have affected the properties of the fresh and hardened concrete.

2-1-8: Aggressive solution

In this investigation two types of sulfates (MgSO₄.7H₂O & Na₂SO₄) and two types of chlorides (CaCl₂.2H₂O & NaCl) are used. Potable water is used as a solvent for these salts. Tables 13 and 14 illustrate the types and concentrations of salts used in curing solution and the actual anions and cations provided by such salts.

Table 13: Types and concentration of salts used in curing solution

<i>Type of salt</i>	<i>Concentration</i>		<i>Salt content % by wt. of water</i>
	<i>ppm</i>	<i>gm/l</i>	
MgSO ₄ .7H ₂ O	12500	12.5	1.25
Na ₂ SO ₄	3150	3.15	0.315
CaCl ₂ .2H ₂ O	5000	5	0.5
NaCl	47500	47.5	4.75

Table 14: Types and concentration of ions used in curing solution

<i>Anions</i>		<i>Cations</i>	
<i>Type</i>	<i>Concentration, ppm</i>	<i>Type</i>	<i>Concentration, ppm</i>
Cl ⁻	31244	Mg ⁺⁺	1233.75
		Na ⁺	19533
SO ₄ ⁻⁻	7001	Ca ⁺	1350

2-2: Mix proportion

To achieve the research objectives, four types of mixes are prepared according to EFNARC method^[9]; SCC without filler, SCC with 10% HRM, SCC with 30% LSP and SCC with 10% HRM + 30% LSP. Mineral admixture used in this study (HRM and LSP) are incorporated as a partial replacement by weight of cement. The details of the mixes used throughout this investigation are given in Table 15.

Table 15: The main details of the mixes used throughout this investigation

<i>Mix designation</i>	<i>Cement kg/m³</i>	<i>HRM kg/m³</i>	<i>LSP kg/m³</i>	<i>Sand kg/m³</i>	<i>Gravel kg/m³</i>	<i>SP l/m³</i>	<i>Water l/m³</i>	<i>w/c ratio</i>
SCC without filler	500	/	/	775	825	4.5	190	0.38
SCC with HRM	450	50	/	775	825	4.5	190	0.38
SCC with LSP	350	/	150	775	825	4.5	190	0.54
SCC with HRM+LSP	300	50	150	775	825	4.5	190	0.54

2-3: Mixing, placing and curing procedures

The mixing process was performed in a drum laboratory mixer of 0.05 m³ to mix concrete ingredients, the mixer must be clean, moist and free from water. In this study Emborg's mixing procedure is adopted in order to achieve the required workability and homogeneity of SCC mixes. The fine aggregate are added to the mixer with 1/3 quantity of water and mixed for 1 minute. Then, the cement and mineral admixtures are added with another 1/3 quantity of water and mixed for 1 minute. After that, the coarse aggregate is added with the last 1/3 quantity of water and 1/3 dosage of superplasticizer, and mixing lasts for 1.5 minute then the mixture is left for 0.5 minute for rest. Finally, the 2/3 of the left over of the dosage of superplasticizer is added and mixed for 1.5 minute. The mixture is then discharged, tested and cast; the total time of mixing was about 5 minute^[10].

The placing process of the concrete mix is the most critical moment. For SCC mixes which requires not any compaction works, the mixes being poured into the tight steel molds until its fully filled without any compaction. All steel molds were prepared for mixing by placing oil along the interior surfaces of the mold in order to prevent adhesion with concrete after hardening. All specimens were demoulded after 24 hr and 28 days initial curing in tap water was performed. After that, half-specimens were partial submerged in a curing tank containing aggressive solution at concentration identical to those existing in soil and groundwater of southern parts of Iraq, while other half of specimens were kept in tap water until the end of long-term curing (i.e. 180 days).

3. Results and Discussion

3-1: Fresh SCC properties

The fresh properties of each mix are evaluated and compared with the literature. The tests results of slump flow, L-box, U-box and V-funnel are shown in Table 16. These results are within the acceptance criteria of (EFNARC,2005)^[10].

