Influence of Internal Sulfate Attack on Some Properties of Self Compacted Concrete

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ABSTRACT

Self-compacted concrete (SCC) is a highly flowable concrete, with no segregation which can be spread into place by filling the structures framework and permeate the reinforcement without any compaction or mechanical consolidation **ACI 237R-14**. One of the most important problems faced by concrete industry in Iraq and Gulf Arab land is deterioration due to internal sulfate attack (ISA) that causes damage of concrete and consequently reduces its compressive strength, increases expansion and may lead to its cracking and destruction.

The experimental program was focused to study two ordinary Portland cements with different chemical composition with (5, 10 and 15) % percentage of high reactivity metakaoline (HRM) as a cement replacement and with W/Cm ratio 0.35. The SCC mixes with AL Shemalia OPC cement that produced in Saudi Arabia (C_3A=7.02%) shows higher resistance to ISA than mixes with Tasluja OPC cement that is produced in Iraq (C_3A=4.13%). The results indicate that the SCC mixes containing 15% HRM shows higher opposition to ISA. A good correlation was obtained between concrete splitting tensile strength and compressive strength from the results of this study.

Keywords: self compacted concrete (SCC), high reactive metakaoline (HRM)

تأثير مهاجمة الاملاح الداخلية على بعض خواص الخرسانة ذاتية الرص

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الخلاصة

تعرف الخرسانة ذاتية الرص بأنها خرسانة ذات أنسيابية عالية بدون حصول أنعزال والتي بالامكان أنتشارها ، و ملئ القالب و تغليف حديد التسليح بدون أي رص ميكانيكي حسب متطلبات الجمعية الامريكية 237R للعام 2014. تعد مهاجمة الاملاح الداخلية من أهم المشاكل التي تواجه صناعة الخرسانة في العراق واراضي الخليج العربي والتي تؤدي الى التدهور الذي يسبب تضرر الخرسانة ويؤدي بالنتيجة الى تقليل مقاومة الانضغاط ، وزيادة التمدد والذي قد يؤدي الى تشققها و دمارها.

البرنامج العملي لهذه الدراسة يبحث تأثير التركيب الكيميائي المختلف لإثنين من السمنت البورتلاندي الاعتيادي ،أضافة نسب من الميتاكاؤلين العالي الفعالية كأستبدال من وزن السمنت (5، 10 و 15)% ونسبة وزن ماء الى سمنت 0,35 .الخلطات الخرسانية ذاتية الرص المستخدم فيها السمنت الاعتيادي الشمالية المصنوع في المملكة العربية السعودية (C_3A=7.02%) أظهرت مقاومة اعلى لمهاجمة الاملاح الداخلية مقارنة بالسمنت الاعتيادي طاسلوجة المصنوع في العراق (C_3A=4.13%). النتائج تشير الى أن الخلطات الخرسانية ذاتية الرص الحاوية على 15% من الميتاكاؤلين العالي الفعالية اظهرت مقاومة اعلى لمهاجمة الاملاح الداخلية. وهناك علاقة بين نتائج مقاومة الانضغاط للخرسانة ومقاومة شد الانفلاق اوجدت من نتائج هذه الدراسة.

الكلمات الرئيسية: خرسانة ذاتية الرص، الميتاكاؤلين العالي الفعالية .

1. INTRODUCTION

Self compacted concrete (SCC) was first developed in Japan 1988 as a mean to create uniformity in the quality of concrete. The SCC differs from conventional concrete in main characteristic features, namely, appropriate flowability, no segregation and no blocking tendency. Durability was the main concern and the purpose to develop a concrete mix that would reduce or eliminate the effect of internal sulfate attack. An excess amount of gypsum in concrete from either, cement or aggregates is of great importance. This is because of their adverse effect on the structure developed of cement paste. Excess percentages of sulfate may impair the physical and mechanical properties of the hardened concrete at subsequent ages. The ettringite formation when occurs homogeneously and immediately (within hours or days) in a mixture or in a deformable concrete – early ettringite formation (EEF) - the related expansion does not cause any significant localized disruptive action. This happens when ground gypsum reacts with anhydrous calcium aluminates within some hours (set regulation) or when a calcium aluminates sulfate (C_4A_3S) hydrates within few days producing a relatively small, homogeneous, harmless and rather useful stress (expansive cements for shrinkage compensating concretes). On the other hand, when ettringite forms heterogeneously and later (after months or years) - delayed ettringite formation (DEF) - the localized related expansion in a rigid hardened concrete produces cracking, spilling, and strength loss, **Collepardi, 2005.**

Husaian, 2008 has studied the influence of high reactivity metakaoline (HRM) as a partial replacement by weight of cement on the properties of SCC in fresh and hardened state. Many different mixes of SCC have been studied, in which concrete mixes contain 500kg/m^3 cement and water/cement ratios ranging between 0.35 - 0.58. Result indicated that the workability of all studied mixes is very good. The inclusion of 10% HRM as a partial replacement by weight of cement decreases the flowability and increases the viscosity of fresh concrete and this leads to use high superplastizer dosage. The addition of HRM as replacement for the weight of cement increases the value of compressive strength and splitting tensile strength by 5 - 22 %, 3 - 25 % respectively as compared with reference mixes without any addition of HRM.

Ahmed, 2010 concluded in her study that the compressive strength was increased to (29, 45 and 69)% for the SCC concrete mixes with replacement of cement by HRM (5, 10 and 15)% by weight of cement at 90-days for the different mixes with 500 Kg/m^3 of cement and 170 Kg/m^3 water. **Salih, and Salman, 2011** results showed that SCC mixes containing metakaoline required higher superplastizer content to 9% by weight of cement compared with 8% by weight of cement for mixes without pozzolanic materials to maintain the self compatibility of mixes. And they saw that a significant improvement was observed in the mechanical properties of mixes including compressive and splitting tensile strength, modulus of rupture, static modulus of elasticity, and impact resistance. The improvement percentages at 28 days were (8.43%, 7.6%, 6.08%, 4.03%, and 30.30%) respectively for SCC with high reactive metakaoline mixes.

