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Mechanical Properties of Self Compacting Concrete Made with Local Materials

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Abstract

The main objective of this research is to investigate the properties of fresh and hardened self-compacting concrete (SCC) made from locally available materials in Basrah governorate-Iraq. The study consists of investigation the influence of volume ratio of coarse aggregate, limestone powder (LSP) to total powder ratio, and powder/water ratio. This is to obtain more information which will contribute to a better understanding to the use of local materials in production of SCC. To achieve these aims, 18 different mixes (17 SCC mixes and one normal concrete (NC) mix were prepared, tested and evaluated. It has been noticed that, with the same W/C ratio, SCC mixes prepared with higher coarse aggregate volume ratio showed higher strengths and modulus of elasticity than mixes prepared with lower coarse aggregate volume ratio. The increment of LSP as a replacement of cement leads to lower strengths and static modulus of elasticity. For the same compressive strength at 28 days, SCC showed 11%, 20% and 26.4% higher flexural, splitting tensile and bond strengths than NC respectively.

Keywords: Self-Compacting Concrete, Limestone Powder, Superplasticizer, Mechanical Properties

الخواص الميكانيكية للخرسانة ذاتية الرص المعمولة من المواد المحلية

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الخلاصة

الهدف الرئيسي لهذا البحث هو التحري عن خواص الخرسانة ذاتية الرص الطرية والمتصلبة المعمولة باستخدام المواد المتوفرة في محافظة البصرة- العراق. البحث يحتوي دراسة تأثير النسبة الحجمية للركام الخشن و نسبة مسحوق الحجر الجيري إلى الوزن الكلي للمسحوق، و نسبة الماء الى المسحوق على الخواص الطرية والمتصلبة للخرسانة ذاتية الرص وذلك للحصول على مزيد من المعلومات التي تساهم في فهم أفضل لاستخدام المواد المحلية في صناعة الخرسانة ذاتية الرص ،ولتحقيق هذه الأهداف، تم تجهيز وفحص وتقييم ١٨ خلطة (١٧ خلطة خرسانة ذاتية الرص وخلطة واحدة خرسانة اعتيادية). لوحظ أنه لنفس نسبة الماء إلى الاسمنت، الخرسانة ذاتية الرص التي أعدت باستخدام نسبة حجمية اعلى للركام الخشن أظهرت ارتفاع المقاومات ومعامل المرونة بالمقارنة مع نظيرتها التي أعدت مع نسبة حجمية اقل للركام خشن. الزيادة في نسبة مسحوق الحجر الجيري كبديل للإسمنت ادت إلى انخفاض المقاومات، ومعامل المرونة والانكماش، ولكن مع امتصاص اعلى . لنفس مقاومة انضغاط في عمر ٢٨ يوم، الخرسانة ذاتية الرص اظهرت مقاومة انحناء ومقاومة شد انشطاري ومقاومة ترابط اعلى ب ١١% و ٢٠ % و٢٦,٤% من الخرسانة الاعتيادية على التوالي.

1. Introduction

Self compacting concrete (SCC) is one of the most important innovations in the concrete technology. It represents a revolution in the field of concrete technology. It have very attractive properties in the fresh state as well as after hardening. It is a highly workable concrete that can flow through densely reinforced or geometrically complex structural elements under its own weight and adequately fills voids without segregation or excessive bleeding without the need for vibration to consolidate it [1,2].

Differences between the hardened properties of SCC and normal concrete may be attributed to the modified mix composition, the better microstructure and homogeneity of SCC and the absence of vibration.

Self-compacting concrete with a similar water cement will usually have a slightly higher strength compared with traditional vibrated concrete, this is attributed to the improved bond between the aggregate and hardened paste in SCC [3]. **Ahmad et al. (2006)** [4] found that, at a constant W/C ratio, no considerable difference in compressive strength of NC and SCC was observed.

Holschemacher and Klug (2002) [5] stated that, for conventional concrete, the ratio between cylinder and cube compressive strength is (0.8 to 0.85). This ratio was essentially higher for SCC (0.9 to 1). Consequently, the compressive strength is less related to the slenderness of the specimens.

Sheinn et al. (2004) [6] found that the flexural strength was slightly higher for SCC than a normal concrete mixture of comparable compressive strength. According to (EFNARC 2005)[8], The tensile to compressive strength ratio of SCC was 10% -30% higher than that of NC . **Turcry et al.** (2002) [9] found that the ratio of tensile to compressive strength was between 0.087 to 0.1 for SCC and 0.075 for comparable normal concrete. **Roziere et al. (2005)** [7] found that increasing the paste volume of SCC reduced tensile strength slightly.

Different test results are found for the bond strength in SCC. Sometimes these studies deliver contradictory results. In the bond tests carried out using pull-out specimens, **Domone (2007)** [10] obtained similar bond strengths for SCC and NC, **Collepardi et al.(2005)**[11] obtained 70% higher strengths with SCC, **Chan et al.(2003)**[12] obtained 5% higher strengths with SCC, and **Sonebi et al. (2001)**[13] strengths 10% to 40% higher with SCC.

