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REINFORCED SELF-COMPACTING CONCRETE BEAMS UNDER TORSION

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Abstract: This research investigates experimentally torsional behavior of reinforced self-compacting concrete beams with variables including plain and reinforced concrete beams, spacing of transverse reinforcement, concrete compressive strength, hollow and solid sections. The experimental work includes investigation of eleven beams tested under pure torsion and divided into three groups. Group (A) denotes the normal strength SCC beams with compressive strength of 32.84MPa. Group (B) covers the high strength SCC beams with compressive strength of 64.65MPa, and finally group (C) is normal strength SCC hollow beams. Test results are discussed based on torque-twist and beam longitudinal elongation behavior.

Keywords: *torsion, self-compacting concrete*.

ألعتبات الخرسانية المسلحة ذاتية الرص تحت تأثير اللي

الخلاصة: تبحث هذه الدراسة عمليا سلوك اللي للعتبات الخرسانية المسلحة ذاتية الرص بمتغيرات تشمل العتبات الخرسانية المسلحة وغير المسلحة بالحديد, المسافات الفاصلة بين حديد التسليح العرضي (الاطواق), مقاومة الانضغاط للخرسانة, المقاطع المجوفة وغير المجوفة. يتضمن الجزء العملي دراسة سلوك احد عشر عتبة تم فحصها تحت تأثير اللي حيث تم تقسيم العتبات الى ثلاث مجموعات. المجموعة (أ) تشير الى العتبات الخرسانية اعتيادية المقاومة ذاتية الرص ذات مقاومة انضغاط (32.84MPa), المجموعة (ب) تشير الى العتبات الخرسانية عالية المقاومة ذاتية الرص ذات مقاومة انضغاط (64.65MPa), المجموعة الاخيرة (ج) هي العتبات الخرسانية اعتيادية المقاومة ذاتية الرص ذات المقطع المجوف. تمت مناقشة النتائج اعتمادا على تصرف اللي - الدوران واستطالة العتبات.

1. Introduction

Self-compacting concrete (SCC) is a new type of concrete which has the ability to flow under its own weight and can spread without vibration, it is also called self-consolidating or self-vibrated concrete. It is thought to be one of the most significant concrete innovations of the past decades. SCC has the ability to spread into place and

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completely fill molds, while flowing around dense reinforcement without any blocking effect. The absence of energy induced self-compaction; shorter construction time and reduction of manpower along with the improved quality of the final product have brought SCC to attract a great deal of interest. However it should be noted that SCC is more sensible to changes in its composition compared to traditional concrete, thus what is acceptable for conventional concrete might not meet SCC requirements [1].SCC was developed in Japan by *Okamura* in the late 1980's to be mainly used for highly congested reinforced concrete structures in seismic regions. Since then SCC has generated tremendous interest among the research scholars, engineers and concrete technologists [2].A reinforced concrete member can be subjected to different types of loading namely, axial, bending, shear and torsion. Among all, torsion failure is a very brittle mode due to the fact that the concrete strut will undergo bending and compression in addition to the in-plane compression resulting from the shear stress[3]. Research related with the structural behavior of SCC is limited, so the torsional behavior of SCC will be investigated in the present research work.

1.2 Torsion in Reinforced Concrete Members

Reinforced concrete members are commonly subjected to bending moments, to transverse shear associated with those bending moments, and in the case of columns, the members are subjected to axial forces often combined with bending and shear. In addition, torsional forces may act, tending to twist a member about its longitudinal axis. Torsional force seldom acts alone and is almost always concurrent with bending moment and transverse shear, and sometimes with axial force as well.

For many years, torsion was regarded as a secondary effect and was not considered explicitly in design, its influence being absorbed in the overall factor of safety of rather conservatively designed structures. Current methods of analysis and design, however, have resulted in less conservatism, leading to somewhat smaller members that, in many cases, must be reinforced to increase torsional strength. In addition, there is an increase in use of structural members for which torsion is a central feature of behavior; examples include curved ridge girders, eccentrically loaded box beams and helical stairway slabs.