Table 16: Results of fresh properties of SCC mixes

Mix Designation	Slump flow		V-funnel		L-box			U-box ΔH (mm)
	D (mm)	T _{50cm} (sec)	T _v (sec)	T _{5min.} (sec)	BR /	T ₂₀ (sec)	T ₄₀ (sec)	
SCC without filler	725	3.6	7	8.5	0.88	1.3	2.8	15
SCC - HRM	690	4.3	8	10	0.83	1.43	3.75	17
SCC - LSP	750	3	6.5	7.5	0.9	1.25	2.5	12.5
SCC- HRM+LSP	710	4.1	7.4	9.2	0.85	1.36	3	15

3-2: Hardened SCC properties

3-2-1: Compressive strength

The compressive strengths of all the test specimens were determined from 150 mm cube specimens. Table 17 summarizes the compressive strength values for all SCC mixes at a various ages of immersion in tap water and (Cl⁻+SO₄²⁻) solution. As shown in Fig.1 all SCC specimens cured in tap water exhibit a continuous increase in compressive strength with the progress of age. This increase in compressive strength is due to the continuity of hydration process which forms a new hydration product within the concrete mass. As well as, Fig.2 illustrates that SCC specimens exposed to (Cl⁻+SO₄²⁻) solution exhibited continuous gain in compressive strength up to 120 days of exposure. Thereafter a slight reduction in strength was observed at 180 days. This reduction is due to attack of sulfate ions which give rise to the formation of expansive compounds such as ettringite and calcium aluminate hydrate. The strength deterioration is also due to leaching out of salts deposited in the voids of concrete.

Table 17: Results of compressive strength of SCC mixes

Compressive strength (MPa) (Tap water)					
Mix Designation	Before exposure at 28 days	60 days	90 days	120 days	180 days
SCC without filler	36.57	43.23	44.48	45.63	47.54
SCC-HRM	41.77	47.42	49.55	51.24	54.44
SCC-LSP	25.53	30.22	31.21	33.45	35.55
SCC-HRM+LSP	31	35.51	37.45	40	41.79
Compressive strength (MPa) (Cl+SO₄²⁻)					
Mix Designation	Before exposure at 28 days	60 days	90 days	120 days	180 days
SCC without filler	36.57	42.25	42.5	42.77	41.95
SCC-HRM	41.77	46.8	48.4	49.33	50.46
SCC-LSP	25.53	29.37	30.62	30.75	29.22
SCC-HRM+LSP	31	34.66	35.7	36.85	36.22

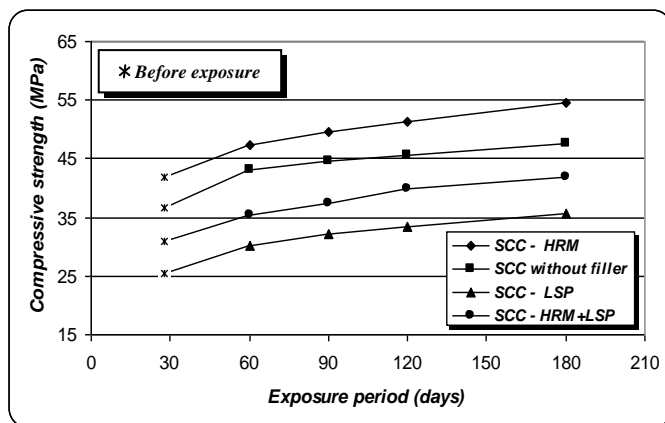


Fig.1 Compressive strength development of SCC mixes exposed to tap water

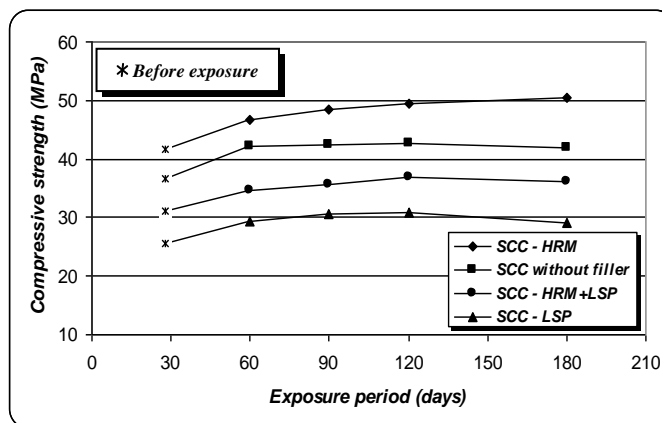


Fig.2 Compressive strength development of SCC mixes exposed to (Cl+SO₄⁻)

3-2-2: Splitting tensile strength

The splitting tensile strength developments of SCC mixes cured in tap water are presented in Table 18 and Fig.3. Also, the results of splitting tensile strength at various exposure periods for all types of SCC mixes are presented in Table 18 and Fig.4.

