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Comparative Study of the Mechanical Behavior of Self Compacting and Conventional Concretes with Strength of 20-80 MPa

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Abstract

The aim of this study is to find a correlation between strength of different concrete specimen shapes and sizes of self-compacting concrete, to evaluate the mechanical properties (compressive strength, splitting tensile strength and modulus of elasticity) and compare them with conventional concrete.

Self-compacting concrete mixes and conventional concrete mixes with different compressive strengths (20, 40, 60 and 80)MPa are used to determine the effects of: compressive strength, splitting tensile strength and modulus of elasticity on these relations. Water curing condition is used and the age tests are 7, 28 and 90 days for self-compacting concrete and 28 days for conventional concrete. The result obtained from this study indicates:

- ***The difference between results of cylinders/cubes of self-compacting concrete compressive strength are lesser than the difference of conventional concrete related to the slenderness of specimens.***
- ***In splitting tensile strength for self-compacting, it appears the tendency the higher splitting tensile strength of self-compacting concrete compared with conventional concrete. The reason for this fact is given by the better microstructure, specially the smaller total porosity and the more even pore size distribution within the interfacial transition zone of self-compacting concrete.***
- ***The modulus of elasticity of self-compacting concrete is less compared with conventional concrete because it often has a higher paste content.***

الخلاصـــــــة

تهدف هذه الدراسة الى ايجاد علاقة بين مقاومة النماذج (مقاومة الانضغاط، مقاومة الشد الانفصالي و معامل المرونة) ذات الاشكال و الاحجام المختلفة من الخرسانة ذاتية الرص و مقارنتها بنتائج نماذج الخرسانة التقليدية.

شملت الدراسة باخذ خلطات بمقاومة انضغاطية مختلفة (٢٠، ٤٠، ٦٠ و ٨٠ ميكاباسكال) لكل من الخرسانة ذاتية الرص و التقليدية في ايجاد قيم كل من: مقاومة الانضغاط، مقاومة الشد الانفصالي و معامل المرونة ولاعمار مختلفة (٧، ٢٨ و ٩٠ يوم) للخرسانة ذاتية الرص و ٢٨ يوم للخرسانة التقليدية و كانت النماذج معالجة بالماء طيلة تلك الفترة و لحين موعد اجراء الفحص. لقد اظهرت النتائج النقاط التالية:

- *كانت الفروقات بين نتائج مقاومة الانضغاط للنماذج الاسطوانية و المكعبة للخرسانة ذاتية الرص قليلة مقارنة مع نتائج الخرسانة التقليدية.*
- *مقاومة الخرسانة ذاتية الرص لاجهادات الشد الانفصالي اكبر من مقاومة الخرسانة التقليدية، و يعود السبب في ذلك الى توزيع الشقوق الشعرية وقلة المسامية و الفجوات في الخرسانة ذاتية الرص.*
- *معامل المرونة للخرسانة ذاتية الرص اقل من معامل المرونة للخرسانة التقليدية و ذلك لكون الاولى تحوي على نسبة عالية من المواد الناعمة.*

1. Introduction

The term self-compacting concrete (SCC) refers to a special type of concrete mixture characterized by high resistance to segregation that can be cast without compaction or vibration, and has the ability to completely fill formwork and achieve full compaction due to its own weight only, even in the presence of congested reinforcement [1]. The use self-compacting concrete (SCC) is spreading world wide because of its very attractive properties in the fresh state as well as after hardening.

In most previous research work and committee reports, efforts were concentrated mainly on fresh properties of SCC, and how to obtain this type of concrete, i.e., concrete mixes were proportioned, tested and adjusted so as to yield the required fresh concrete properties, in order to be able to classify this concrete as SCC. While the concrete strength of the SCC mix was considered satisfaory if it exceeded a certain specified value, no matter if this strength is close to or much higher than this value. This methodology in research directed most researches on hardened SCC to give only descriptive or comparative results of the behavior of SCC mixes as compared to corresponding conventional concrete (CC) mixes, concentrating their work on rather narrow compressive strength domain.

Several researchers [2,3] reported that using a SCC with different types of fillers will affect the microstructure of the cement matrix as well as the interfacial transition zone between the cement paste and the aggregate. This superiority in microstructure have a decisive importance on the failure propagation under loading of concrete. The reason for this is given by the fact that the SCC have smaller total porosity and more even pore size distribution within the interfacial transition zone of SCC as well as less void content in the matrix due to its better degree of compaction. Also SCC has a higher volume of paste (lower coarse aggregate content with limited maximum aggregate size of 10 to 20mm), which means longer path for cracks to propegats through the matrix. All these factors will have an affect on the cracking mechanism of SCC as compared to CC and, so, on the mechanical properties.