2. Experimental Work

In the present research, a series of reinforced SCC beams were tested to investigate the torsional behavior of such beams. The variable parameters and material used in the test program will be explained. The tests were conducted on eleven reinforced concrete simply supported beams with a square cross section of (15cm $\times$ 15cm) and having overall length of 118.5cm (Fig. 1). The beams were loaded at the ends with eccentric loads using steel arm of length 56 cm. The clear span which was tested for torsion was 81cm. The main variables in these tests were plain against reinforced concrete beams, spacing of transverse reinforcement, concrete compressive strength, hollow and solid sections. The reinforcing bars were deformed 6mm diameter for longitudinal and 5mm diameter for stirrups. For all tested beams, 135-degree standard hook was formed at the ends of each stirrups bar. Additional stirrups were placed at the ends of specimen spaced at 3cm to prevent failure at the steel arm region. In the experimental work, two mixes were used. The first mix was normal strength SCC while the second mix was high strength SCC. Details of the eleven tested concrete beams are shown in Table (1).

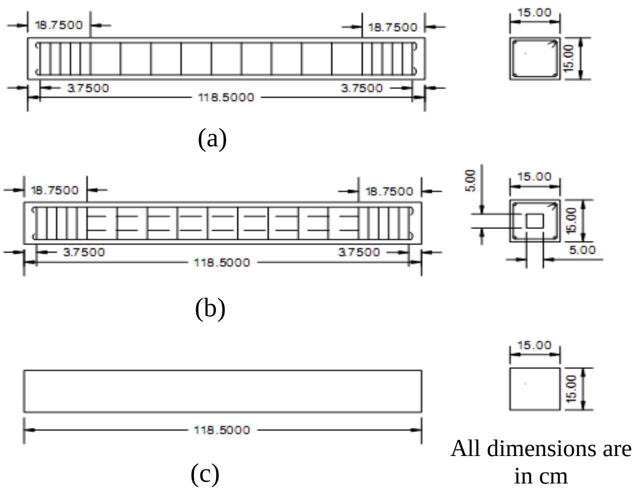


Figure (1) Beams Dimensions and Reinforcing Detailing.

a- Solid Reinforced Beams with Variable Stirrups Spacing.

b- Hollow Reinforced Beams with Variable Stirrups Spacing.

c- Concrete Beams Without Longitudinal Bars or Stirrups.

Table (1) Details of the Tested Beams

Group	Beam designation	f′c (MPa)	Spacing of stirrups (mm)	Hollow dimensions (mm*mm)
A	Ap	32.84	-	-
	A100	32.84	100	-
	A80	32.84	80	-
	A60	32.84	60	-
B	Bp	64.65	-	-
	B100	64.65	100	-
	B80	64.65	80	-
	B60	64.65	60	-
C	Cp	32.84	-	50*50
	C100	32.84	100	50*50
	C80	32.84	80	50*50

Group (A) denotes the normal strength SCC beams with compressive strength of 32.84MPa. Group (B) refers to the high strength SCC beams with compressive strength of 64.65MPa. Group (C) is normal strength SCC hollow beams with compressive strength of 32.84 MPa.

2.1 Materials

To produce self-compacting concrete, special mixes are required according to the mix design methods of EFNARC 2002[4] and other researchers. SCC materials are similar to materials used in conventional concrete but with some modification.

2.1.1 Cement

In the current research, ordinary Portland cement type I of (Al-jesser) mark made in Iraq was used. Test results of the chemical composition and physical properties comply with the requirements of the Iraqi Standard Specification I.Q.S. No.5, 1984[5].

2.1.2 Fine Aggregate

The sand which was used in the present research is brought form Al-Ukhaider region in Karbala. It is a natural sand and has fineness modulus of 2.36. The sieve analysis and physical properties comply with the limits of the Iraqi Specification No.45/1984[6].

2.1.3 Coarse Aggregate

Al-Niba'ee region crushed gravel of maximum size 10 mm was used in the present work. The grading of the aggregate and its physical properties agree with the Iraqi specification No.45/1984[6] respectively.