Results demonstrated that, in general all SCC specimens exhibited a continuous increase in splitting tensile strength with an increase in the age when they are immerse in tap water, as well as, the results indicated that the splitting tensile strength of SCC specimens subjected to (Cl+SO₄⁻) solution exhibited noticeable strength increase at 60 days of exposure, beyond this period a reduction in splitting tensile was observed. The increasing in splitting tensile strength at 60 days of test is most probably attributed to filling up of pores by reaction product and crystallization salts. This phenomena has also been reported by several investigators (Ganjian & Pouya, 2005)^[11].

Table 18: Results of splitting tensile strength of SCC mixes

Splitting tensile strength (MPa) (Tap water)					
Mix Designation	Before exposure at 28 days	60 days	90 days	120 days	180 days
SCC without filler	2.48	3.05	3.4	3.88	4.24
SCC-HRM	2.61	3.34	3.75	4.69	5.57
SCC-LSP	2.12	2.39	2.54	2.97	3.38
SCC-HRM+LSP	2.37	2.86	3.1	3.45	3.72
Splitting tensile strength (MPa) (Cl+SO ₄ ⁻)					
Mix Designation	Before exposure at 28 days	60 days	90 days	120 days	180 days
SCC without filler	2.48	3.12	3.33	3.55	3.45
SCC-HRM	2.61	3.39	3.69	4.48	4.88
SCC-LSP	2.12	2.45	2.29	2.61	2.57
SCC-HRM+LSP	2.37	2.9	2.84	3.12	3.1

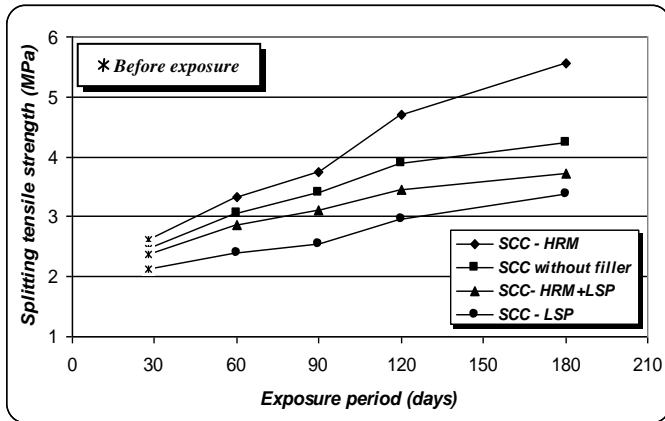


Fig.3 Splitting tensile strength development of SCC mixes exposed to tap water

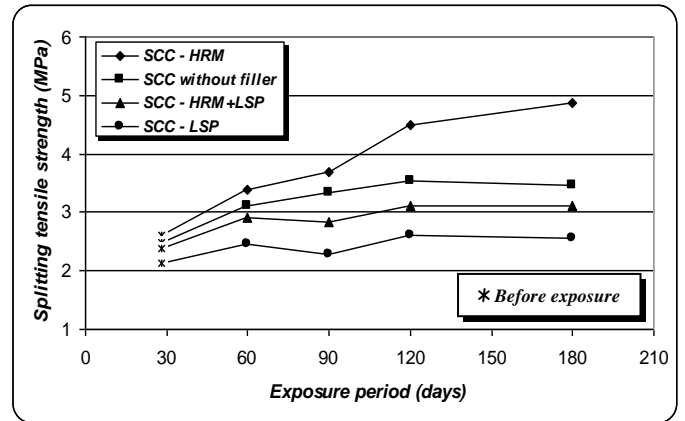


Fig.4 Splitting tensile strength development of SCC mixes exposed to (Cl+SO₄⁻)

3-2-3: Static modulus of elasticity

The static modulus of elasticity for all mixes is experimentally determined at ages 28, 60, 90, 120 and 180 days, the results of these tests are listed in Table 19, and plotted in Figs.5 and 6.

It can be observed from these results that SCC tends to have lower modulus of elasticity, the static modulus of elasticity of SCC specimens ranged between (20.54-38.26)GPa. The reason for this behaviour is due to the high content of ultrafines and additives as dominating factors, and, accordingly, minor occurrence of coarse and stiff aggregate at SCC.