The main aim of this study is to investigate the effect of size and shape of concrete specimens on some mechanical properties of self-compacting concrete, namely compressive strength and splitting tensile strength. Also other properties of hardened SCC were investigated as the rate of development of compressive strength with age of concrete and the modulus of elasticity of concrete. Mathematical regressions were developed relating both splitting tensile strength and modulus of elasticity for both types of concrete (SCC and CC) to their cylinder compressive strength. Similar materials were used in these concrete in order to have a reasonable and practical comparison between SCC and CC with wide spectrum of compressive strength spectrum of (20-80MPa).

2. Failure Mechanism of Concrete

According to Griffith's theory, cracks, flaws, voids and defects exist within a brittle material. These may be present in the material before any load is applied or may be initiates fracture as a result of high stress concentrations induced at or near the crack when the material is loaded [4-6]. He concluded that the strength of any ideal material (without formed as a result of its application. Griffith's theory states that the presence of such cracks flaws or defects) is very much larger than the strength of the same material with flaws and defects. The failure, generally, begins in the location of the critical flaws and defects (the larger and normal on stress direction), consequently the flaws or voids grow and the gross-area of the material decreases resulting in the increase in the applied stress, leading finally to failure. Since the number of critical flaws or defects increases as specimen size increases, the probability of large specimens failure becomes larger than the probability of small specimens failure, which is inverted in the same manner in the compressive strength [4].

Concrete is not only a brittle material, but it is a compsite that is made of a mixture of fine and coarse constituents bonded together by the hyraulic cement (paste). Investigations have shown that very fine cracks at the interface between the coarse aggregate and the cement paste exist, in fact, even prior to application of the load on the concrete [7]. They are probably due to inevitable differences in mechanical properties between the coarse aggregate and the cement paste, coupled with shrinkage and thermal movement. According to Slate and Hover [8], preloading microcracks are largely responsible for the low tensile strength of concrete. Microcracking is a general feature of concrete. As long as the cracks are stable, their presence is not harmful. Paradoxically, while the interface between coarse aggregate and the hydrated cement paste is the locus of early microcracks, it is the presence of coarse aggregate particles that prevents the opening of a single wide crack: these particles act as microcrack arrestors. The hetrogeneity of concrete is thus beneficial. The microcracks in aggregate-paste bond surfaces form at all the possible angles with the direction of the external force. As a result, the local stress varies substantially above and below the nominal applied stress.

As an increasing load is being applied, these microcracks remain stable up to about 30%, or more, of the ultimate load and then begin to increase in length, width and number. The overall stress under which they start to grow is sensitive to the water/cement ratio of the paste. This is the stage of slow crack propagation. Upon further increase in load, up to between 70 to 90 % of the ultimate strength, cracks open through the mortar (cement paste and fine aggregate), which tends to form a bridge between bond cracks over the shortest distance between them so that contiuous cracking pattern is formed [9]. Hence the resulting cracks continue for a minimum distance through the paste. Such cracking pattern would be expected if one considers that the strength of the paste is greater than that of the paste-aggregate bond. Thus, bond failure at the aggregate particle interface will generally occur before failure of either the paste matrix or aggregate particles.

3. Experimental Works

The first step in this work was to design and obtain SCC and CC mixes with nominal compressive strengths of 20, 40, 60 and 80MPa.

The materials used in this experimental work were the same for both the SCC and CC, in order to be able to get a clear and representitive comparison of the behavior of these two types of concrete and to be able to compare between their mechanical properties, without the inteference or effect of the concrete constiuents intrensic properties. The materials used in this experimental work are as given below:

1. Cement

The cement used in this study was Ordinary Portland cement (Type I). This Cement conformed with the requirements of the ASTM C150 standards.

2. Aggregate

Natural siliceous desert sand was used as fine aggregate and crushed river gravel with maximum size of 14 mm was used as coarse aggregate. Both types of aggregate conformed to ASTM C33 requirements.

3. Superplasticizer

For the production of SCC as well as high strength CC a superplasticizer is needed. In this work Gelnium 51 superplasticizer was used, it's composition is based on polycarboxylic ether. This superplasticizer conformed to the requirements of types A and F and of ASTM C494 standard.

4. Limestone Powder

The filler powder used was crushed limestone with a finenss of 3100cm^2/gm (100% passing sieve 0.075mm). The particle size of the filler powder according to EFNARC [10] must be less than 0.125mm to be most beneficial. The chemical composition of the limestone powder is shown in **Table (1)**.