2.1.4 Water

Tap water was used for both mixing and curing of concrete.

2.1.5 Limestone Powder

Limestone powder (locally named Gubra) has been used as filler for SCC production in the present work. It has been found that to increase workability and early strength, as well as to reduce the required compaction energy, the particle size of the limestone powder according to EFNARC2002[4] must be less than 0.125 mm to be most beneficial.

2.1.6 Superplasticizer

To produce SCC, a superplasticizer known as (High Water Reducing Agent HWRA) was used. It has the trade mark known as Glenium 51. It is compatible with all Portland cements that meet recognized international standards. Glenium 51 is a new generation of modified polycarboxylic ether. Also, it is free from chlorides and complies with ASTM C494-05[7] types A and F. The concrete which contains superplasticizer exhibits a large increase in slump without segregation.

2.1.7 Steel Reinforcement

In the current research, deformed steel bars of 6mm diameter were used as longitudinal reinforcement with concrete cover of 15mm and deformed steel bars of 5mm diameter were used as stirrups with variable spacing, Fig.2 shows the steel reinforcement and the mold used in casting the beam samples.

Figure (2). Steel Reinforcement and Wooden Mold

2.2 Mix Design

To meet the self compactability requirements and the designed compressive strength, many trial mixes were carried out in the Laboratory of Constructional Materials at the College of Engineering / AL-Mustansiriayah University. The final mixes which have been used for casting the tested samples were performed in the Structural Laboratory of the College. The SCC mix was designed according to EFNARC2002[4]to satisfy SCC fresh properties. In the present work, two mix designs were made to produce normal strength SCC with f'_c=32 MPa, high strength SCC with f 'c=64MPa respectively. In the first SCC mix, cement content was 400 kg/m^3, fine aggregate content was 797 kg/m^3, coarse aggregate content was 767 kg/m^3, limestone powder content was 170 kg/m^3, water content was 190 l/m^3 and the superplasticizer content was 7.5 l/m^3. The proportion of these components by weight is 1:1.4:1.35 and the w/p (water to powder) ratio is 0.33. In the second high strength mix, cement content was 550 kg/m^3, fine aggregate content was 855 kg/m^3, coarse aggregate content was 767 kg/m^3, limestone powder content was 50 kg/m^3, water content was 165 l/m^3 and the superplasticizer content was 20 l/m^3. The proportion of these contents by weight is 1:1.33:1.28 and the w/p ratio is 0.275.

2.3 Mixing Procedure for SCC

In the present research, the laboratory mixing procedure used was outlined by Emborg [8] and modified by Al-Jabri [9]. The procedure is stated as follows:

1. The fine aggregates are added to the mixer with 1/3 quantity of water and mixed for 1minute.
2. The cement and mineral admixtures are added with another 1/3 quantity of water. Then, the mixture is mixed for 1 minute.
3. The coarse aggregate is added with the last 1/3 quantity of water and 1/3 dosage of superplasticizer, and the mixing time lasts for 1½ minutes then the mixer is left for 1/2 minute to rest.
4. Then, the 2/3 of the leftover of the dosage of superplasticizer is added and mixed for 1½ minutes.
5. The concrete is then discharged, tested for fresh properties and cast.

2.4 Fresh Properties of SCC

The fresh properties of SCC are listed in Table (2).

Table (2) Results of SCC Fresh Properties

Mix type	Slump flow mm	T_{50} sec	L –box (H1/H2)
N-SCC	770	2.5	1.0
H-SCC	730	4	0.92
Limits	650-800	2-5	0.8-1.0

2.5 Mechanical Properties of Hardened Concrete

The mechanical properties of SCC including the concrete compressive strength at (28) days of age, flexural strength (modulus of rupture),the splitting tensile strength and the static modulus of elasticity are listed in Table (3).