The modulus of elasticity (MOE) of SCC is typically equal to or slightly less than that of normal concrete due to the higher paste volume and reduced maximum aggregate size [8], but **Mamaghani et al.(2010)**[14] concluded that MOE for the SCC mixes is higher than that of the NC mix counterpart.

The relationships between the compressive strength (fc) and the other mechanical properties (flexural strength ,splitting tensile strength, and modulus of elasticity) for SCC have been studied and proposed by many researchers such as, **Khaleel (2007)**[15], **Sekhar and Rao(2008)**[16], **Vilanova et al.(2011)**[17] and **Aslani and Nejadi (2012)**[18], these proposed relationships depict that they are usually expressed in terms of $(fc)^n$,where n is a real number .

2. Research Significance

The fundamental objective of this work was to provide information on the fresh and hardened properties of self-compacting concrete produced using available local raw materials in Basrah city to support the practical work of other partners in assessing the practical use of SCC in building, and to facilitate the introduction of SCC technology into general construction practice.

3. Experimental program

In order to achieve the aim of the study, eighteen concrete mixes (seventeen mixes were SCC and one was NC) are designed, prepared and tested for fresh and hardened properties of concrete.

3.1 Materials

Ordinary Portland cement with specific gravity of 3.15 and Blaine fineness 3120 cm^2/g was used. Grinded limestone which has been brought from local market is used;

this material is locally named as "Al-Gubra". It were screened in order to get powder by using sieve 0.125 mm. Specific surface of the limestone powder used was 3100cm^2/g. Specific gravity of the limestone powder was 2.69. Table (1) shows Physical properties and chemical composition of the used cement and limestone powder**.** A local natural coarse and fine aggregate from Zubair ,Basrah ,that meet the requirement of Iraqi standard no 45 -1984[19] were used. Table (2) presents the grading of coarse and fine aggregates. The coarse and fine aggregate each had a specific gravity of 2.65, water absorption of 0.65 and1.1% respectively. High efficiency acrylic copolymer-based superplasticizer as per ASTM C494 –type A, D and G specification[20] having a specific gravity of 1.08 and a total solid content of 40% was used. Ordinary tap water is used for mixing, casting and curing.

Table (1) - Physical properties and chemical composition of cement and limestone powder

	cement	Limestone powder
Physical properties		
Sitting time (min)		
initial	130	----
final	240	----
Compressive strength(MPa)		
7 days	20.5	----
28 days	28.8	----
Specific surface,blaine,cm^2/g	3120	3100
Chemical analysis,%		
Lime (CaO)	62.00	88.5
Silica (SiO_2)	21.00	1.38
Alumina (Al_2O_3)	5.26	0.72
Iron Oxide (Fe_2O_3)	3.00	0.12
Magnesia (MgO)	2.70	0.13
Sulfate (SO_3)	2.10	0.21
Loss on Ignition (LOI)	1.10	3.94
Insoluble residue (I.R.)	0.49	----
Lime saturation factor (L.S.F)	0.92	----
Tricalcium silicate (C_3S)	47.11	
Dicalcium Silicate (C_2S)	30.81	
Tricalcium Aluminate (C_3A)	8.87	
Tetracalcium Aluminoferrite (C_4AF)	9.12	

Table (2)- Grading of coarse and fine aggregate

Coarse aggregate			Fine aggregate		
Sieve size mm	Passing (%)	Iraqi standard No. 45-1984	Sieve size mm	Passing (%)	Iraqi standard No. 45-1984 Zone 2
20	100	95-100	4.75	99	90-100
14	80	-	2.36	90	75-100
10	37	30-60	1.18	75	55-90
5	2	0-10	0.60	53	35-59
2.36	1	-	0.30	17	8-30
			0.15	2	0-10

3.2 Mix Proportions

University College London Method (2010)[21] and BRE method (2002)[22] were used to design SCC mixes and NC mix respectively. The details of the mixes are shown in Table (3).For SCC mixes, the coarse aggregate volume ratios were 30%, 32%, 34% and 36% of concrete volume, the sand to mortar ratio was kept constant at 45% by volume throughout all SCC tests and for each coarse aggregate content, the limestone powder was 10%, 20% and 30% by weight of total powder weight, the rest of it was cement. The W/P ratio was 0.31 for coarse aggregate volume ratios of 30%, 32%, 34% and 36% of concrete volume, while W/P ratio was 0.36 and LSP/P ratios were from 10% to 50 % for coarse aggregate volume of 36% only, where the W/C ratio ranged from 0.345 to 0.720 as shown in Table (3) to cover wide range of the compressive strength. The superplasticizer dosage was selected to give 700 mm slump flow for all SCC mixes. Normal concrete mix (NC) with slump of 100 mm is used for comparison with mix No.13, the two mixes have same W/C ratio (0.4), cement content (459kg/m^3) and total aggregate / powder ratio of 3.81, if one considers the amount of limestone powder (51 kg/m^3) just as the finest fraction in particle size distribution of the aggregate. The particle size distribution of aggregate used for the NC mix was (40% sand and 60% gravel) as shown in Table (3).