Table (1) Chemical analysis of the limestone powder

Oxide	Content %
CaO	56.10
SiO_2	1.38

Fe_2O_3	0.12
Al_2O_3	0.72
MgO	0.13
SO_3	0.21
L.O.I	40.56

** L.O.I : loss On Ignition*

3-1 Mix Proportioning Concrete

Mix proportional of SCC must satisfy the criteria on filling ability, flowability, passability and segregation resistance. The mix design method used in the present study is according to EFNARC [10]. Numerous trial mixes were prepared to obtain both the fresh concrete properties as well as the target concrete compressive strength. Four different SCC mixes were designed to yield nominal compressive strengths of 20, 40, 60 and 80MPa.

The details of the four SCC mixes are shown in **Table (2)**. On the other hand, corresponding CC mixes were designed according to British mix proportioning method given in BS 5328. **Table (3)** gives the details of these mixes.

Table (2) Details of self-compacting concrete mixes

Mix	W/C* ratio	Water kg/m^3	Cement kg/m^3	Limestone kg/m^3	Sand kg/m^3	Gravel kg/m^3	SP** kg/m^3
S20#	0.74	185	250	250	739	870	2
S40	0.60	180	300	200	758	890	2.4
S60	0.50	175	350	150	778	890	3.5
S80	0.38	170	450	50	778	890	5.4

W/C*: Water/Cement ratio.
#: nominal compressive strength.
SP**: Superplasticizer.

Table (3) Details of conventional concrete mixes

Mix	W/C ratio	Water kg/m^3	Cement kg/m^3	Sand kg/m^3	Gravel kg/m^3	SP kg/m^3
C20	0.70	222	317	720	1136	----
C40	0.50	200	400	728	1092	----
C60	0.36	170	446	762	1050	3.6
C80	0.28	160	570	665	1000	4.6

3-2 Testing of Fresh SCC

Fresh concrete testing is of serious importance for the production of SCC. The main characteristics of self-compacting concrete are the properties in the fresh state. Production of SCC is focused on its ability to flow under its own weight without vibration and the ability to obtain the homogeneity without segregation of aggregate. The slump flow, V-funnel and L-box are used for assessment of fresh properties of self-compacting concrete in this study (for more details about the material and testing, one can see M.Sc. thesis of Ali [11]) . The tests results of the fresh properties of the four SCC mixes are shown in **Table (4)**.

Table (4) Fresh properties of SCC mixes

Mix	Slump Flow (mm)	T_{500mm} (sec)	V-Funnel		L-Box		
			T_V (sec)	T_{V5} (sec)	Blocking Ratio	T20 (sec)	T40 (sec)
S20	742	4.50	7.97	9.28	0.90	1.18	3.01
S40	738	5.00	8.40	9.75	0.89	1.65	3.35
S60	745	4.00	6.65	8.05	0.93	0.99	2.51
S80	755	3.50	6.00	7.50	0.94	0.59	2.02

3-3 Testing of Hardened Concrete

3-3-1 Compressive Strength

Four types of specimen (varied in shape and size) were tested to determine the concrete compressive strength. The concrete compressive strength was determined in accordance to ASTM C39 and BS1881. These types of specimens investigated were:

1. 150x300mm. cylinders.
2. 100x200mm. cylinders.
3. 150x150x150mm. cubes.
4. 100x100x100mm cubes.

The concrete compressive strength of each strength of mix represents the average of three specimens. The concrete specimens were tested at three ages, 7, 28 and 90 days of water curing.

3-3-2 Splitting Tensile Strength Test

Splitting tensile strength tests were conducted in accordance to ASTM C496 on two different cylinder sizes of:

1. 150x300mm. cylinder.
2. 100x200mm. cylinder.

The splitting tensile strength of each mix represents the average of three specimens. The concrete specimens were tested at the age of 28 days of water curing only.

3-3-3 Static Modulus of Elasticity

The modulus of elasticity was determined according to ASTM C469-02. The modulus of elasticity of each mix was the average of three (150x300mm) cylinder specimens. The concrete specimens were tested at three ages, 7, 28 and 90 days of water curing only.

4. Results and Discussions

All results are analyzed by using STATISTICA software, where the relationship between results is selected from the best coeffeicient of correlation (R).

4-1 Concrete Compressive Strength

The results of compressive strength for both the SCC and CC are shown in **Table (5)**. The effect of size and shape of specimen on the compressive strength of both SCC and CC is shown in **Table (6)**.