Table (3) Properties of Hardened Concrete

Mix Type	Compressive Strength(f'c) MPa	Modulus of Rupture(fr) MPa	Splitting Tensile Strength(ft) MPa	Modulus of Elasticity(Ec) MPa
Normal Strength SCC	32.84	4.41	3.12	24897
High Strength SCC	64.65	6.80	4.56	35287

3. Testing Procedure

Torsion application was conducted by placing the tested beams on freely supported rollers at both ends with clear span of 1160mm; lever arm with maximum eccentricity of 560mm with respect to the longitudinal axis of the beam was made from steel sections and attached to the tested beams by four large bolts in each arm. In order to obtain pure torsion, the center of the arms should be within the centerline of supports. A steel channel section of (1.75 m) length was laid diagonally on the lever arms to distribute the load from the center of the universal machine to the arms; Fig.3 shows the test setup. The load was applied at increments of (2 kN), readings were recorded manually using four dial gages (two of them for the angle of twist and the others for elongation). The strain readings of demec points which were attached diagonally at two faces of the tested beams was recorded each (6 kN), Fig.4 shows the dial gages and demec points arrangement. In addition, at each load stage, crack propagation was recorded according to cracks occurrence. The torque is gradually increased up to failure of the tested beam.

3.1 Angle of Twist Measurements

The method used to calculate the angle of twist is performed by using dial gages attached to the bottom fiber of each end of beams at a point laid at (65 mm) from the center of the longitudinal axis of the beam as shown in Fig.4c. The dial gages recorded the down values to find the twist angle in radians.

3.2 Elongation Measurements

Two dial gages were fixed at the center of the beam ends to measure the elongation of the beam as shown in Fig.4d.

Figure (3), Test setup

(a)

(b)

(c)

(d)

Figure (4), Demec Points and Dial Gages Arrangement and (b)-demec points arrangement (C) and (d)-dial gages arrangement

4. Experimental Results and Discussion

4.1 Test Results of Normal Strength SCC Beams (Group A)

For normal strength self-compacting concrete (SCC), four beams were tested to investigate the influence of the selected experimental variables on the torsional behavior. Three of these beams were reinforced longitudinally with 6mm diameter deformed bars and 5mm diameter deformed stirrup bar at (100mm, 80mm and 60mm) spacing. The fourth beam was cast from plain concrete. Fig. 5 and 6 respectively show the torque-twist and torque-elongation behavior of normal strength SCC. The values of cracking and ultimate torques and corresponding angle of twists and elongations are shown in Table 4 .In the present research, the tested beams having stirrup spacing of 80mm were designed to have minimum transverse and longitudinal steel reinforcement according to volumetric ratio of steel of about 1% to avoid the failure of beam at cracking torque [10]. Beam (A80) was chosen to be the reference beam. For beam (Ap) which was plain SCC beam, the cracking torque was equal to ultimate torque and equal to 1.12 kN.m. The plain concrete beams practically had no torsional ductility because of the absence of steel reinforcement in longitudinal and transverse direction which resisted the applied torque beyond the cracking stage. The formation of a first inclined crack occurred when the ultimate torque was applied. The beam failed suddenly and separated into two parts, Fig.7. The torque-twist behavior of beam (Ap) is shown in Fig.5 and it is approximately constant up to 50% of the ultimate torque.

For the reference beam (A80), diagonal crack was observed at 3.36 kN.m applied torque. At larger values of the applied torque, the diagonal cracks at different regions of the tested beam were formed; these cracks joined together and formed a single major spiral crack. As the applied torque increased, spiral cracks developed at about 45 degrees to the longitudinal axis of the beam and spread over the test region. Because the beam was reinforced with equal amounts of reinforcement in both longitudinal and transverse directions, all cracks were inclined at 45 degrees throughout the loading history as shown in Fig.8. The ultimate torque capacity of beam (A80) is 8.96 kN.m. The tested beam (A80) shows ductile behavior which is due to the presence of reinforcing steel bars in both longitudinal and transverse directions. Beam (A100) in which the stirrups spacing is larger than the spacing of the reference beam (A80) by 25%, the first diagonal crack initiated at a value of torque equal to 2.8 kN.m. The formation of diagonal and spiral cracks continued until the maximum torque capacity was reached at 6.4 kN.m ,Fig.9. For beam (A60) in which the stirrups were placed at 75% of the spacing of reference beam (A80), the torque-twist behavior was approximately linear until the first diagonal cracks occurred at 6.72 kN.m. After that, the shape of torque-twist diagram became nonlinear and reached the maximum torque at 10.64 kN.m. Beam (A60) had a ductile behavior and larger value of ultimate angle of twist (4.644 deg./m) and smaller ultimate elongation (0.26 mm). Fig.10 shows the cracks pattern of beam (A60).