3.3 Preparation Specimens and Test Methods

The slump flow, V-funnel, L-box and the sieve stability tests were carried out in accordance with **EFNARC (2005)** [3] ,all these test methods are used for the assessment of fresh properties of SCC in this study. SCC specimens for the hardened state tests are cast in molds without being mechanically compacted. All samples are demolded after 24 hrs, marked and cured in water until testing age. Standard 100mm cubes were used to determine compressive strength at ages 7,28,90 days according to **BS1881: part 116** [23] and Standard 150 mm cubes and (150*300 mm) cylinders were used to determine compressive strength at age 28 days only according to **BS 1881: part 116** and **ASTM C39-03**[24] respectively. The flexural, splitting and bond strengths were carried out according to **ASTM C78**[25], **C496**[26] and**C234**[27] respectively. Modulus of elasticity of concrete tests was carried out in accordance with **ASTM C469** [28].

Table (3)-Mix proportions and fresh properties of the used mixes.

Mix symbol	Vca % by vol.	LSP/P ratio % by wt.	W/P ratio	W/C ratio	Cement (kg/m^3)	LSP (kg/m^3)	Sand (kg/m^3)	Gravel (kg/m^3)	Water (kg/m^3)	SP (kg/m^3)	Slump flow (mm)	T500 sec	V funnel time sec	Blocking ratio %
١	30	١٠	٠,٣١	٠,٣٤٥	٥٤٢	٦٠	826	٧٨٧	١٨٧	٤,٠	700	2.80	8.68	93
٢		٢٠	٠,٣١	٠,٣٨٧	٤٧٨	١١٩	826	٧٨٧	١٨٥	٤,٠	700	2.77	8.58	93
٣		٣٠	٠,٣١	٠,٤٤٢	٤١٤	١٧٨	826	٧٨٧	183	٤,٠	700	2.76	8.55	93
٤	32	١٠	٠,٣١	٠,٣٤٥	٥٢٦	٥٨	٨٠٣	٨٤٠	١٨٢	٤,٠	700	2.78	8.61	91
٥		٢٠	٠,٣١	٠,٣٨٧	462	١١٦	٨٠٣	٨٤٠	١٨٠	٤,٠	700	2.74	8.50	91
٦		٣٠	٠,٣١	٠,٤٤٢	٤٠٣	١٧٢	٨٠٣	٨٤٠	١٧٨	٤,٠	700	2.70	8.37	91
٧	34	١٠	٠,٣١	٠,٣٤٥	٥١١	57	779	٨٩٢	١٧٦	٤,٠	700	2.77	8.58	88
٨		٢٠	٠,٣١	٠,٣٨٧	451	١١٣	779	٨٩٢	١٧٥	٤,٠	700	2.73	8.46	88
٩		٣٠	٠,٣١	٠,٤٤٢	391	١٦٧	779	٨٩٢	١٧٣	٤,٠	700	2.68	8.31	88
١٠	36	١٠	٠,٣١	٠,٣٤٥	٤٩٥	٥٥	٧٥٥	944	١٧١	٤,٠	700	2.74	8.49	85
١١		٢٠	٠,٣١	٠,٣٨٧	437	١٠٩	٧٥٥	944	١٦٩	٤,٠	700	2.71	8.40	85
١٢		٣٠	٠,٣١	٠,٤٤٢	٣٧٩	١٦٢	٧٥٥	944	167	٤,٠	700	2.65	8.21	85
١٣	٣٦	١٠	٠,٣٦	٠,٤٠٠	459	٥١	٧٥٥	944	١٨٤	٣,٠	700	2.18	7.00	83
١٤		٢٠	٠,٣٦	٠,٤٥٠	٤٠٥	١٠١	٧٥٥	944	182	٣,٠	700	2.17	6.81	83
١٥		٣٠	٠,٣٦	٠,٥١٥	٣٥١	١٥١	٧٥٥	944	181	٣,٠	700	2.14	6.75	83
١٦		٤٠	٠,٣٦	٠,٥٩٥	299	199	755	944	179	3.0	700	2.13	6.72	82
١٧		٥٠	٠,٣٦	٠,٧٢٠	247	247	755	944	178	3.0	700	2.12	6.69	82
١٨ (NC)	٣٩,٨	-	٠,٤٠	٠,٤٠٠	٤٥٩	-	700	1050	١٨٤	-	-			

4. Results and Discussion

In order to study the hardened properties of the SCC developed in this study, a number of specimens are cast after a series of fresh self-compactability concrete tests.

The SCC specimens are cast in molds without being mechanically consolidated. All of the samples are demolded after 24 hrs and cured in water until test.

Reasons for possible differences between the hardened properties of SCC and NC may be the modified mix proportion as mentioned before in the introduction, the better microstructure and homogeneity of SCC and the absence of vibration [29].

4.1 Compressive Strength

To study the effect of volume of coarse aggregate and W/C ratio on the compressive strength of SCC, standard 100 mm cubes were tested at ages of 7, 28 and 90 days. Test results are shown in Table (4) and Fig(1) .

It can be deducted from Table (4) that, for the same W/C ratio, the compressive strength increases with the increase of coarse aggregate volume ratio. This is because, mixes with low coarse aggregate volume ratio have higher powder content which lead to stresses induced by shrinkage.