Table (6) Effect of size and shape of specimen on concrete compressive strength (average conversion factors)

Self Compacting Concrete						Conventional Concretem				
	$f`_{c100}$	f'_{c150}	f_{cu100}	f_{cu150}			f'_{c100}	f'_{c150}	f_{cu100}	f_{cu150}
f'_{c100}	1.00	1.032	0.900	0.940		f'_{c100}	1.00	1.052	0.792	0.861
f'_{c150}	0.969	1.00	0.873	0.912		f'_{c150}	0.951	1.00	0.753	0.819
f_{cu100}	1.111	1.146	1.00	1.045		f_{cu100}	1.263	1.329	1.00	1.088
f_{cu150}	1.063	1.096	0.957	1.00		f_{cu150}	1.161	1.221	0.919	1.00

Table (7) Mathematical regressions for relating conversion factors of concrete compressive strength of specimens with different size and shape

Self compacting concrete	R*	Conventional concrete	R
$f_{cu150}/f_{cu100}= 0.886x(f_{cu150})^{0.018}$	0.980	$f_{cu150}/f_{cu100} = 0.831x(f_{cu150})^{0.024}$	0.993
$f'_{c150}/f'_{c100}= 0.953x(f'_{c150})^{0.005}$	0.950	$f'_{c150}/f'_{c100} = 0.880x(f'_{c150})^{0.019}$	0.999
$f'_{c150}/f_{cu150}= .805+0.002xf'_{c150}$	0.981	$f'_{c150}/f_{cu150}= .628+0.003xf'_{c150}$	0.982
$f'_{c100}/f_{cu100}= .777+0.002xf'_{c100}$	0.989	$f'_{c100}/f_{cu100}= .605+0.003xf'_{c100}$	0.979

***R: cofficient of correlation of the regression (may be accepted if its value greater than 0.9).**

The conversion factors are built on average values of strength of different specimen types obtain for the complete spectrum of nominal compressive strength investigated (20-80MPa). From this table it can be seen that the effect of size and shape of specimen on the compressive strength of concrete is less effective in SCC than in CC, this can be seen clearly from the factors in **Table (6)**, all conversion factors for SCC are closer to unity as compared to corresponding conversion factors of the CC. The reason for this behavior can be attributed to the better quality of paste microstructure and transition zone in SCC as compared to CC, as the first type of concrete exhibit lower percentage of voids, defects and flows [2,3] and on the longer path of failure through the cement mortar in SCC compared to CC, due to its higher fine material contents (lower coarse aggregate content).

In **Table (7)**, more detailed regressions were obtained to relate the compressive strength of concrete obtained using different size and shape of specimens, in these relationships the concrete compressive strength was introduced because it was clear that these conversion factors are not constant, but depend on the level of compressive strength of concrete.

Figure (1) to **Fig.(4)** clearly shows that the values of conversion factors for relating concrete compressive strength of different shapes and sizes are related to concrete compressive strength level of the concrete itself.