Table (4) Values of Torque and Corresponding Angle of Twist and Elongation at Cracking and Ultimate Stages of Normal Strength SCC Beams (Group A)

Beam Designation	Cracking stage			Ultimate stage			T_u/T_{cr}
	Torque (kN.m)	Angle of twist (deg./m)	Elong-ation (mm)	Torque (kN.m)	Angle of twist (deg./m)	Elong-ation (mm)	
Ap	1.12	0.2292	0.04	1.12	0.2292	0.04	1.00
A80	3.36	0.2820	0.00	8.96	2.3522	1.04	2.66
A100	2.80	0.0793	0.75	6.44	0.3614	4.24	2.30
	6.72	0.4231	0.00	10.64	4.6440	0.26	1.58

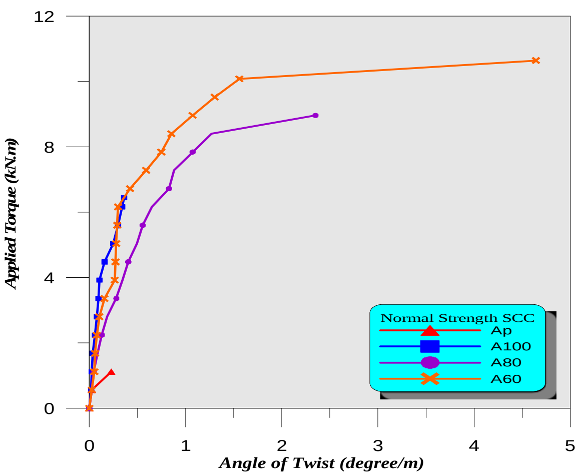


Figure (5), Torque -Twist Behavior of Normal Strength SCC Beams (Group A)

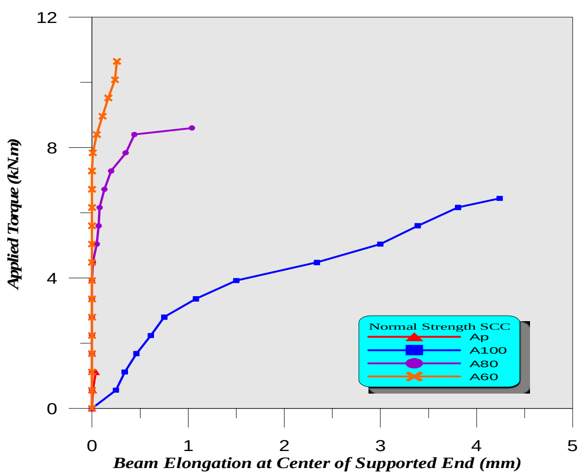


Figure (6), Beam Longitudinal Elongation of Normal Strength SCC Beams (Group A)

Figure (7), Failure Mode of Normal Strength SCC Beam (Ap)

Figure (8), Crack Pattern and Failure Mode of Normal Strength SCC Beam (A80)

Figure (9), Crack Pattern and Failure Mode of Normal Strength SCC Beam (A100)

Figure (10), Crack Pattern and Failure Mode of Normal Strength SCC Beam (A60)

4.2 Test Results of High Strength SCC Beams (Group B)

For the high strength self-compacting concrete (SCC) (group B), four beams were tested under pure torsion to study the experimental variables. Three of these beams were reinforced longitudinally with 6mm diameter deformed bars and 5mm diameter stirrup deformed bars at (100mm, 80mm and 60mm) spacing. The fourth was plain concrete beam. The torque-twist and torque- longitudinal elongation behavior of these high strength SCC beams are shown in Fig.11 and 12 respectively.