The resistance of high performance concrete to internal sulfate attack after adding natural gypsum to sand as a partial replacement by weight was studied by **AL-Robayi, 2005**. The sulfate contents (0.5, 1.5, 2.0, and 2.5 %) in fine aggregate were studied. He concluded that there was a reduction in strength at early ages (less than 28 days) for normal and high performance concrete. This reduction was related to the increase of sulfur trioxide content (SO_3) in sand. At later ages (more than 28 days) in High Performance Concrete, the reduction in strength decreased while in normal concrete it increased continuously. The low permeability and pozzolanic action of HRM could be the cause of strength improvement. **Alwash, 2013** studied the effect of using local fillers (pigment and metakaolin) on self compacting concrete, $SO_{3\%}$ content in sand were investigated by using five levels, these levels were [0.24% , 0.5% , 1% , 2% , and 3%], which yielded [3.05% , 3.47% , 4.28 % , 5.9% , and 7.52%] total SO_3 content by weight of cement respectively for SCC mixes with pigment powder filler and [3.08%, 3.5% ,4.31% , 5.94% , and 7.56%] for self compacted concrete mixes with metakaolin powder. There is an optimum gypsum content (SO_3=1.0%) by wt. of sand which gives the highest results in compressive strength, flexural strength and ultrasonic pulse velocity of self compacted concrete. The mechanical properties will be decreased as gypsum content increases beyond this limit.

2. MATERIAL CHARACTERISTICS

2.1 Cement

Two ordinary Portland cements conforming the **IQS NO.5/1984** are used. Tasluja OPC cement that is produced in Iraq and AL Shemalia OPC cement that is produced in Saudi Arabia. The chemical analysis of the two cements used is listed in **Table 1,** while **Table 2** consist of the physical properties for the same cements.

2. 2 Fine aggregate

The natural fine aggregate used in this study is from Al-Ukhaider district. The grading of sand is within the Iraqi specification **IQS NO.45/1984** and affirms to zone two. **Table 3** shows the sieve analysis of fine aggregate used and **Table 4** shows the physical properties and sulfate content of fine aggregate used.

2.3 Natural gypsum

The natural gypsum was brought from the State Company of Geological Survey and Mining. It was crushed and grinded by hammer and passed through the same sieve set of fine aggregate used in the mix of internal sulfate attack to get the same gradation and to avoid the affect of large surface area of particles, the gypsum was used as a partial replacement by weight of sand with limited percentage. To control the content of SO_3, the quantity of natural gypsum add to the sand is according to Eq.(1).

$$W= [(R- M \%) \times S]/N \tag{1}$$

where:
W is the weight of natural gypsum ground needed to be added to sand (kg).
R is the percentage SO_3 required in sand %.
M is the actual SO_3 in sand (0.1 %).
S is the weight of sand in the mix (kg).
N is the percentage SO_3in the used gypsum.
The chemical composition of the gypsum used is listed in **Table 5.**

2.4 Coarse aggregate

A crushed natural coarse aggregate with maximum size of 14mm was used. It was brought from Al-Niba`ee region. The grading of the aggregate used is within the Iraqi specification **IQS NO.45/1984.** The coarse aggregate sieve analysis is shown in **Table 6,** while **Table 7 s**hows the physical properties and sulfate content for the same aggregate used.

2.5 Mixing water

The water used in this study was potable water for both casting and curing of concrete specimens.

2.6 High reactive metakaoline (HRM)

HRM is a reactive aluminosilicate pozzolan produced by clinking China clay at temperatures between 700 – 900°C. In this work, the locally available China clay was burned using the burning kiln at 700°C for one hour then left to cool down**, Raya, 2003** and **Justice, 2005.** The chemical composition of HRM in powder form is shown in **Table 8**, satisfying the **ASTM C 618 –08.** At 28-days the accelerated pozzolanic strength activity index with Portland cement was 105% (min 75%). The specific gravity and the fineness were 2.62 and 19000 cm^2/g respectively.

2.7 Chemical admixture

A high performance concrete superplasticizer (Sika ViscoCrete -5930) is a third generation for concrete and mortar as chemical admixture was used in this research. It meets the requirements for superplasticizer according to **ASTM C494-05.T**ypes G and F. **Table 9** shows the typical properties of the superplasticizer used.

3. PREPARATION OF CONCRETE SAMPLES

3.1 Mix Proportion

The method of mix design for the self compacted concrete used in the study is accordance to **EFNARC, 2002.** The materials contents are revised after gaining acceptable self-compatibility by assessing fresh concrete tests. Water to cementituse is 0.35 used for all mixes in this study and the optimum dosage of superplasticizer (Sika ViscoCrete -5930) (1.2 liter for each 100 kg of cement) is prevailed from several trail mixes, by fixing the W/Cm ratios, and increasing the dosage of the admixture gradually to ensure the self-compatibility. The mix proportion is presented in **Table 10.**

3.2 Mixing, Casting and Curing of Concrete

The mixing process was done by manually operated mixer according to ASTM C192, 2006. Cast iron cube moulds, with dimensions of (150x150x150) mm and (150x300) mm cylindrical moulds are provided, cleaned and oiled before adding water to the mix. Nylon bag were used to cover the moulds, after 24hr the moulds were opened and the concrete were placed in water curing tanks until the time of test (7, 28, 90 and 180-day).

4. TEST PERFFORMED

4.1 Fresh concrete tests

4.1.1 Slump flow test and T50cm test

The horizontal free flow of self-compacting concrete is assessed by the slump flow test. This test is widely used; it gives an evaluation of resistance to segregation and an indication of filling ability. The benefit of T50cm test is to measure the viscosity of SCC by measuring the speed of flow, **EFNARK, 2002**.as shown in **Fig. 1**.

4.1.2 V-funnel test and V-funnel test at $T_{5minutes}$

This test is to estimate the filling ability and viscosity of the self-compacting concrete. High flow time can also be associated with low deformability due to a high paste viscosity, and with high inter-particle friction**, EFNARK, 2002**, as shown in **Fig. 2**.

4.1.3 L-Box test

The flow of self-compacted concrete is assessed to this test, and furthermore it gives a conception to reinforcement blocking. This test is largely used. It estimates passing and filling ability of SCC, **EFNARK, 2002**. As shown in **Fig. 3**.

4.2 Hardened concrete tests

4.2.1 Compressive strength test

The compressive strength test in this study was done according to the **BS 1881: Part 116: 1983**. The concrete cubes of (150x150x150) mm were tested at ages of (7, 28, 90, 180-day). The load at failure was registered and the compressive strength was calculated by taking the average of 3- cubes for each test age.

4.2.2 Splitting tensile strength

The splitting tensile strength test was carried out in accordance with the **ASTM C496-/C496M-11**. (150×300) mm cylindrical concrete specimens were used. This test was done at ages of (7, 28, 60, 90 and 180) days.

4.2.3 Ultrasonic pulse velocity (UPV)

According to the **ASTM C597–02.**The ultrasonic pulse velocity test was done using portable equipment called PUNDIT. The equipment was used with direct transmission method by placing the transducer on opposite face of the concrete cubes (150x150x150) mm.