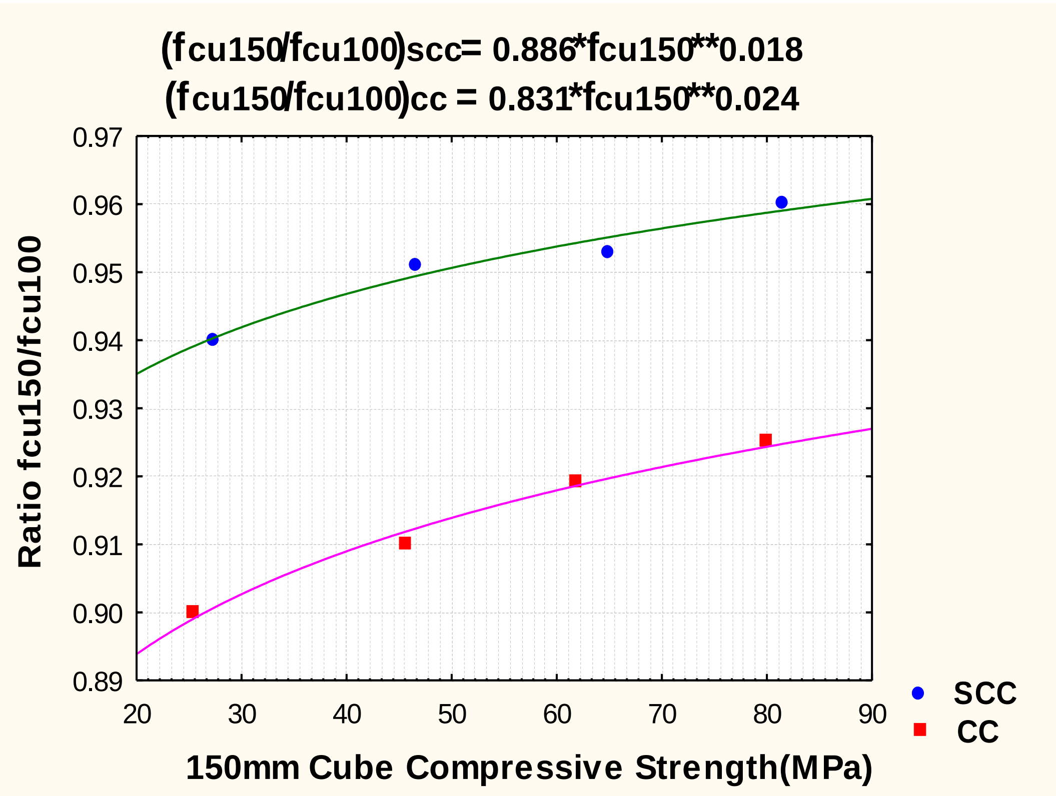

Figure (1) Variation of conversion factor (f_{cu150}/f_{cu100}) with 150mm cube compressive strength

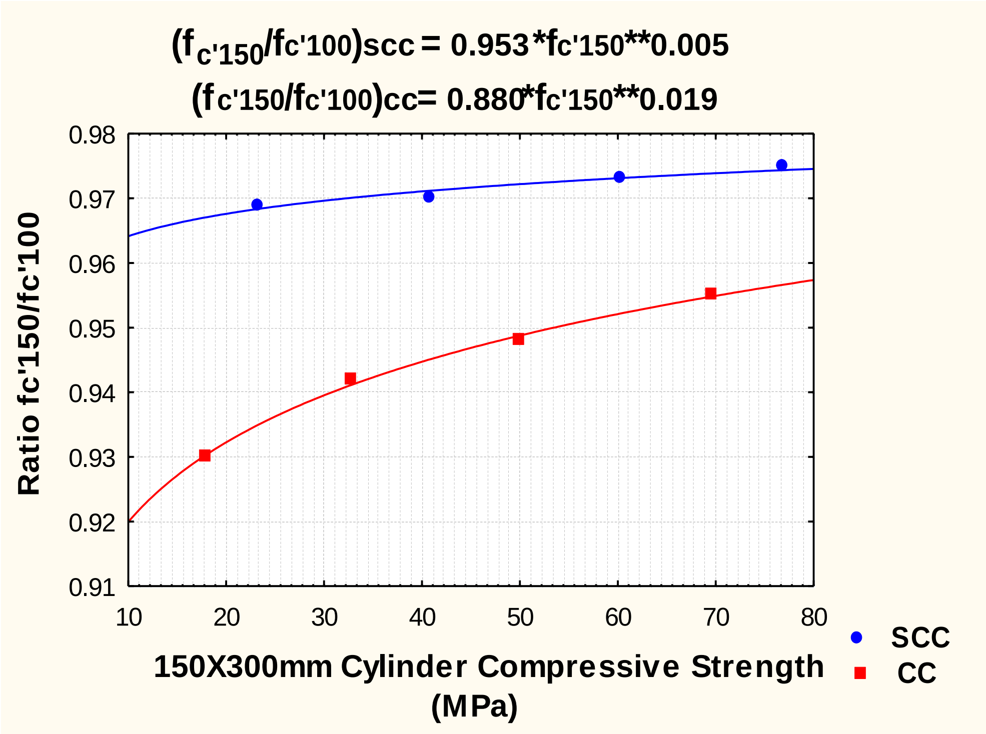

Figure (2) Variation of conversion factor (f'_{c150}/f'_{c100}) with 150x300mm cylinder compressive strength