In literature, LSP was described neither cementitious nor pozzolanic materials. Therefore, it is accepted that LSP contributes little to the strength, therefore; the compressive strength for each group of SCC mixes decreases with increase LSP/P ratio, this due to that increase of LSP content leads to reduces the cement content, for this reason, the W/C ratio increases and the compressive strength decreases as shown in Table(4) and Fig.(1).

The development of 100 mm cube compressive strength with age for all concrete mixes is shown in Table (4). It can be shown from Table (4) that, the average ratio of 7 days to 28 days compressive strength of SCC mixes was about of 0.79 compared to 0.73 for normal concrete (Mix 18). This behavior may be attributed to use superplasticizer and limestone powder in SCC mixes. The inclusion of fine limestone powder in SCC mixes may have an accelerating effect on C_3S hydration and early strengths [30].

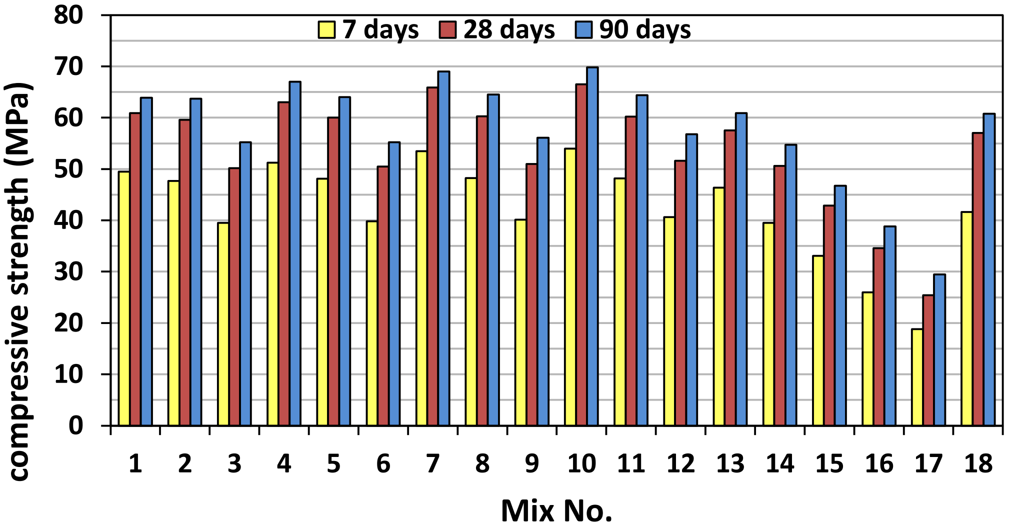

Figure (1)- The 100mmcube compressive strength development of all mixes.

Table (4)-Hardened concrete test results

Set No.	Mix No.	LSP/P %	Vca %	W/C	100 mm cube compressive strength (MPa)			150 mm cube and 150*300mm cylinder Compressive strength (MPa) at 28 days			Flexural strength (MPa)			Splitting strength (MPa)			28 days modulus of elasticity , Ec (MPa)	28 days Bond strength (MPa),fb
					7 days	28 days	90 days	f_{cu}	f_c'	f_c'/f_{cu}	7 days	28 days	90 days	7 days	28 days	90 days		
1	1	10	30	٠,٣٤٥	49.50	60.90	63.91	55.50	48.30	0.87	5.25	6.97	7.31	3.33	4.50	4.67	33.12	9.13
	2	20		٠,٣٨٧	47.68	59.60	63.71	54.50	47.40	0.87	5.02	6.67	7.00	3.31	4.47	4.66	32.97	8.91
	3	30		٠,٤٤٢	39.53	50.20	55.22	45.70	38.85	0.85	4.41	5.90	6.19	2.95	3.99	4.2	31.58	7.42
2	4	10	32	٠,٣٤٥	51.21	63.00	67.00	57.20	50.05	0.88	5.25	7.00	7.35	3.42	4.62	4.73	34.05	9.21
	5	20		٠,٣٨٧	48.10	60.00	64.00	54.60	47.15	0.86	5.04	6.70	7.03	3.31	4.48	4.68	33.65	8.92
	6	30		٠,٤٤٢	39.80	50.50	55.21	45.90	39.00	0.85	4.43	5.90	6.19	2.90	3.92	4.11	32.22	7.57
3	7	10	34	٠,٣٤٥	53.50	65.90	69.00	59.90	52.70	0.88	5.26	7.00	7.35	3.48	4.70	4.82	35.17	9.89
	8	20		٠,٣٨٧	48.24	60.30	64.50	54.80	47.40	0.86	4.95	6.63	6.96	3.33	4.50	4.70	34.36	9.31
	9	30		٠,٤٤٢	40.15	51.00	56.10	46.40	39.40	0.85	4.45	5.92	6.21	2.88	3.89	4.01	32.97	7.82
4	10	10	36	٠,٣٤٥	54.00	66.50	69.80	60.45	52.80	0.87	5.43	7.20	7.56	3.62	4.90	5.03	35.98	10.1
	11	20		٠,٣٨٧	48.16	60.20	64.41	54.70	47.30	0.86	5.13	6.80	7.14	3.34	4.52	4.68	35.00	9.57
	12	30		٠,٤٤٢	40.62	51.60	56.80	46.90	39.90	0.85	4.58	6.10	6.40	2.90	3.92	4.20	33.67	7.80
5	13	10		٠,٤٠٠	46.37	57.50	60.90	52.30	45.00	0.86	4.75	6.32	6.63	3.29	4.44	4.59	34.63	8.99
	14	20		٠,٤٥٠	39.53	50.60	54.70	46.00	39.30	0.85	4.39	5.85	6.14	2.95	3.99	4.12	33.50	8.12
	15	30		٠,٥١٥	33.10	42.90	46.76	39.10	32.80	0.84	4.06	5.40	5.67	2.80	3.78	3.91	32.11	7.65
	16	40		٠,٥٩٥	26.00	34.60	38.80	31.50	26.15	0.83	3.23	4.30	4.51	2.37	3.20	3.53	28.88	7.10
	17	50		٠,٧٢٠	18.80	25.40	29.46	23.60	19.00	0.81	2.73	3.64	3.82	2.00	2.70	3.04	24.46	6.20
NC	18(NC)	.	39.6	٠,٤٠٠	41.60	57.00	60.80	52.10	43.30	0.83	4.31	5.7	5.98	2.74	3.70	4.00	34.88	7.11