5. RESULTS AND DISCUSSION

5.1 Fresh Concrete

The increased of total effective SO_3% content in all cases, resulted in a considerable decrease in the slump flow of the concrete presented in **Table 11.** For Iraqi and Saudi Arabia cements, slump flow values ranged between (776 - 800) mm and the T50 cm of slump flow values ranged between (2.2 - 4.51) sec. For the V–funnel test the time of the concrete to pass through ranges between (6.1-10.3) sec and L-box results ranged between (0.81-0.95).

5.2 Hardened Concrete

The results of compressive strength test for all concrete mixes used in this study are shown in **Table 12.** The results declared that all concrete mixes including (reference mix) shows a consecutive increase in compressive strength with the progress of age. This increase in compressive strength is submitted in **Fig. 4** and **Fig. 6** for all concrete mixes using Iraqi cement. The results showed that HRM when used improves the compressive strength of concrete and increases the resistance to ISA. This behavior is due to the consumption of $Ca(OH)_2$, which gives a micro filling action due to the higher pozzolanic reaction. The addition of 15% of HRM as a cement replacement increases the compressive strength for all mixes with age relative to their reference. The percentage increase of compressive strength at 28 days are (14.35%) and (20.6%) for total SO_3% by wt. of sand (1.5) for Tasluja OPC and AL Shemalia OPC cements respectively. This behavior is due to reaction of HRM (silica –based product) with $Ca(OH)_2$ during the hydration of C_3S and C_2S of cement produces CSH gel contributes the densification of concrete matrix, pore-size and grain-size refinement processes **Justice, 2005**. The reduction of compressive strength increases with increase in total SO_3% content as it is presented in the results for both types of cement. This behavior is due to the formation of DEF which is a type of internal sulfate attack that occurs when the constituents of concrete provide an initial source of sulfate, **Pavoine, et al., 2012.** That affects cementitious materials which possibly causes cracking and swelling of concrete**, Collepardi, 2003.**

The concrete mixes using AL Semalia cements produced in Saudi Arabia with higher C_3A content (C_3A =7.02%) show higher resistance to ISA than Tasluja cement produced in Iraq (C_3A =4.13%) and that is confirmed with the literatures.

Table 12 also shows the results of splitting tensile strength for all mixes. The splitting tensile strength of concrete mixes contained HRM increases with the progress of curing age and it increases with increase the HRM a cement replacement to 15% as presented in **Fig. 5** and **Fig. 7** for all concrete mixes using Iraqi cement. These results are due to the reduction in the micro cracking and by strengthening the transition zone because of the pozzolanic reaction**, Naji, 2012.** The increase in splitting tensile strength for reference mix is continued for all ages due to the continuity of hydration process, other concrete specimens the splitting tensile strength is reduced with the increase of total SO_3% content due to the effect of ISA as the formation of DEF. **Fig. 9** shows the relationship between compressive strength and splitting tensile strength at different ages with R^2 equal to 0.952.

Table 13 shows the Ultrasonic pulse velocity (UPV) results for reference mixes and concrete mixes with HRM as a cement replacement with different percentages of sulfate content and this is submitted in **Fig. 8.** The results demonstrate that the pulse velocity for reference mix is increased with the age. The other mixes with the increased total SO_3% content, the pulse velocity is less increased than reference mix with the age and that increase continued till 90-day then the pulse velocity starts to decrease. That is compatible with the results of compressive strength test. The relation between the compressive strength with ultrasonic pulse velocity for different concrete mixes demonstrated in **Fig. 10**. The results indicate that the compressive and pulse velocity are related to each other with R^2 equal to 0.9309.

When using SO_3% by wt. of sand more than 1.5% there is reduction in compressive strength, splitting tensile strength and ultrasonic pulse velocity in later ages (180 days) than (90 days) curing age compared with other mixes containing less than 1.5% of SO_3% by wt. of sand.

6. CONCLOSIONS

1. A good workability properties of fresh concrete was detected for all SCC mixes containing Sika ViscoCrete -5930 and HRM , the results shows that the slump flow test ranges between

(767- 800) mm and T50 cm results range between (2.2-4.51) sec. The V–funnel time results ranges between (6.1-10.3) sec and L-box results ranges (0.81-0.95).
2. The results show that mixes containing HRM as cement replacement materials improves the compressive strength of concrete and increases the resistance to ISA.
3. The concrete mixes using AL Shemalia OPC cement that produced in Saudi Arabia (C_3A =7.02%) cements show higher resistance to ISA than Tasluja OPC cement that produced in Iraq (C_3A =4.13%).
4. The compressive strength and splitting tensile strength of concrete mixes contained HRM increases with the progress of curing age for mixes containing less than 1.5% of SO_3 by wt. of sand. By increasing the SO_3 % beyond this limit all the mechanical properties will be declined spicily at later ages.

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NOMENCLATURE

ACI	American Concrete Institute
ASTM	American Society for Testing and Materials
BS	British standard
DEF	delayed ettringite formation
EEF	early ettringite formation
HRM	high reactive metakaoline
IQS	Iraq standard specification
ISA	internal sulfate attack
SCC	self compacted concrete

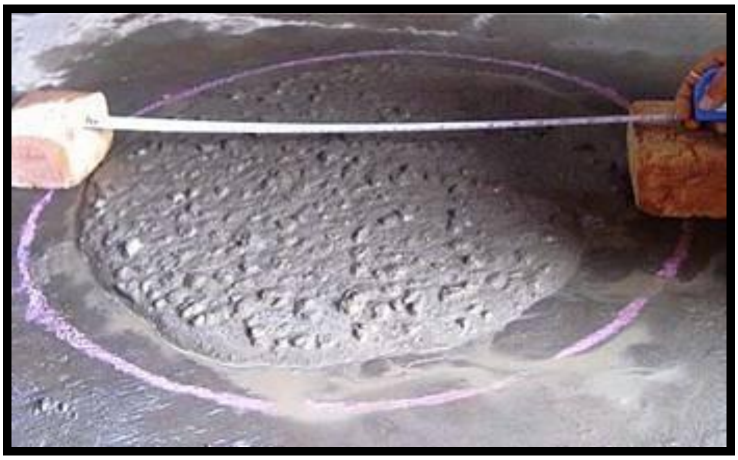

Figure 1. Slump flow test.