Values of cracking and ultimate torques and corresponding angles of twist and elongations are shown in Table 5.The plain SCC beam (Bp) had no torsional ductility and the formation of the first inclined crack occurred when the ultimate torsion was applied. The beam suddenly failed and separated into two parts (Fig.13). Failure crack surfaces were distinctly smoother for this beam because the higher compressive strength concrete contained larger amount of fine components. The sudden failure is also observed at the compressive strength of high strength SCC cylinders test.

Fig.11 shows that the torque-twist behavior of beam (Bp) is linear up to cracking torque. For beam (B80), the first diagonal crack appears at 5.6 kN.m applied torque. Number of cracks which are parallel to the first crack increases as the applied torque is increased until the maximum torque is reached (Fig.14). In this way, characteristic of spiral cracks developed around the tested beam faces. Because of the reduced spacing of stirrups at the region of attachment of loading arm to the tested beam, inclination of the cracks in these regions was steeper than that of cracks occurring at the effective span.

There is no significant difference in the crack pattern of high strength and normal strength SCC due to absence of larger sizes of coarse aggregate in mix components of SCC because of the fact that the cracks penetrate through the coarse aggregate as well as the matrix in vibrated HSC while they pass around the coarse aggregate in vibrated NSC. The ultimate torsional capacity of beam (B80) is 14.0 kN.m. For beam (B100), the first diagonal crack initiated at applied torque of 2.8 kN.m, Figure (11). Beam (B100) as well as beam (B80) show ductile behavior and large ratio of ultimate torque to cracking torque of about 4.65 which is the largest ratio obtained of all tested beams. The beam has approximately linear torque-twist curve until a torque of 12.0 kN.m.

The ultimate torque capacity of beam (B100) is 13.02 kN.m. Beam (B60) which has smaller spacing of stirrups shows higher values for cracking torque of (7.28 kN.m) and ultimate torque of (16.52 kN.m). Also it is observed that larger value of angle of twist (5.2476 deg. /m) and largest elongation of (1.27 mm) are achieved. Cracks propagation during the test history were similar to cracks occurring in beam (B80) but they were slightly wider and produced larger elongation value. Figures (15 and 16) show the crack pattern and failure modeof beams (B100) and(B60) respectively.

Table (5) Values of Torque and Corresponding Angle of Twist and Elongation at Cracking and Ultimate Stages of High Strength SCC Beams (Group B)

Beam Designation	Cracking stage			Ultimate stage			T_u/T_{cr} (%)
	Torque (kN.m)	Angle of twist (deg./m)	Elong-ation (mm)	Torque (kN.m)	Angle of twist (deg./m)	Elong-ation (mm	
Bp	2.52	0.1498	0.040	2.52	0.1498	0.04	1.00
B80	5.60	0.2300	0.040	14.00	2.8000	1.20	2.50
B100	2.80	0.0793	0.060	13.02	2.3698	1.10	4.65
B60	7.28	0.6346	0.015	16.52	5.2476	1.27	2.27