Table(4) reveals that the mixes with relatively low W/C ratios gain strength more rapidly than mixes with high W/C ratios, this phenomena can be explained as follows, in mixes with low W/C ratios, the cement particles are closer to one another and continuous system of gel can be established more rabidly[30].

To study the relation between cube and cylinder compressive strength, 150 mm cubes and (150x300) mm cylinders were cast and tested at age of 28 days. The results are presented in the Table (4). The ratio of cylinder to cube compressive strength at 28 days for SCC mixes (f_c'/f_{cu}) varies from 0.8 at strength of 25 MPa to about 0.88 at strength of 60 MPa, this means that this ratio increases with the increase of strength. This agrees with **Domone (2007)**[10]. While f_c'/f_{cu} ratio for conventional concrete (Mix (18)) is 0.83 compared with 0.86 of self-compacting concrete (Mix (13)), that means, this ratio for SCC is greater than that for NC, this in line with **Domone (2006)**[31] and **Holschemacher(2004)**[29]. These ratios illustrate that they are higher than the ratios for the conventional concrete. Consequently, the compressive strength is less related to the slenderness of the specimens.

4.2 Effect of W/C Ratio on Compressive Strength of SCC

Test results of the present study showed a good correlation between compressive strength and water cement ratio for SCC mixes made with local material as illustrated in Fig. (2).The lower water cement ratio leads to the higher compressive strength. The following relationship represents the best fit for the test results:

$$f_{cu} = 138.5 \times e^{-2.46\ W/C} \quad \text{--------------------(1)}$$

Where f_{cu} is 150mm cube compressive strength (MPa) at age 28 day, *W/C* represents the water/cement ratio (by weight) of the SCC mixture.

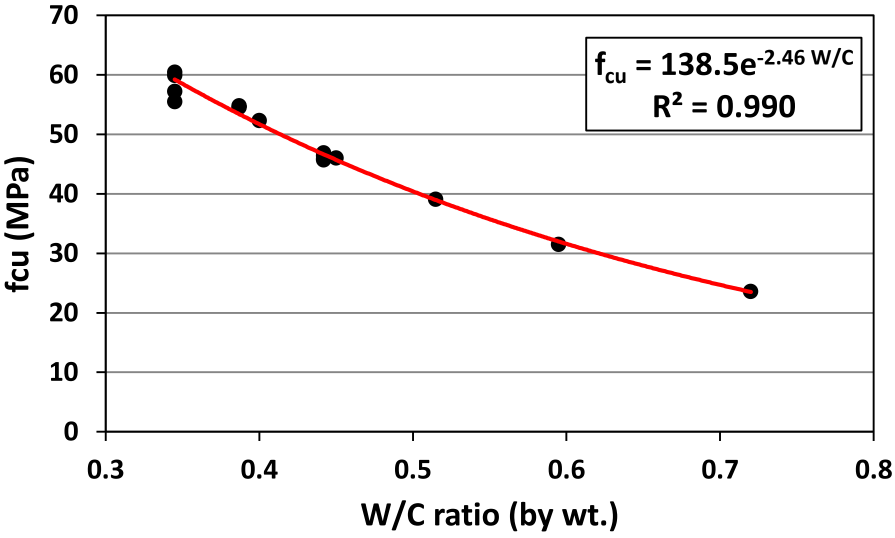

Figure (2)- The relationship between compressive strength and water to cement ratio.

4.3 Flexural Strength

The results of flexural strength (modulus of rapture) are presented in Table (4), it can be seen that, for the same W/C ratio and LSP/P ratio, the flexural strength relatively increases with increasing the coarse aggregate volume ratio. The reasons for that are as mentioned for compressive strength.

From Table (4) it can be noticed that the flexural strength is reduced with increasing of LSP/P ratio, for the same reasons stated for compressive strength. Also it can be noticed that Mix(13)(SCC) exhibited 11% more flexural strength than mix(18)(NC) at 28days test. This may be due to the enhancement of the microstructure of the concrete, which results in a lower porosity moreover to the better pore distribution within the interfacial transition zone between the aggregate and cement matrix of SCC, furthermore in conventional vibrated concrete, vibration can increase the local water/cement ratio around coarse aggregate and weaken bond strength.