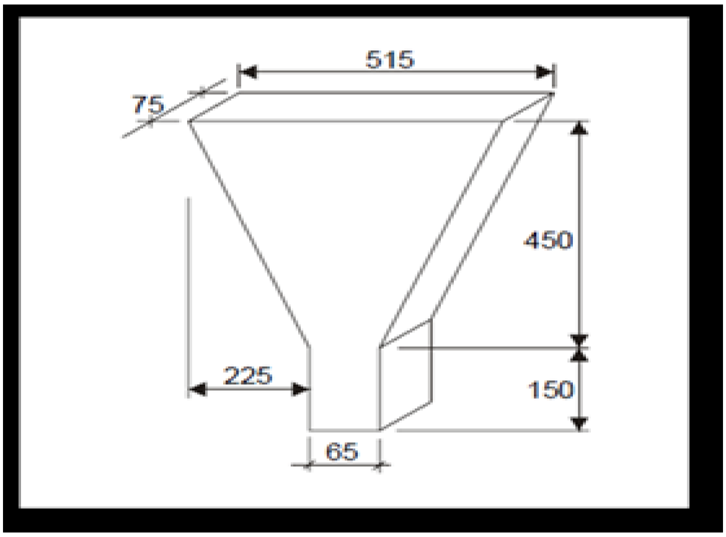

Figure 2. V-Funnel test.

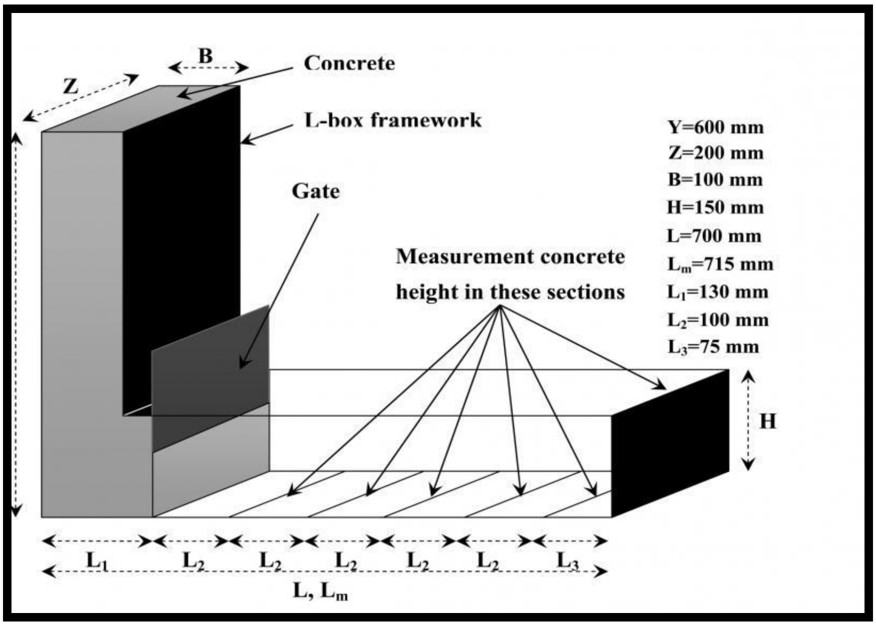

Figure 3. L-Box Test.

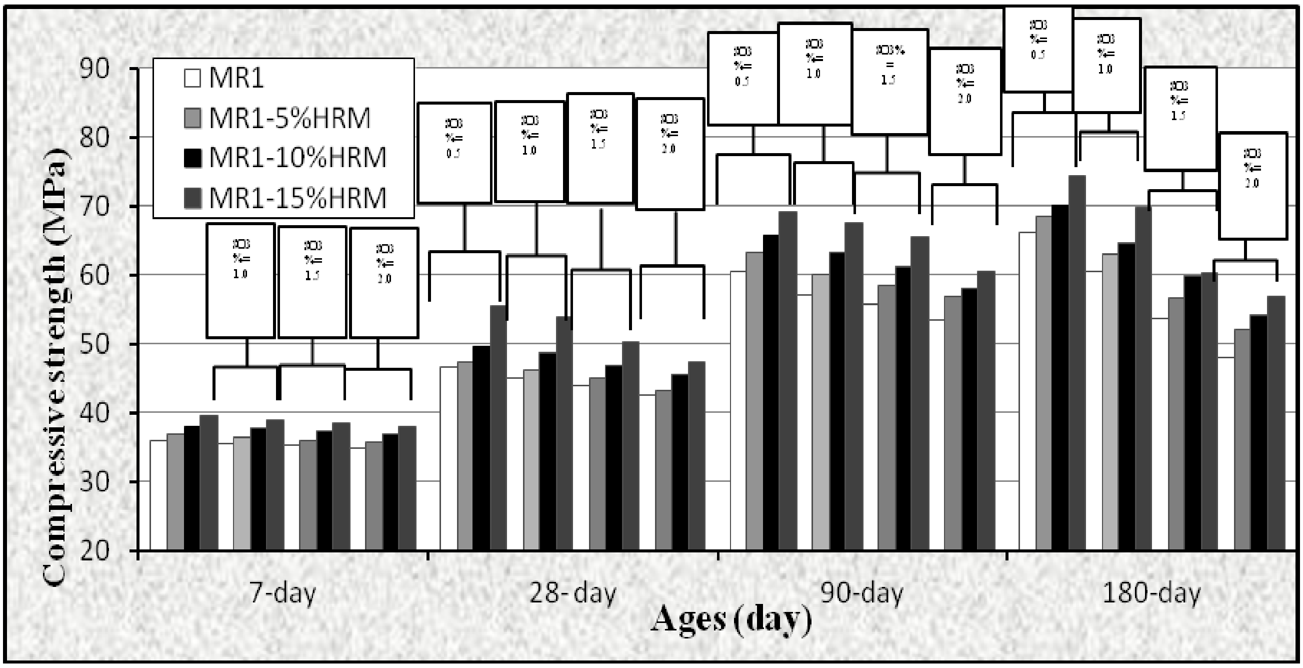

Figure 4. Compressive strength verses ages for different SO_3% content of SCC mixes using Iraqi Cement.