The results also indicated that in general, all SCC specimens cured in tap water exhibited an increase in elastic modulus at all ages of the test compared with those exposed to (Cl⁻+ SO₄⁻) solution. This increase in elastic modulus of SCC specimens is due to the increase in modulus of elasticity of the matrix caused by the development of the interfacial bond strength between cement paste and fine aggregate.

Table 19: Results of static modulus of elasticity of SCC mixes

<i>Static modulus of elasticity (GPa) (Tap water)</i>					
<i>Mix Designation</i>	<i>Before exposure at 28 days</i>	<i>60 days</i>	<i>90 days</i>	<i>120 days</i>	<i>180 days</i>
<i>SCC without filler</i>	26.62	29.94	30.72	32.66	34.9
<i>SCC-HRM</i>	29.6	32	34.71	35.58	38.26
<i>SCC-LSP</i>	20.54	23.5	25	25.2	27.24
<i>SCC-HRM+LSP</i>	22.78	26.64	27.45	29.24	31.37
<i>Static modulus of elasticity (GPa) (Cl+SO₄⁻)</i>					
<i>Mix Designation</i>	<i>Before exposure at 28 days</i>	<i>60 days</i>	<i>90 days</i>	<i>120 days</i>	<i>180 days</i>
<i>SCC without filler</i>	26.62	28.68	28.84	28.74	27.19
<i>SCC-HRM</i>	29.6	31.2	33.83	33.81	32.98
<i>SCC-LSP</i>	20.54	23	23.17	22.18	21.65
<i>SCC-HRM+LSP</i>	22.78	25.16	25.85	25.72	24.38

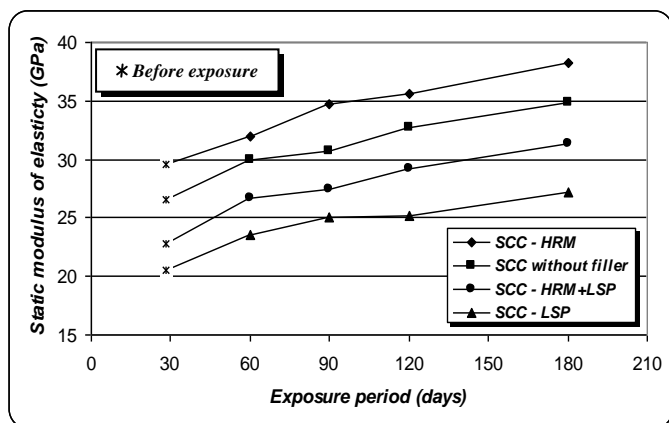


Fig.5 Static modulus of elasticity development of SCC mixes exposed to tap water

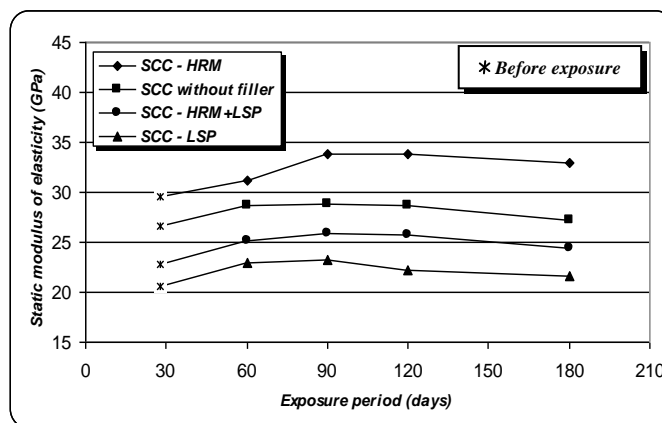


Fig.6 Static modulus of elasticity development of SCC mixes exposed to (Cl⁻+SO₄²⁻)

3-2-4: Weight change test

The test results of weight change versus time for SCC mixes cured in tap water are depicted in Table 20 and Fig.7, while the results of weight change for SCC exposed to (Cl⁻+SO₄²⁻) solution are shown in Table 20 and Fig.8.

A continuous increase of the weight, which was observed for all SCC specimens cured in tap water. The general increase of the weight may be attributed to the continuous water absorption, slowly compensating for the chemical shrinkage due to the hydration of the cement. Similar observation was reported by (Persson, 2003)^[12]. Whereas, the further increase in weight change of SCC specimens exposed to aggressive solution may be due to gypsum and potential ettringite formation.