As for compressive strength, the development of flexural strength with age is faster in SCC mixes compared to NC mix. Referring to Table (4), the ratio of 90 days to 7 days flexural strength ranged from 1.39 to 1.41 with average value 1.4 for SCC mixes compared to 1.46 for NC mix.

Figure (3) indicates the relationship between cube compressive strength and flexural strength. It is clear that the flexural strength increases with the increase of compressive strengths. The best fitted curve can be presented by Eqs.(2) and (3). The flexural strength values showed good correlations with the compressive strength of cube and cylinder (R^2=0.988 and R^2=0.989), this may be attributed to the use same material for each mixture and the homogenous nature of the SCC mixes. Below are the expressions which represent the relationship between compressive strength (cube and cylinder) and flexural strength for SCC mixes.

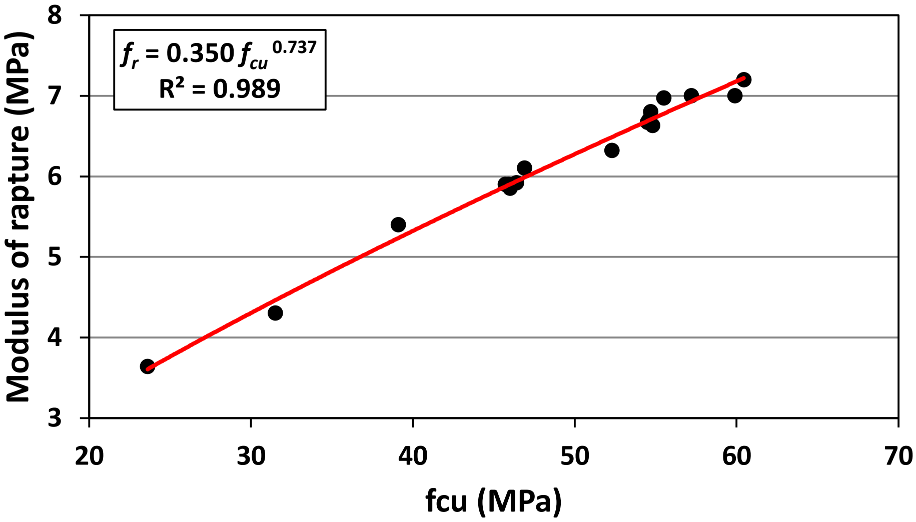

Figure (3): Relationship between cube compressive strength and flexural strength for SCC.

$f_r = 0.35\, f_{cu}^{\ 0.737}$ ---------------------------------(2)

$f_r = 0.491\, f_c'^{\ 0.677}$ ---------------------------------(3)

The relationships proposed by other researches are shown below for comparison:

$f_r = 1.73\, f_{cu}^{0.3784}$ (**Khaleel (2007)** [15]) ---------------(4)

$f_r = 0.119\, f_{cu}^{0.929}$ (**Sekhar and Rao (2008)** [16]) ------(5)

$f_r = 0.43\, f_c'^{\ 0.68}$ (**Vilanova et al.(2011)**[17]) ------------(6)

4.4 Splitting Tensile Strength

The results of splitting tensile strength are presented in Table (4). It can be seen that for the same W/C ratio and same LSP/P ratio, the splitting tensile strength relatively increases with the increase of the coarse aggregate volume ratio for the same reasons stated for compressive strength.

From Table (4) it can be observed that, the splitting tensile strength reduced with increasing of LSP/P ratio, this due to the same reasons which are as mentioned for compressive strength.

It can also be noticed that, Mix (13) (SCC) exhibited 20% higher 28days splitting tensile strength than Mix(18) (NC).This may be due to the same reasons stated for the flexural strength.

The development of splitting tensile strength with age is shown in Table (4). The ratio of 90 days to 7 days splitting strength ranged from 1.38 to 1.52 with average value 1.41 for

SCC mixes. This ratio was 1.4 for Mix (13) and 1.46 for Mix (18). It can be deducted that SCC develop splitting tensile strength faster than NC. This may be due to the presence of LSP in SCC mix.

The experimental results of splitting tensile strength and compressive strength (cube at age 28 days) are shown in Fig.(4). From this figure it is clear that, the increase in compressive strength leads to an increase in the splitting tensile strength. It appears that the higher splitting tensile strength of SCC is due to the enhanced microstructure of the concrete, which results in a lower porosity.