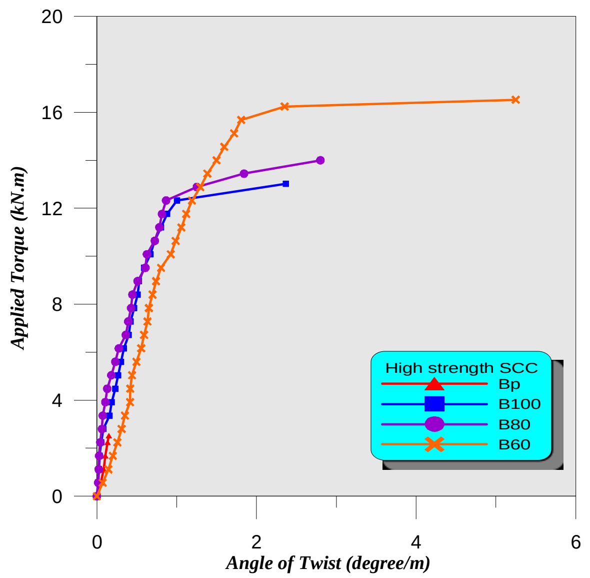
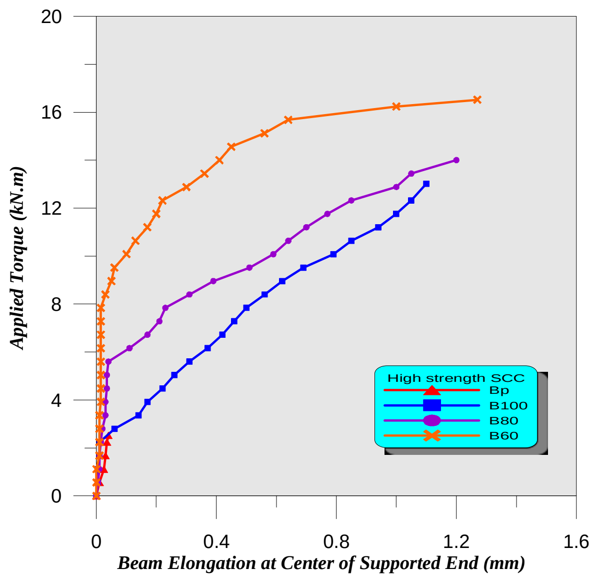


Figure (11), Torque –Twist Behavior of High Strength SCC Beams (Group B)



Figure(12), Beam Longitudinal Elongation of High Strength SCC Beams (Group B)

Figure (13), Failure Mode of High Strength SCC Beam (Bp)

Figure (14), Crack Pattern and Failure Mode of High Strength SCC Beam (B80)

Figure (15), Crack Pattern and Failure Mode of High Strength SCC Beam (B100)

Figure (16), Crack Pattern and Failure Mode of High Strength SCC Beam (B60)

4.3 Test Results of Hollow SCC Beams (Group C)

For hollow self-compacting concrete (SCC) beams (group C), three beams were tested to investigate the torsional behavior. Two of these beams were reinforced longitudinally with 6mm diameter deformed bars and 5mm diameter stirrup deformed bar at (100mm and 80mm) spacing. The third was plain concrete beam. The torque-twist and torque- longitudinal elongation behavior of hollow SCC beams are shown respectively in Figures (17) and (18). Values of cracking and ultimate torques and corresponding angles of twist and elongations are shown in Table (6).

For plain hollow SCC beam (Cp), the cracking and ultimate torques have the same value (1.12 kN.m) ,this response is similar to that of solid beam having the same compressive strength (Ap). Values of twisting angle and elongation are less than the values occurring in solid beam (Ap) and they are 0.1760 deg. /m and 0.01 mm respectively. Finally, beam (Cp) failed suddenly and divided into two segments, Fig.19.
For beam (C80), the cracking torque appeared at 5.04 kN.m. This value is greater than cracking torque of beam (A80), (3.36 kN.m) by about 50%. The ultimate torque value was 9.80 kN.m which is slightly greater than the ultimate torque of beam (A80), (8.96 kN.m)by about 10%. From the torque-twist behavior shown in Fig.17, the beam (C80) has a ductile response and the ultimate value of angle of twist is 3.609 deg./m. Fig.18 reveals that beam (C80) has no significant elongation until the cracks appeared at torque value equal to 5.04kN.m. Figure (20) shows the cracks pattern and failure mode of beam (C80) .

The overall behavior of the last beam of this group, beam (C100) is similar to the behavior of beam (C80) with regard to torque-twist behavior as shown in Fig.17. The cracking torque was observed at a value of 3.36kN.m which is greater than the value of cracking torque of beam (A100) by about 20%. While the ultimate torque capacity is reached at a torque level of 6.10 kN.m which is smaller than ultimate torque of beam (A100) by about 5.3%. Crack formation and propagation in (group C) is similar to that of solid normal strength SCC beams of (group A). Fig.21 shows the cracks pattern and failure mode of beam (C100).

