Strengthening of Ferrocement Beams in Torsion by CFRP Strips

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Abstract

Torsion is resisted well by closed form reinforcement, due to the circulatory nature of the torsion inducing shear flow stresses in a beam. Therefore, it will be more efficient to have strengthening schemes, which are wrapped in closed form around the cross section. An experimental work was carried out and used superplasticizer with mix 1:1.5 to improve the mechanical properties of mortar. 12 rectangular beams (50x120)mm and 1m length are cast, strengthened and tested under pure torsion. The Variables considered in the test program include: effect number of wire mesh layers (unit), this unit consists of two layers of wire mesh with skeletal steel, (2, 3, 4) units and effect spacing of CFRP strips, (100,160,200) mm c/c. Test results are discussed based on torque – rotation behavior and influence of parameters on ultimate torque and failure modes. Generally, using optimum dosage of super plasticizer (1.4 % of weight of cement) gave compressive strength 65.65 MPa. Increasing the number of units from 2 to 4(reinforcement near the surface of beam section) led to increased ultimate torque by (13.44 %) and from 2 to 3(uniformly distributed reinforcement) led to increases the ultimate torque by only (3.24 %). When the beams are strengthened with CFRP strips, the lowest and highest increase in torque is at 112 % (4-units,@200 spacing) and 312 % (4-units,@100 spacing), respectively. The ultimate torque of beams with CFRP strips @ 100 mm and 160 mm spacing is greater than beams with CFRP strips @ 200 mm spacing by (94.34,45.28) %, respectively for the group having 4-units.

Keywords: Ferrocement, Superplasticizer**,** Wire mesh layers (unit), CFRP strips, Ultimate torque, Rotation.

تقوية العتبات السمنتية المسلحة في اللي بواسطة ألياف الكاربون البوليمرية

الخلاصة

ان اللي يقاوم بصورة افضل من قبل التسليح المغلق بسبب الطبيعة الدائرية للي حيث يحصل جريان القص في العتبة. لذلك فأن التقوية للي تكون كفاءتها اكثر عند استعمالها بصورة مغلقة حول المقطع. يتضمن البرنامج العملي إضافة الملدن المتفوق إلى الخلطة 1:1.5 لتحسين الخواص الميكانيكية للمونة. 12 عتبة مستطيلة (50 x

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120)ملم وطول 1 متر تم صبها وتقويتها وفحصت تحت تأثير اللي الصرف. و المتغيرات المأخوذة بنظر الاعتبار في هذا البحث تشمل:- تأثير عدد طبقات الشبكات السلكية (وحدة) حيث تتكون هذه الوحدة من طبقتين من الشبكات السلكية مع الهيكل الحديدي، (2, 3, 4) وحدة و تأثير مسافات شرائح ألياف الكاربون البوليمرية المسلحة ، (100, 160, 200) ملم. تم مناقشة نتائج الفحص اعتمادا على تصرف اللي – الدوران واستطالة العتبة وتأثير المتغيرات على عزم اللي الاقصى واطوار الفشل. واظهرت النتائج ان استخدام النسبة المثلى من الملدن المتفوق (1.4 من وزن السمنت) اعطى مقاومة انضغاط 65.65 نيوتن\ملم2 . وثبت ان زيادة عدد طبقات الوحدات من 2 وحدة إلى 4 وحدات (التسليح يكون قرب سطح مقطع العتبة) يؤدي إلى زيادة مقاومة اللي القصوى بمقدار (13.44%) والزيادة من 2 وحدة إلى 3 وحدات (التسليح يكون موزع بصورة منتظمة) يؤدي إلى زيادة مقاومة اللي القصوى بمقدار (3.24%). عند تقوية العتبات بشرائح الياف الكاربون البوليمرية المسلحة ثبت ان اقل زيادة واعلى زيادة لمقاومة اللي القصوى عند مقارنتها مع العتبة المرجعية (بدون شرائح) هي 112% (لعتبة مسلحة ب 4 وحدات وتحوي شرائح على مسافة 200ملم) و 312% (لعتبة مسلحة ب4 وحدات وتحوي شرائح على مسافة 100 ملم)على التوالي. وثبت ان مقاومة اللي القصوى للعتبات المقوات بشرائح الياف الكاربون البوليميرية المسلحة وعلى مسافة 100 ملم , 160 ملم اكبر من العتبات المقوات بالشرائح على مسافة 200 ملم بمقدار (94.34% ,45.28 %) على التوالي وهي لمجموعة مسلحة ب4 وحدات.