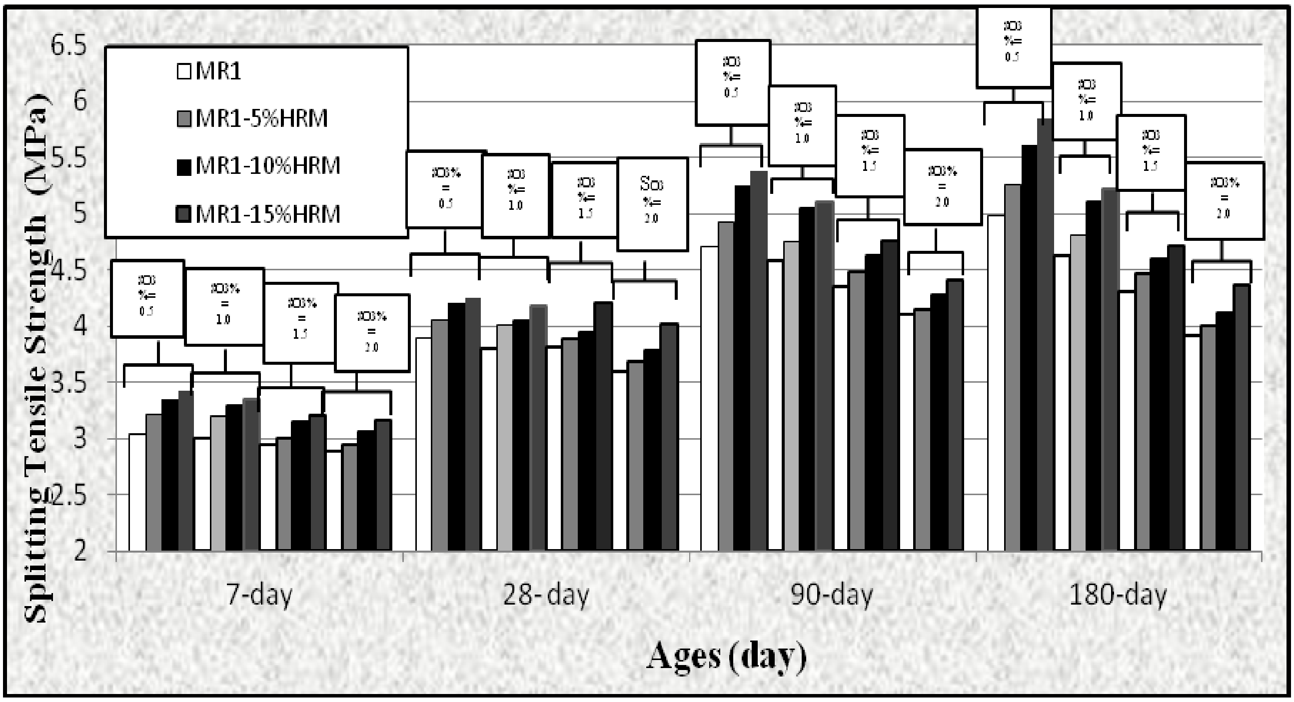

Figure 5. Splitting tensile strength verses ages for different SO_3% content of SCC mixes using Iraqi Cement.

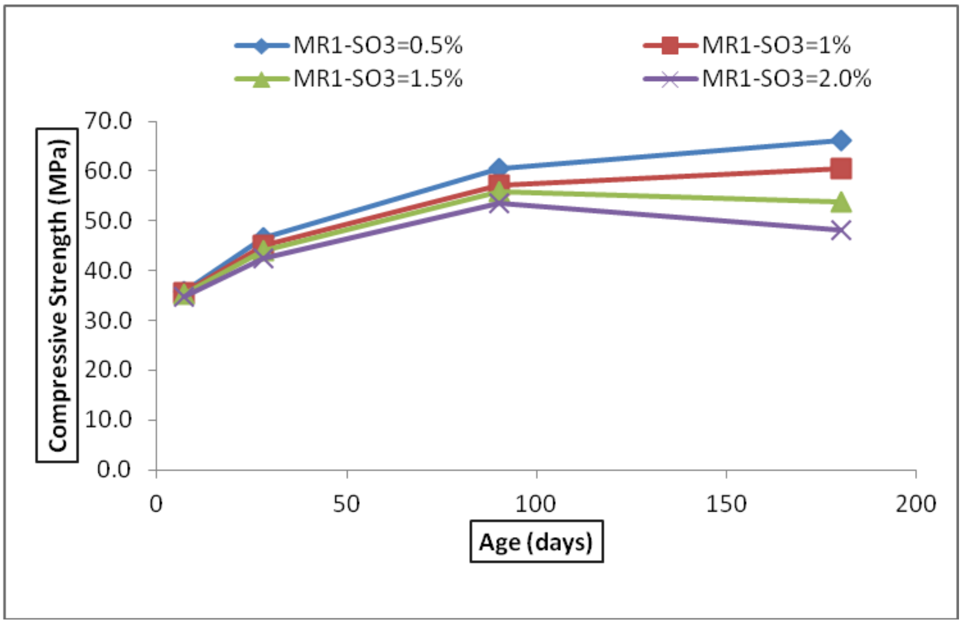

Figure 6. Relationship between compressive strength and Age for Different SO_3% content of SCC mixes using Iraqi Cement.

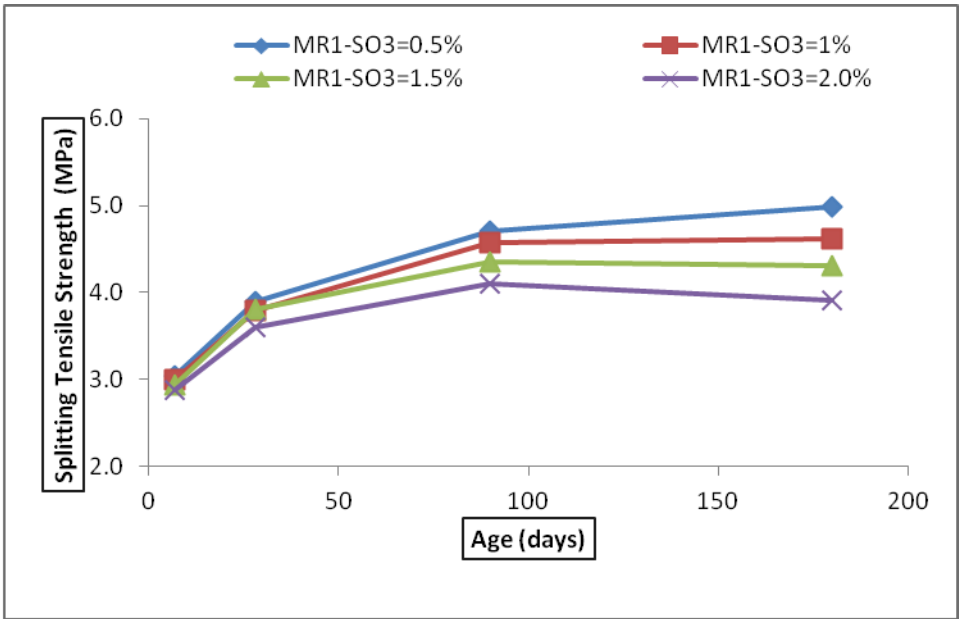

Figure 7. Relationship between Splitting tensile strength and Age for Different SO_3% content of SCC mixes using Iraqi Cement.