Table (6) Values of Torque and Corresponding Angle of Twist and Elongation at Cracking and Ultimate Stages of Hollow SCC Beams (Group C)

Beam Designation	Cracking stage			Ultimate stage			T_u/T_{cr}
	Torque (kN.m)	Angle of twist (deg./m)	Elong-ation (mm)	Torque (kN.m)	Angle of twist (deg./m)	Elong-ation (mm)	
Cp	1.12	0.1760	0.01	1.12	0.1760	0.01	1.00
C80	5.04	0.2203	0.05	9.80	3.6092	0.61	1.94
C100	3.36	0.1763	0.04	6.10	2.7568	0.90	2.75

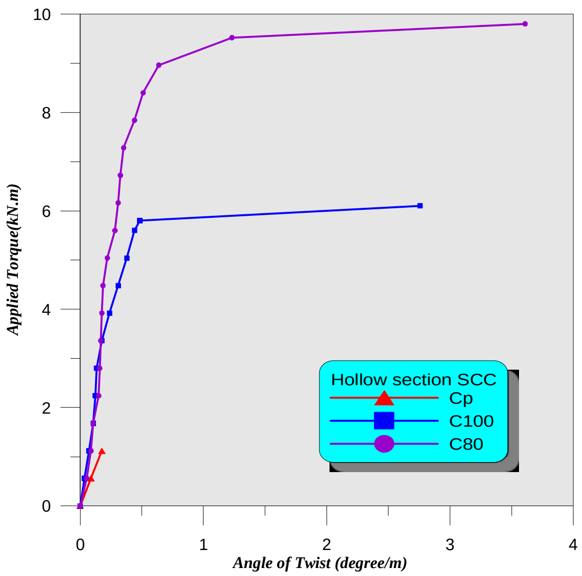


Figure (17), Torque –Twist Behavior of Hollow SCC Beams (GroupC)

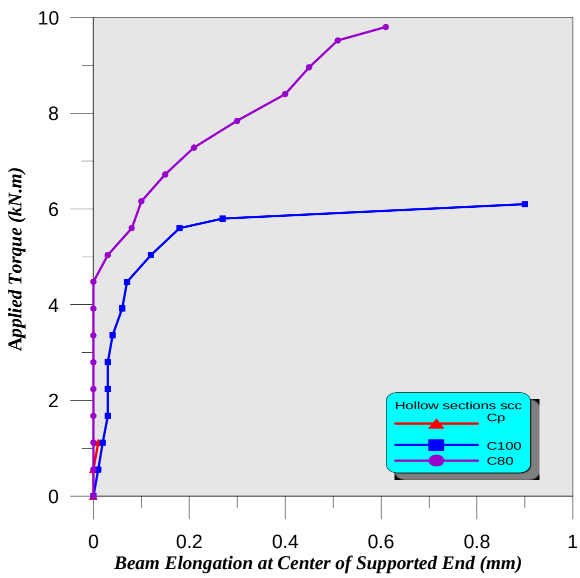


Figure (18), Beam Longitudinal Elongation of Hollow SCC Beams (GroupC)

Figure (19), Failure Mode of Hollow Normal Strength SCC Beam (Cp)

Figure (20), Crack Pattern and Failure Mode of Hollow SCC Beam (C80)

Figure (21), Crack Pattern and Failure Mode of Hollow SCC Beam (C100)

5. Conclusions

1- For self-compacting (normal strength, high strength and hollow) concrete beams without longitudinal reinforcement or stirrups, cracking torque is equal to ultimate torque.

2- It was observed that the use of high strength self-compacting concrete beams significantly increases the cracking and ultimate torques of the tested beams in comparison with normal strength self-compacting concrete.

3- From the experimental test, it was observed that the cracking torque of hollow self-compacting concrete beams with longitudinal reinforcement and stirrups are higher than the cracking torque of corresponding solid normal strength self-compacting concrete beams, while the ultimate torque was slightly higher or slightly smaller than the ultimate torque of corresponding solid normal strength self-compacting concrete beams. The cracking and ultimate torques in hollow and solid normal strength self-compacting concrete beams without longitudinal reinforcement or stirrups are the same.

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