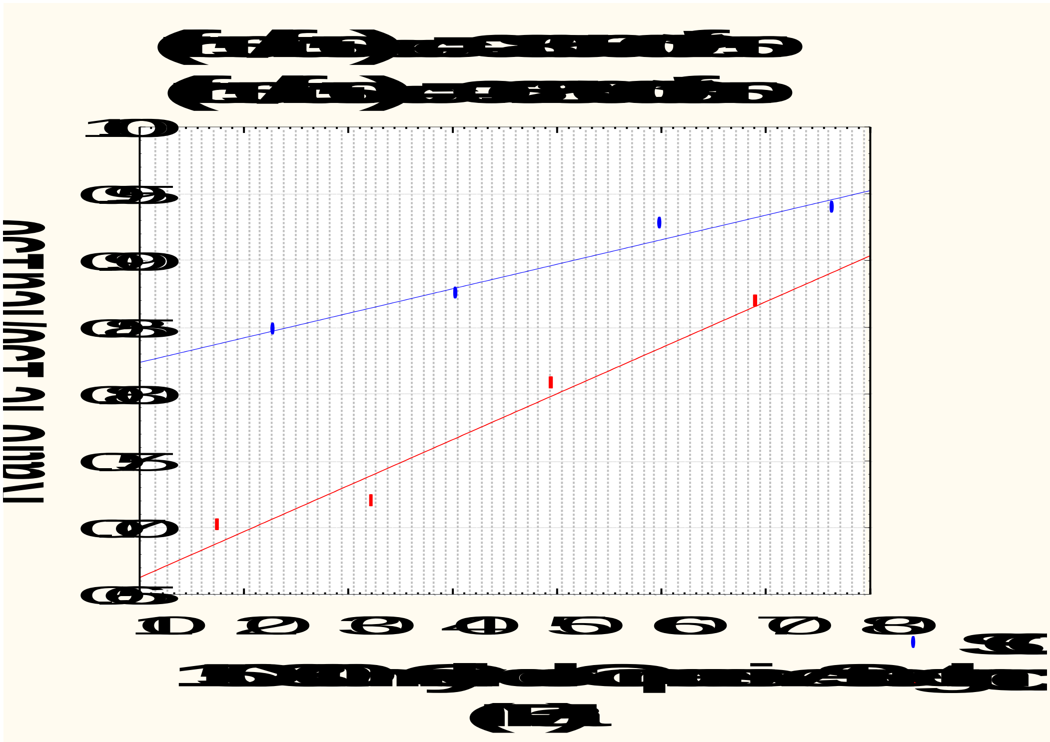

Figure (3) Variation of conversion factor (f'_{c150}/ f_{cu150}) with compressive strength for SCC and CC of 150x300mm cylinders

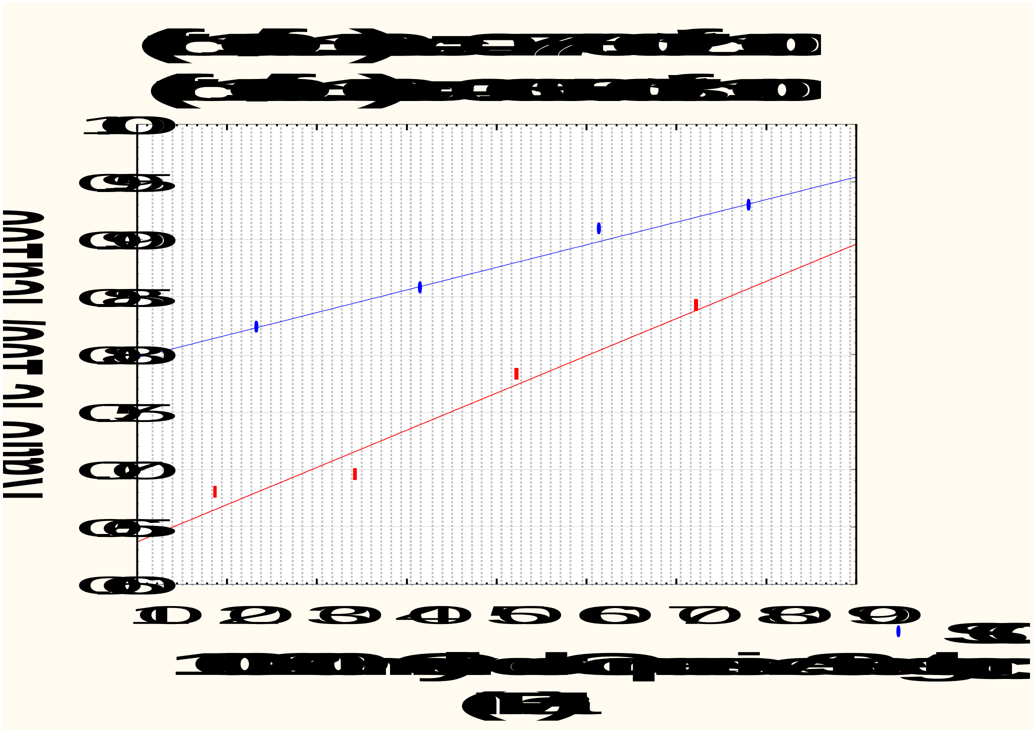

Figure (4) Variation of conversion factor (f'_{c100}/ f_{cu100}) with compressive strength for SCC and CC of 100x200mm cylinders

4-2 Splitting Tensile Strength

The splitting tensile strength (f_t) is determined on cylinders measured 150X300mm and 100X200mm and cured in water for 28 days.