Table 20: Results of weight change test of SCC mixes

Weight change (%) (Tap water)					
Mix Designation	Before exposure at 28 days	60 days	90 days	120 days	180 days
SCC without filler	0.2	0.28	0.34	0.41	0.48
SCC-HRM	0.12	0.19	0.26	0.31	0.39
SCC-LSP	0.28	0.35	0.48	0.53	0.61
SCC-HRM+LSP	0.25	0.33	0.42	0.49	0.53
Weight change (%) (Cl ⁻ +SO ₄ ²⁻)					
Mix Designation	Before exposure at 28 days	60 days	90 days	120 days	180 days
SCC without filler	0.2	0.33	0.41	0.53	0.74
SCC-HRM	0.12	0.2	0.31	0.4	0.51
SCC-LSP	0.28	0.44	0.61	0.78	0.98
SCC-HRM+LSP	0.25	0.4	0.52	0.67	0.85

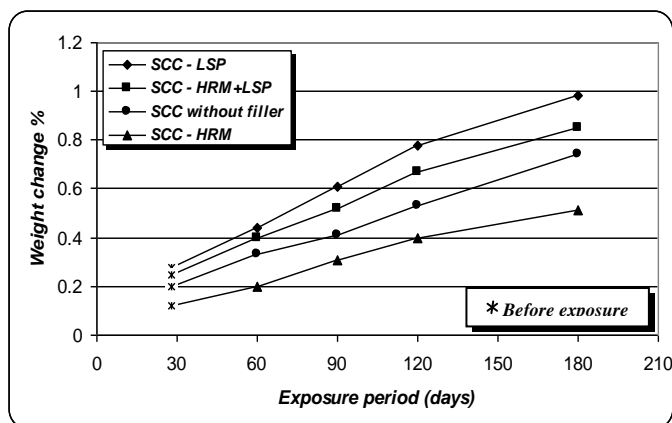


Fig.7 Weight change test development of SCC mixes exposed to tap water

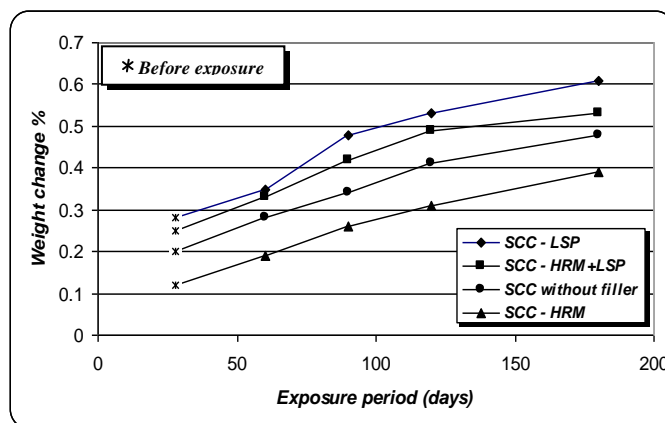


Fig.8 Weight change test development of SCC mixes exposed to (Cl⁻+SO₄²⁻)

3-2-5: Length change test

Length change values of SCC mixes in water and (Cl⁻ +SO₄²⁻) solution are summarized in Table 21, and illustrated in Figs.9 and 10.

The results of expansion indicated that SCC specimens cured in tap water continue to gain small amounts of length extension over time. This slight increase in length change values over time can be attributed to a considerable increase in the volume of pores due to C-S-H interlayer space and small capillaries during hydration. On the other hand, it may be due to the relaxation in gel due to the presence of water by moist curing. The results also elucidated that the expansion values development is more pronounced in SCC specimens exposed to (Cl⁻ +SO₄²⁻) solution compared to the corresponding concrete cured in tap water, This behaviour is attributed to the reaction of sulfate ions with calcium hydroxide and calcium aluminate hydrate to form gypsum and ettringite. The gypsum and ettringite formed as a result of sulfate attack is significantly more voluminous (1.2 to 2.2 times) than the initial reactants.