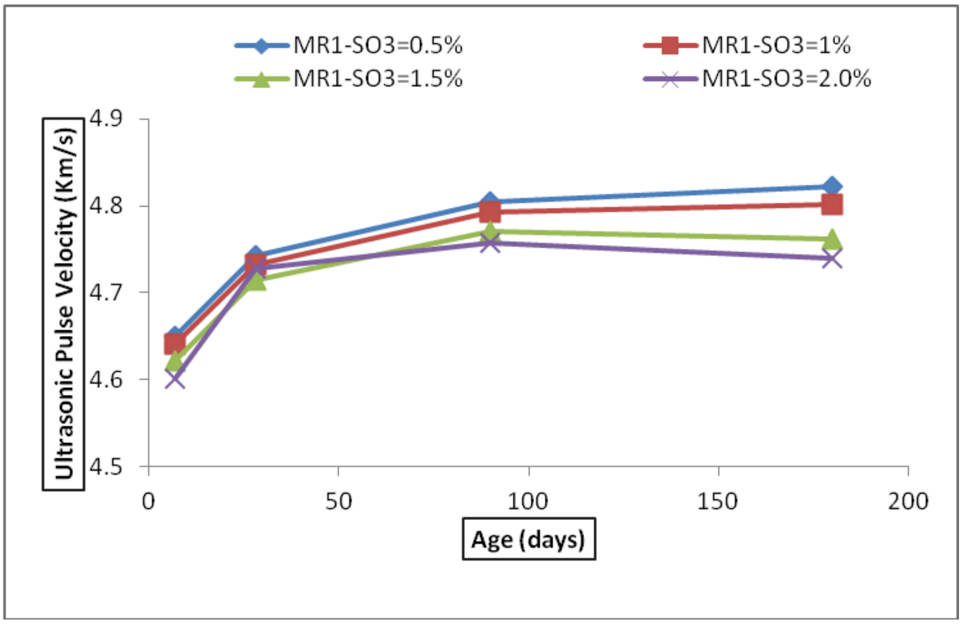

Figure 8. Relationship between Ultrasonic Pulse Velocity and Age for Different SO_3% content of SCC mixes using Iraqi Cement.

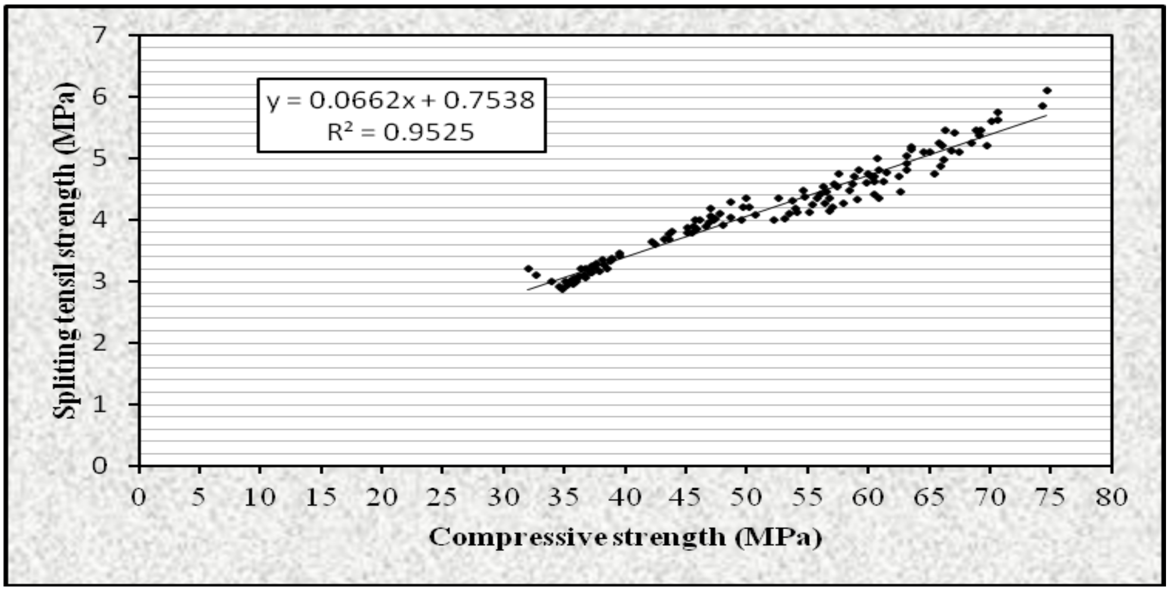

Figure 9. Relationship between compressive strength and splitting tensile strength.

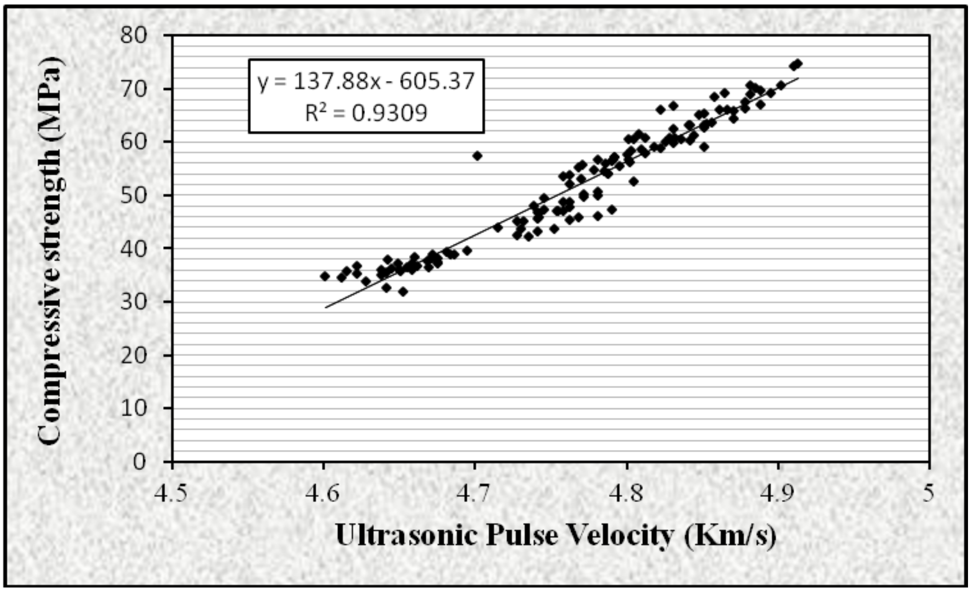

Figure 10. Relationship between compressive strength and ultrasonic pulse velocity.

Table 1. Chemical composition of cement used.