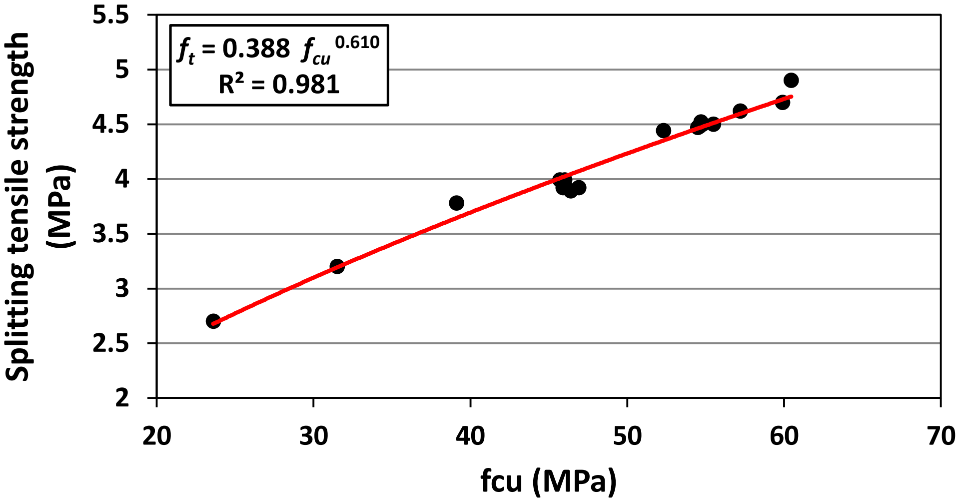

Figure (4): Relationship between cube compressive strength and splitting tensile strength for SCC mixes.

The relations between the splitting tensile and (cube and cylinder) compressive strength (Eqs.(7) and (8)) are obtained based on test results as shown below:

$f_t = 0.388\ f_{cu}^{0.61}$ ----------------------(7)

$f_t = 0.561\ f_c'^{\,0.56}$ ----------------------(8)

For comparison, the following relationships for SCC are presented in literature:

$f_t = 0.73\ f_{cu}^{0.44}$ (**Khaleel (2007)** [15]) ---------------------(9)

$f_t = 0.0753\ f_{cu}^{1.0382}$ (**Sekhar and Rao (2008)** [16]) -----------(10)

$f_t = 0.26\ f_c'^{\,0.71}$ (**Vilanova et al.(2011)**[17]) --------------(11)

$f_t = 0.082\ f_c'^{\,0.962}$ (**Aslani** and **Njadi(2012)** [18]) ----------(12)

From Table (4) it can be noticed that the ratio of flexural to cube compressive strength for SCC mixes at 28 days ranges from 11.69 to 15.42 % with average value of 12.74%, while the ratio of splitting tensile to compressive strength for SCC mixes ranges from 7.85 to 11.40 % with average value of 8.67%. In general, as compressive strength increase, the ratio of tensile to compressive strength (f_r/f_{cu} and f_t/f_{cu}) decreases,

For the same compressive strength, Mix (13) (SCC) exhibited higher ratio of flexural and splitting strength to compressive strength than Mix (18) (NC) as presented in Table (4).

4.5 Static Modulus of Elasticity (Ec)

The modulus of elasticity of concrete depends on the proportion of Young's moduli of the individual components and their percentages by volume. Thus, the modulus of elasticity of concrete increases for high contents of aggregates of high rigidity, whereas it decreases with increasing hardened cement paste content and increasing porosity. Therefore, SCC is expected to have lower modulus of elasticity because of the higher content of ultrafines and additives [5].

Average results obtained from three individual specimens for each concrete mix are given in Table (4). It can be noticed that the modulus of elasticity increases with the increment in the volume ratio of coarse aggregate. This is attributed to that the volume of paste and the sand/aggregate ratio decrease with the increase in volume ratio of coarse aggregate.

The modulus of elasticity for each set of SCC mixes decreases with the increase of LSP/P ratio, this due to that increase of LSP content leads to rise W/C ratio for that the porosity of cement paste increases.

From Table (4), it can be noticed that Mix(13) (SCC) with cylinder compressive strength of 45 MPa gives lower 28days modulus of elasticity than Mix(18) (NC) with cylinder compressive strength of 43.3MPa. This is due to lower aggregate fraction used in SCC compared to that in conventional concrete in addition to that, SCC incorporates a higher sand/ aggregate ratio(to increase its segregation resistance and passing ability).

Figure (5) reveals that, the compressive strength of concrete and the elastic modulus of concrete are related, the increase in one is similarly reflected in an increase in the other.

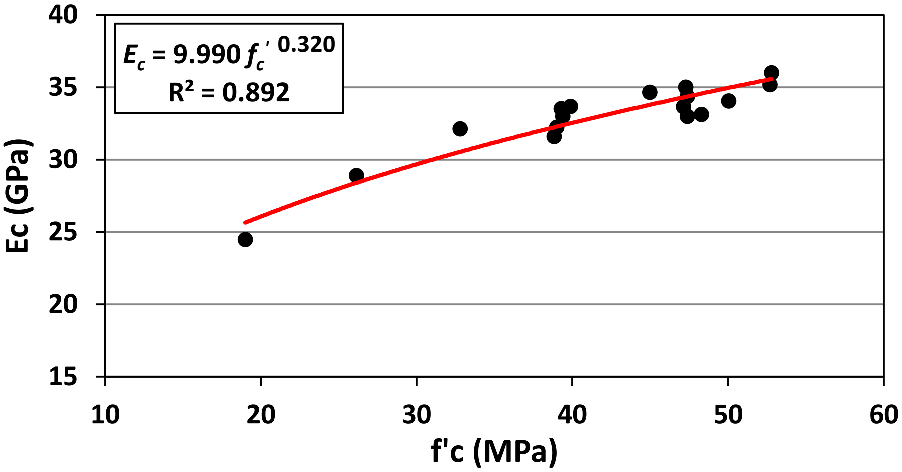

Figure (5)- Relationship between cylinder compressive strength and static modulus of elasticity of SCC mixes.