Table 21: Results of length change test of SCC mixes

Length change (%) (Tap water)					
Mix Designation	Before exposure at 28 days	60 days	90 days	120 days	180 days
SCC without filler	0.024	0.032	0.042	0.052	0.06
SCC-HRM	0.018	0.024	0.032	0.036	0.042
SCC-LSP	0.03	0.042	0.052	0.06	0.068
SCC-HRM+LSP	0.028	0.038	0.048	0.056	0.062
Length change (%) (Cl⁻+SO₄²⁻)					
Mix Designation	Before exposure at 28 days	60 days	90 days	120 days	180 days
SCC without filler	0.024	0.036	0.054	0.08	0.122
SCC-HRM	0.018	0.026	0.038	0.052	0.074
SCC-LSP	0.03	0.052	0.084	0.12	0.172
SCC-HRM+LSP	0.028	0.044	0.066	0.096	0.142

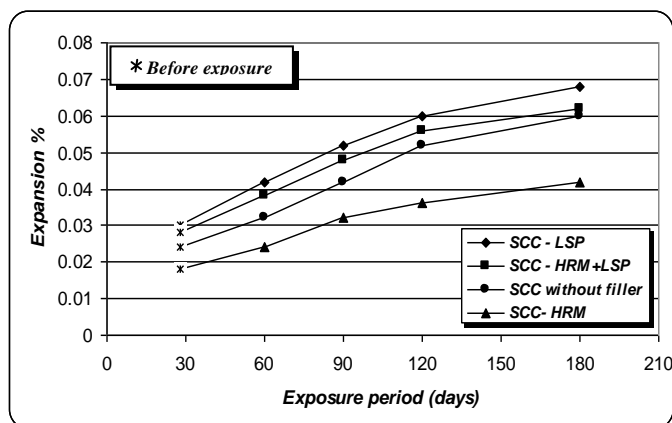


Fig.9 Length change test development of SCC mixes exposed to tap water

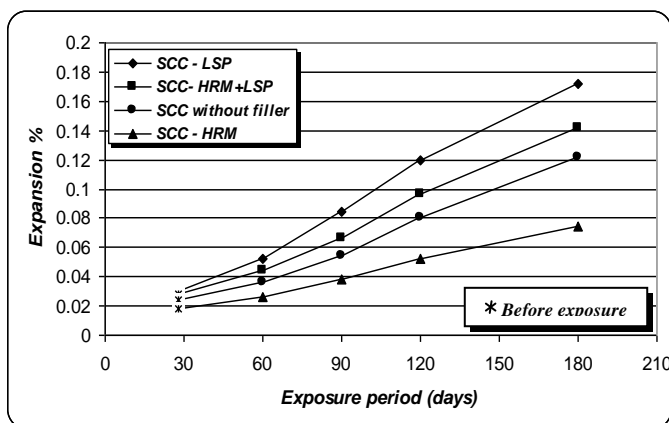


Fig.10 Length change test development of SCC mixes exposed to (Cl+SO₄⁻)

3-2-6: Ultrasonic pulse velocity

The values of ultrasonic pulse velocity measurements for SCC mixes at different curing ages are presented in Table 22, and plotted in Figs.11 and 12.

The test results show that the velocity of the ultrasonic waves for all SCC specimens cured in tap water increases with the increase in age up to 180 days. This behaviour is mainly attributed to the increase in the density of concrete with age and the reduction in points of discontinuity.

The test results also indicate that all SCC specimens exposed to (Cl+SO₄⁻) solution showed a reduction in U.P.V at all exposure periods compared to corresponding SCC cured in tap water, This behaviour is attributed to the formation of micro-cracks resulted by sulfate attack, and these micro-cracks connecting to each other to form larger cracks over time of exposure. In such a case, the pulse will diffracted around the larger cracks, thereby increasing the travel path and travel time, leading to decrement in pulse velocity.

Table 22: Results of U.P.V of SCC mixes

U.P.V (km/sec) (Tap water)					
Mix Designation	Before exposure at 28 days	60 days	90 days	120 days	180 days
SCC without filler	3.98	4.28	4.45	4.5	4.64
SCC-HRM	4.2	4.54	4.64	4.78	4.94
SCC-LSP	3.75	4.02	4.1	4.16	4.32
SCC-HRM+LSP	3.81	4.16	4.33	4.41	4.55
U.P.V (km/sec) (Cl+SO ₄ ⁻)					
Mix Designation	Before exposure at 28 days	60 days	90 days	120 days	180 days
SCC without filler	3.98	4.2	4.32	4.4	4.37
SCC-HRM	4.2	4.5	4.59	4.68	4.73
SCC-LSP	3.75	3.95	4.02	4.02	3.95
SCC-HRM+LSP	3.81	4.09	4.2	4.24	4.2