Oxide Content %	Tasluja OPC cement (Iraqi)	AL Shemalia OPC cement (Sudi Arabia)	Limits of Iraqi specification IQS NO.5/1984
SiO_2	20.6	20.4	-
Al_2O_3	4.49	5.1	-
Fe_2O_3	4.59	3.84	-
CaO	60.23	60.34	-
SO_3	2.1	2.68	≤ 2.8 %
MgO	2.97	4.58	≤ 5 %
L.O.I	2.11	2.35	≤ 4 %
I.R	1.2	0.62	≤ 1.5 %
L.S.F	0.97	0.89	0.66-1.02
Compound Composition (Bogue` s Equation)			
C_3S	51.85	43.20	-
C_2S	19.89	25.95	-
C_3A	4.13	7.02	-
C_4AF	13.96	11.68	-

- Chemical tests were conducted by Central Organization for Standardization and Quality Control, Ministry of Planning

Table 2. Physical properties of cements used.

Properties	Tasluja OPC Cement (Iraqi)	AL Shemalia OPC Cement (Sudi Arabia)
Specific surface (Air permeability test),m^2/kg	350	365
Autoclave expansion,%	0.04	0.04
Setting time (vicate apparatus), a. Initial - hr:min b. Final - hr:min	 1:30 4:40	 1:25 4:30
Compressive strength MPa(N/mm^2): 3-days 7-days	 17.5 26.5	 16.8 27.2

- Physical tests were conducted by the Central Organization for Standardization and Quality Control, Ministry of Planning.

Table 3. Sieves analysis of fine aggregate.

Sieve Size	% Passing by Weight	Limits of IQS NO.45/1984 (Zone 2)
10mm	100	100
4.75mm	95.1	90-100
2.36mm	80.5	75-100
1.18mm	72.8	55-90
600µm	45.5	35-59
300µm	24.5	8-30
150µm	4.8	0-10

Table 4. Physical properties and sulfate content of fine aggregate used in experimental work.

Properties	Results	IQS NO.45/1984
Fineness modulus	2.76	
Specific gravity	2.58	
Absorption ,%	1.2	
Moisture content,%	0.4	
Material passing sieve size 75µm%	2.5	Max. 5% for natural fine aggregate
Sulfate content (SO_3), %	0.1	Max. 0.5%

-Tests are carried out in the Material Laboratory of the Engineering College -Baghdad University

Table 5. The chemical properties of Gypsum.

Compound Composition	Percent %
SiO_2	8.34
R_2O_3	2.25
CaO	32.02
MgO	0.95
SO_3	42.1
I.R	6.99

Table 6. Sieves analysis of coarse aggregate with 14mm maximum size.

Sieve size	% Passing by Weight	Limits of IQS NO.45/1984
20mm	100	100
14mm	95	90-100
10mm	75	50-85
5mm	4	0-10

Table 7. Physical properties and sulfate content of coarse aggregate.

Properties	Results	IQS NO.45/1984
Specific gravity (SSD)	2.65	--
Absorption ,%	0.3	--
Moisture content ,%	0.2	--
Passing sieve size 75µm,%	1.5	Max. 3%
Sulfate content (SO_3),%	0.03	Max. 0.1%

-Tests are carried out in the Material Laboratory of the College of Engineering-Baghdad University

Table 8. Chemical analysis of HRM

Oxides %	Content (%)	Mineral Admixture Class N ASTM C 618 –03
SiO_2	57.46	-
Fe_2O_3	1.52	-
Al_2O_3	36.82	-
CaO	0.9	-
SO_3	< 0.07	Max. 4.0%
L.O.I	1.3	Max. 10%
Moisture content	0.82	Max. 3.0%
$SiO_2 + AL_2O_3 + Fe_2O_3$ min %	95.8	Min. 70%

-The chemical analysis done by Geological Survey and Mining

Table 9. Typical properties of superplasticizer (Sika ViscoCrete -5930)

Form	Viscous liquid
Basis	Aqueous solution of modified polycarboxlate
Appearance	Turbid liquid
Relative density	1.08 kg/1t.±0.005

Table 10. The mix proportions used in preparing the test specimens

Index	Cement type	Cement (kg/m^3)	HRM (kg/m^3)	Fine aggregate (kg/m^3)	Coarse aggregate (kg/m^3)
Ref. -MR1	Iraqi	560	0	728	784
MR1-5%HRM		532	28	728	784
MR1-10%HRM		504	56	728	784
MR1-15%HRM		476	84	728	784
Ref.-MR2	Saudi Arabia	560	0	728	784
MR2-5%HRM		532	28	728	784
MR2-10%HRM		504	56	728	784
MR2-15%HRM		476	84	728	784

Table 11. Fresh concrete test results (slump flow, T 50cm slump flow, V-funnel and L-box)

Mixes No.	Cement type	SO_3 (%) by wt. of sand	Tests			
			Slump flow (mm)	T 50cm slump flow (sec)	V-funnel (sec)	L-box (h_2/h_1)
			650-800*	2-5*	6-12*	0.8-1.0*
Ref. -MR1	Iraqi	0.5	800	2.2	6.1	0.95
MR1-5%HRM			798	2.25	6.15	0.93
MR1-10%HRM			795	2.3	6.31	0.91
MR1-15%HRM			792	2.4	6.45	0.9
Ref.-MR2	Saudi Arabia		801	2.3	6.11	0.94
MR2-5%HRM			798	2.35	6.17	0.94
MR2-10%HRM			796	2.4	6.33	0.92
MR2-15%HRM			791	2.45	6.51	0.9
Ref. -MR1	Iraqi	1.0	794	2.5	7.01	0.88
MR1-5%HRM			791	2.56	7.11	0.87
MR1-10%HRM			788	3.1	7.27	0.85
MR1-15%HRM			785	3.15	7.34	0.85
Ref.-MR2	Saudi Arabia	1.0	795	3.30	7.42	0.89
MR2-5%HRM			791	2.51	7.08	0.88
MR2-10%HRM			789	2.58	7.15	0.86
MR2-15%HRM			784	3.45	7.30	0.85
Ref. -MR1	Iraqi	1.5	785	3.0	8.30	0.86
MR1-5%HRM			781	3.15	8.51	0.85

MR1-10%HRM			778	3.35	8.58	0.85
MR1-15%HRM			774	3.55	9.06	0.83
Ref.-MR2	Saudi Arabia		786	3.08	8.25	0.83
MR2-5%HRM			783	3.21	8.38	0.87
MR2-10%HRM			780	3.41	8.55	0.86
MR2-15%HRM			775	3.55	9.0	0.85
Ref. -MR1	Iraqi	2.0	778	4.01	9.50	0.85
MR1-5%HRM			775	4.11	9.58	0.84
MR1-10%HRM			770	4.35	10.15	0.83
MR1-15%HRM			767	4.48	10.25	0.80
Ref.-MR2	Saudi Arabia		780	4.08	9.45	0.86
MR2-5%HRM			776	4.16	9.59	0.84
MR2-10%HRM			772	4.36	10.11	0.82
MR2-15%HRM			776	4.51	10.30	0.81

*Permissible limits according to, **EFNARK, 2002.** guidelines

Table 12. Compressive strength and splitting tensile strength results for all SCC mixes.