From this figure the relationship between cylinder compressive strength and modulus of elasticity is obtained as given by Eq.(13):

$$E_c = 9.99\, f_c'^{\,0.32} \quad \text{----------------------- (13)}$$

In comparison with the following relationships for SCC:

$E_c = 5.88\, f_c'^{\,0.44}$ **(Vilanova et al. (2011)** [91]) ------------ (14)

$E_c = 9.455\, f_c'^{\,0.345}$ (**Aslani** and **Njadi(2012)** [92]) ---------- (15)

The $E_c/(f_c')^{0.5}$ ratio for all SCC mixes is greater than the value of recommended by **ACI 318M-11 Code** [32] for structural normal weight concrete. This means that the equation of **ACI 318M-11 Code** can be used in calculating E_c of SCC for structural applications.

4.6 Bond Strength

The bond strength between embedded reinforcement bar and concrete depends on bar diameter and mechanical properties attributed to the surface deformation, as well as concrete strength. In line with codes of practice, it is usual to express bond strength in terms of the square root of the compressive strength [13].

Table (4) illustrates the results of bond strength at age of 28 days strength for all mixes with different volume of coarse aggregate and LSP/P ratio. It is noticed that mixes with higher volume of coarse aggregate and lower LSP/P ratio exhibited higher bond strength, because of increasing in compressive strength leads to increasing in bond strength.

Also it can be seen that the bond strength of SCC (Mix(13)) was 26.4% higher than that of NC (Mix(18)), this probably result from the modification of the transition zone of the SCC as well as vibration can increase the local water/cement ratio around the bar and weaken bond strength due to the formation of bleeding water at the steel concrete interface .

Figure (6) indicates the relationship between cube compressive strength and bond strength. It is clear that the bond strength increases with the increase of compressive strengths. The best relationships between cylinder and cube compressive strength and bond strength can be presented by Eqs.(16) and (17).

$$f_b = 1.211\, f_{cu}^{0.5} \quad \text{-----------------------(16)}$$

$$f_b = 1.516\, f_c'^{\,0.461} \quad \text{------------------------(17)}$$

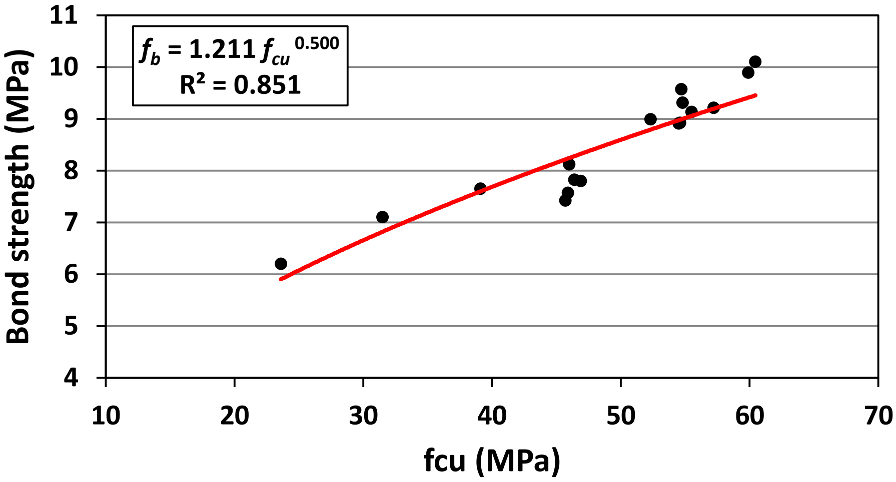

Figure (6)- Relationship between cube compressive strength and bond strength of SCC mixes.

5. Conclusions

1- The compressive strength, flexural strength, splitting tensile strength, bond strength and modulus of elasticity increase with increasing of the volume ratio of coarse aggregate and decreasing of LSP/P ratio.

2- With the same W/C ratio, no significant differences between the 28-days cube compressive strength of SCC and that of NC. But the development of compressive strength at early ages was faster for SCC.

3- The ratio of cylinder to cube compressive strength at 28 days (fc'/fcu) increases with the increase of compressive strength for SCC mixes, where this ratio varies from 0.80 at strength of 25 MPa to about 0.88 at strength of 60 MPa. The (fc' /fcu) ratio of SCC was greater than that of NC .

4- There is a good relationship between cube compressive strengths at 28 days of SCC mixes and W/C ratio (exponential form formula with correlation factor, R2, of 0.99).

5- For the same compressive strength, SCC showed 11% more 28days flexural strength than NC. SCC exhibited 20% higher 28days splitting tensile strength than NC. The 28 days bond strength of SCC was 26.4% higher than that of NC.

6- There are good relationships between compressive strength and flexural strength, splitting tensile strength, bond strength, and modulus of elasticity for SCC mixes.

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