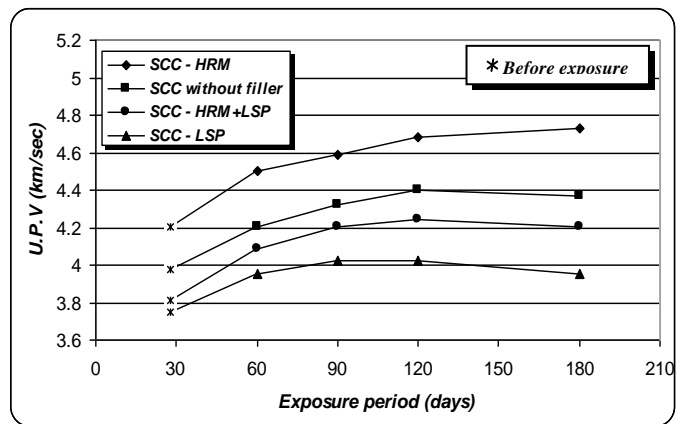
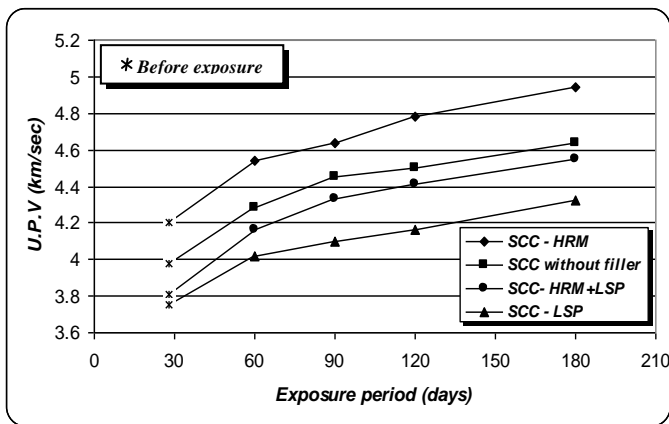


Fig.11 U.P.V development of SCC mixes exposed to tap water

Fig.12 U.P.V development of SCC mixes exposed to (Cl+SO4⁻)

4. Conclusion

Based on the test results obtained from experimental program and the interpretation of the results, the following conclusions can be drawn:

1. SCC mixes cured in tap water showed a considerable improvement in compressive strength, splitting tensile strength, static modulus of elasticity and U.P.V as compared with the mixes exposed to (Cl+SO₄⁻) solution.
2. The employment of 10% HRM as a partial replacement by weight of cement was found effective in improving the resistance of SCC to sulfate attack.
3. In compressive strength test, the percentage increase in compressive strength of HRM-SCC, SCC without filler, HRM-LSP-SCC and LSP-SCC cured in tap water were 7.88%, 13.3% and 15.3% and 21.6%, respectively measured relative to their corresponding concrete exposed to (Cl+SO₄⁻) solution at the age of 180 days.
4. In splitting tensile strength test, the percentage increase in tensile strength of HRM-SCC, SCC without filler, HRM-LSP-SCC and LSP-SCC cured in tap water were 14.1%, 22.9% and 20% and 31.5%, respectively measured relative to their corresponding concrete exposed to (Cl+SO₄⁻) solution at the age of 180 days.
5. The static modulus of elasticity of HRM-SCC, SCC without filler, HRM-LSP-SCC and LSP-SCC cured in tap water increased considerably at all ages compared to their corresponding SCC exposed to (Cl+SO₄⁻) solution. At 180 days of exposure to (Cl+SO₄⁻) solution, the percentage reduction in static modulus of elasticity were 13.8%, 22.1%, 20.5% and 22.3%, respectively measured relative to their corresponding concrete cured in tap water.
6. A continuous increase of the weight change % over 180 days was observed for all concrete specimens exposed to tap water and (Cl+SO₄⁻) solution.
7. SCC made with high reactive metakaolin achieved very low sulfate expansion compared to that of LSP-SCC, HRM-LSP-SCC and SCC without filler. The percentage increase in expansion values after 180 days of exposure to (Cl+SO₄⁻) solution were 64.8%, 91.9% and 132.4% for SCC without filler, HRM-LSP-SCC and LSP-SCC respectively measured relative to HRM-SCC.

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