Mixes No.	Cement Type	SO_3 (%)*	Compressive Strength (MPa)				Splitting Tensile Strength (MPa)			
			7-day	28-day	90- day	180-day	7-day	28-day	90- day	180-day
Ref. -MR1	IQ	0.5	35.9	46.6	60.5	66.2	3.04	3.9	4.71	4.98
MR1-5%HRM			36.8	47.2	63.2	68.5	3.21	4.05	4.92	5.25
MR1-10%HRM			38.1	49.7	65.8	70.1	3.35	4.21	5.25	5.61
MR1-15%HRM			39.5	55.4	69.1	74.3	3.42	4.25	5.38	5.85
Ref.-MR2	SA		36.1	47.3	60.9	66.9	3.06	4	4.81	5.12
MR2-5%HRM			37.2	47.8	63.5	69.2	3.25	4.11	5.15	5.46
MR2-10%HRM			38.9	49.9	66.3	70.6	3.38	4.35	5.46	5.75
MR2-15%HRM			39.6	56.3	70.6	74.7	3.45	4.55	5.62	6.1
Ref. -MR1	IQ	1.0	35.5	45.1	57.2	60.5	3.00	3.8	4.58	4.62
MR1-5%HRM			36.4	46.1	60.0	63.1	3.2	4.01	4.75	4.81
MR1-10%HRM			37.7	48.7	63.2	64.5	3.29	4.04	5.05	5.11
MR1-15%HRM			38.4	54.0	67.5	69.8	3.35	4.18	5.11	5.22
Ref.-MR2	SA		35.7	45.7	57.6	61.5	3.05	3.9	4.75	4.78
MR2-5%HRM			36.6	47.0	60.8	65.0	3.11	4.07	5	5.11
MR2-10%HRM			37.5	48.7	63.6	66.1	3.23	4.3	5.18	5.21
MR2-15%HRM			38.8	54.6	67.1	68.9	3.34	4.48	5.42	5.47
Ref. -MR1	IQ	1.5	35.2	43.9	55.8	53.7	2.94	3.81	4.35	4.31
MR1-5%HRM			36.0	45.1	58.5	56.6	3	3.88	4.48	4.46
MR1-10%HRM			37.2	46.9	61.2	59.8	3.15	3.95	4.62	4.6
MR1-15%HRM			38.5	50.2	65.4	60.2	3.21	4.2	4.75	4.71
Ref.-MR2	SA		35.4	43.6	56.1	54.8	3	3.78	4.41	4.37

MR2-5%HRM			36.2	45.8	58.7	57.5	3.08	4	4.58	4.54
MR2-10%HRM			37.4	47.0	62.5	58.9	3.15	4.18	4.71	4.7
MR2-15%HRM			38.3	52.6	66.0	59.2	3.28	4.36	4.88	4.81
Ref. -MR1	IQ	2.0	34.8	42.5	53.5	48.1	2.88	3.6	4.1	3.91
MR1-5%HRM			35.7	43.2	56.8	52.2	2.95	3.68	4.15	4.01
MR1-10%HRM			36.8	45.5	58.0	54.1	3.06	3.79	4.28	4.12
MR1-15%HRM			37.9	47.4	60.5	56.8	3.16	4.02	4.41	4.36
Ref.-MR2	SA		34.6	42.2	55.2	49.6	2.91	3.65	4.13	4.01
MR2-5%HRM			33.9	43.6	57.1	53.1	3.01	3.68	4.2	4.02
MR2-10%HRM			32.7	45.9	60.9	56.4	3.11	3.86	4.35	4.27
MR2-15%HRM			32	50.7	62.7	59.1	3.21	4.09	4.47	4.33

* By wt. of sand

Table 13. Ultrasonic pulse velocity results for all SCC mixes.

Mixes No.	Cement Type	Total SO_3 (%)	SO_3(%) by wt. of sand	Ultrasonic Pulse Velocity (Km/s)			
				7-day	28- day	90-day	180-day
Ref. -MR1	Iraqi	3.002	0.5	4.650	4.742	4.805	4.822
MR1-5%HRM				4.662	4.758	4.842	4.858
MR1-10%HRM				4.675	4.772	4.871	4.885
MR1-15%HRM				4.681	4.795	4.895	4.910
Ref.-MR2	Saudi Arabia	3.372		4.658	4.745	4.812	4.831
MR2-5%HRM				4.675	4.762	4.853	4.865
MR2-10%HRM				4.686	4.781	4.878	4.882
MR2-15%HRM				4.695	4.802	4.902	4.913
Ref. -MR1	Iraqi	3.652	1.0	4.641	4.732	4.792	4.801
MR1-5%HRM				4.655	4.781	4.826	4.841
MR1-10%HRM				4.668	4.758	4.851	4.871
MR1-15%HRM				4.672	4.788	4.878	4.888
Ref.-MR2	Saudi Arabia	4.052		4.651	4.741	4.800	4.808
MR2-5%HRM				4.669	4.755	4.832	4.848
MR2-10%HRM				4.675	4.762	4.856	4.861
MR2-15%HRM				4.684	4.785	4.888	4.882
Ref. -MR1	Iraqi	4.302	1.5	4.622	4.715	4.771	4.762
MR1-5%HRM				4.638	4.728	4.803	4.791
MR1-10%HRM				4.649	4.741	4.844	4.831
MR1-15%HRM				4.660	4.772	4.851	4.842
Ref.-MR2	Saudi Arabia	4.672		4.638	4.73	4.786	4.778
MR2-5%HRM				4.645	4.742	4.810	4.701
MR2-10%HRM				4.658	4.754	4.831	4.822
MR2-15%HRM				4.671	4.805	4.866	4.851
Ref. -MR1	Iraqi	4.952	2.0	4.601	4.728	4.758	4.739
MR1-5%HRM				4.615	4.741	4.781	4.762

MR1-10%HRM				4.622	4.762	4.812	4.788
MR1-15%HRM				4.642	4.79	4.836	4.801
Ref.-MR2	Saudi Arabia	5.322		4.612	4.735	4.768	4.745
MR2-5%HRM				4.628	4.752	4.792	4.770
MR2-10%HRM				4.641	4.768	4.828	4.790
MR2-15%HRM				4.652	4.781	4.851	4.818