The results of splitting tensile strength for self-compacting concrete and conventional concrete are shown in **Table (8)**. From this table it can be seen that effect of size of test specimen on the splitting tensile strength is not affected by the concrete compressive strength. A single factor can be proposed to relate the f_{t100} to f_{t150} and as follows:

For SCC $f_{t100} = 1.074 \times f_{t150}$

For CC $f_{t100} = 1.014 \times f_{t150}$

Table (8) Splitting tensile strength for different SCC and CC at 28 days

Mix	f_{t100} (MPa)	f'_{c100} (MPa)	f_{t150} (MPa)	f'_{c150} (MPa)	f_{t100}/f'_{c150} (%)	f_{t100}/f'_{c100} (%)	f_{t150}/f'_{c150} (%)
S20	3.21	24.00	3.01	23.25	1.066	13.38	12.95
S40	3.70	42.06	3.45	40.80	1.072	8.80	8.46
S60	4.42	61.96	4.09	60.29	1.080	7.13	6.78
S80	5.10	78.74	4.73	76.77	1.078	6.48	6.16
C20	3.04	19.27	2.75	17.92	1.105	15.77	15.34
C40	3.25	34.84	2.94	32.81	1.105	9.43	8.96
C60	4.20	52.74	3.81	50.01	1.102	7.96	7.62
C80	4.71	72.82	4.27	69.56	1.103	6.47	6.14

On the other hand, the ratio of the splitting tensile strength to corresponding concrete compressive strength decreases with the increase in concrete compressive strength, and also decreases with the increase in the specimen size for both SCC and CC. Therefore the splitting tensile strength was related to the cylinder compressive strength using a power regression, the regressions obtained are given in **Table (9)**. From previous literature, the values of the power of the regression varied between 0.50 to 0.75. The former value is used by the ACI 318 [12] and ACI 363 [13] committees, but Gardner and Poon [14] found a value nearer the latter, cylinders being used in both cases. The British code BS 8007 [15]: adopted a power of 0.70, but bearing in mind that the concrete compressive strength was based on cube specimens. In this work a power of the best fit regression was found to be closer to the value of 0.50, so this value was adopted in the regressions. From **Table (9)**, it can be seen that SCC has slightly higher splitting tensile strength than CC (about 0.60-2.00 % only for the two specimen sizes).

Table (9) Mathematical regressions relating concrete splitting tensile strength (MPa) to its compressive strength (MPa)

Self compacting concrete	R	Conventional concrete	R
$f_{t150} = 0.546 \times f'_{c150}{}^{0.50}$	0.949	$f_{t150} = 0.535 \times f'_{c150}{}^{0.50}$	0.902
$f_{t100} = 0.579 \times f'_{c100}{}^{0.50}$	0.960	$f_{t100} = 0.575 \times f'_{c100}{}^{0.50}$	0.909

4-3 Modulus of Elasticity

The values of the modulus of elasticity of both SCC and CC that has obtained from this work is given in **Table (10)**.

Table (10) Modulus of elasticity of SCC and CC mixes at 28 days

Mix	E_{scc}* (GPa)	$f'_{c\ 150}$ (MPa)	Mix	E_{cc}* (GPa)	$f'_{c\ 150}$ (MPa)
S20	22.49	23.25	C20	25.61	17.92
S40	28.01	40.80	C40	32.91	32.81
S60	32.90	60.29	C60	39.28	50.01
S80	37.79	76.77	C80	44.09	69.56

***** *Escc, Ecc: SCC and CC modulus of elasiticity***

From this table it can be seen clearly that the modulus of elasticity of SCC is lower compared to CC mixes. Mehta and Monteiro [16] showed that the coarse aggregate type affects the elastic modulus of concrete. The aggregate rigidity and porosity seem to be the most important factor, because these two properties determines the ability of aggregate to restrain matrix strain. Dense aggregate usually used in normal concrete has higher elastic modulus compared to the elastic modulus of the paste itself. As a result, the larger amount of coarse aggregate with a high elastic modulus of elasticity will result in high modulus of elasticity of concrete. This agrees with the studies carried out by Holschemacher and Klug [2].

Mathematical regressions were obtained to define the modulus of elasticity of concrete in terms of its compressive strength. A power relationship was adopted, with a power of (0.50), thus to be in line with other codes of design and previous research works [12,13]. **Table (11)** gives the regressions for both SCC and CC. Also, **Fig.(5)** shows the variation the modulus of elasticity of both SCC and CC. From these regressions, it can be concluded that the modulus of elasticity of SCC is about 25% lower than CC with corresponding compressive strength. This agrees with the studies carried out by Holschemacher and Klug [2].

Comparing the SCC modulus of elasticity using the obtained regression, with that of ACI 318 ($f'_c \leq 40.2$MPa), one can clearly conclude that the ACI 318 gives values of modulus of elasticity that are 8% higher than that of the SCC, while compareing the obtained regression with that proposed by ACI 363 ($21 \leq f'_c \leq 84$MPa), the ACI 363 regression yields values that are 12% higher than the obtained equation at $f'_c = 20$MPa, while yields values that are 6% lower for $f'_c = 80$MPa.

Table (11) Mathematical regressions relating concrete modulus of elasticity (GPa) to its compressive strength (MPa)

Self compacting concrete	R	Conventional concrete	R
$E_{scc} = 4.346 \times f_c{'}_{150}{}^{0.50}$	0.949	$E_{cc} = 5.533 \times f_c{'}_{150}{}^{0.50}$	0.960

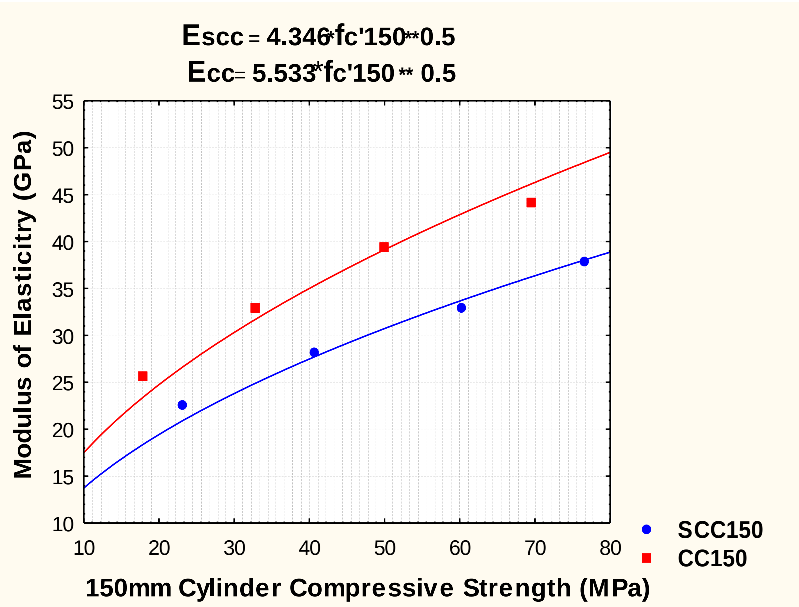

Figure (5) Relationship between SCC and CC modulus of elasticity with their cyliner compressive strength

5. Conclusions

From the present study, the effect of specimen size and shape on the mechanical properties of self-compacting concrete, with different strength levels (20-80MPa), compared with conventional concrete, and the relations between these properties, have been obtained, as following:

1. The shape of compressive strength specimens had lower effect on the measured compressive strength of SCC than on CC. On average the cylinder compressive strength was (0.90 and 0.912) of the corresponding cube compressive strength for SCC and (0.792 and 0.819) for CC.
2. The size of compressive strength test specimen also had lower effect on SCC compared to CC. On average the smaller size specimens (cylinder and cube) were only 1.032 and 1.045 of the larger corresponding specimens for SCC, while the corresponding values for CC were 1.052 and 1.088 respectively.
3. Conversion factors for effect of size and shape of compressive strength specimens increased (approached unity) as the the concrete compressive strength increased from (20 to 80MPa). Mathematical regressions were obtain to calculate the variation of these conversion factors.
4. The rate of development of concrete compressive strength increased with the increase in concrete compressive strength, the ratio of 150 mm cylinder compressive strength at 7 day to that at 28 days increased from 0.553 to 0.725 as the strength of concrete increased from (20 to 80MPa). On the other hand, the corresponding 90 days to 28 days ratios decreased from 1.462 to 1.175 with this increase in compressive strength.
5. The effect of size of cylinder on the splitting tensile strength was almost the same for both SCC and CC. the smaller test specimens (100mm cylinders) were 6% and 7% higher than the larger specimen for SCC and CC respectively.
6. The splitting tensile strength of SCC was only 2% higher than CC, for the 150mm cylinders, and only 0.6% higher for the 100mm cylinders.
7. The modulus of elasticity of SCC was about 25% lower than that of the corresponding CC.

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Notation

Ecc:	modulus of elasticity of conventional concrete.
Escc:	modulus of elasticity of self compacting concrete.
f_{cu100}, f_{cu150} :	100 and 150 mm cube specimens compressive strength.
f'_{c100}, f'_{c150}:	100x200 and 150x300 mm cylinders compressive strength.
f_{t100}, f_{t150}:	100x100x500 and 150x150x750 mm prisms splitting tensile strength