INTRODUCTION

Ferrocement is a type of thin wall reinforced concrete commonly constructed of hydraulic cement mortar reinforced with closely spaced multiple layers of thin wire mesh and /or small diameter rods, uniformly dispersed throughout the matrix of the composite (1). From the architectural stand-point, ferrocement is very useful, since it can be molded into different shapes and these shapes can be undulating (2). Variety of methods are available for strengthening the structures, for example adding on new structural material, post-tensioning cables, or changing the structural system (3). These methods have been proven to work well in many situations. However, they may, in some cases have drawbacks that make the method too expensive to use or not as effective as wanted to be in terms of time and structural behavior. During the last few years, it has become more and more customary to strengthen concrete structures by bonding advanced composite materials to their surface. The method involves a material with high tensile strength and relatively high stiffness being bonded to the surface of a structural element to serve as additional reinforcement (4). The most common material used is Fiber Reinforced Polymers (FRPs), which are made from a variety of fibers and resins and may be found in different forms. There is a great interest to the civil engineering community in FRP because using Carbon Fiber Reinforced Polymer (CFRP) among relatively new technologies having many advantages (5).

EXPERIMENTAL WORK (6)

Materials

Cement

Ordinary Portland cement (type I) of Caresta mark was used in casting all the specimens. It was manufactured in Iraq, and had the chemical composition and physical properties given in **Tables (1 and 2).** The tests were carried out by The National Center for Construction Laboratories and Researches (NCCLR). This cement conforms to ASTM C150-05 (7) and Iraqi specification (IOS 5/1984)(8) .

Fine Aggregate

Natural sand from Al-Ekhaidher region in Iraq was used for mortar mixes of this study. The fine aggregate passed through 2.36 mm conforming to the ASTM C-33 -05 (9). The obtained results indicated that the fine aggregate grading was zone -2 and within the limits of Iraqi specification (IOS 45/1984) (10). The sand gradation and chemical composition are given in Table (3).

Admixtures

The super plasticizer used throughout this work was "GLENIUM 51" with optimum dosage. This dosage was obtained from trial mixes. GLENIUM 51 was manufactured by BASF Construction Chemicals, UAE. GLENIUM 51 has been primarily developed for the applications in the ready mixed concrete industries where the highest durability and performance are required. Due to its capability of water reduction, this material was classified as type (A) and (F) in ASTM C494-05 (11). The properties of the superplasticizers are given in Table (4).

Reinforcement

Locally available woven hexagonal chicken wire mesh with an average diameter of 0.40 mm and skeletal smooth mild steel with an average diameter of 3 mm has been used. A chemical test was carried out to a sample from wire mesh to determine the material properties. The test results indicated that the main wire mesh material is steel with some ratio of metals(12) as given in Table (5). Several strand wires were taken from the mesh and tested by UTM (Universal Testing Machine) of 30 kN capacities for tension to determine the average yield stress (fy), the ultimate strength (fu) and modulus of elasticity (E)(12). The result of this test and the stress-strain curve for the tested wire mesh is given in Table (6) and Figure (1).

Table (1) Chemical Composition of Cement (*).

Compound Composition (Oxides)	Chemical Composition	% (weight)	Iraqi Specification No. 5/1984
Calcium oxide	CaO	67.14	---
Silicon dioxide	SiO2	18.23	---
Aluminum oxide	Al2O3	4.72	---
Iron Oxide	Fe2O3	2.86	---
Magnesium oxide	MgO	1.79	‹ 5
Sulphur trioxide	SO3	2.35	‹ 2.8
Loss on ignition	L.O.I	2.50	‹ 4
Insoluble residue	I.R	0.80	‹ 1.5
Lime saturation factor	L.S.F	0.73	0.66 – 1.02
Tricalicium aluminates	C3A	7.67	---
Tricalicium silicate	C3S	42.94	---
Dicalicum silicate	C2S	29.18	---
Tetracalicum aluminates ferrite	C4AF	11.06	---

(*) *All tests were made at the National Center for Construction Laboratories and Researches.*

Table (2) Physical Properties of Cement (*).

Physical properties	Project's cement(Caresta)	Iraqi specification No. 5/1984
Fineness using Blaine air permeability apparatus (m^2/kg)	459	› 230
Soundness using autoclave method	0.05 %	‹ 0.80 %
Setting time using Vicat's method		
Initial (hrs : min)	1 :50	› 45 min
Final (hrs : min)	4 : 00	‹ 10 hrs
Compressive strength for cement paste cube (50 mm) at:		
3 days (MPa)	33.60	› 15
7 days (MPa)	38.60	› 23
28 days (MPa)	45.60	----

(*) *All tests were made at the National Center for Construction Laboratories and Researches.*

Table (3) Results of Fine Aggregates Tests.

Sieve Size (mm)	% Passing	
	Fine Aggregate	(IOS 45/1984) Limitations for Zone No. 2
4.75	93	90-100
2.36	75	75-100
1.18	60	55-90
0.6	44	35-59
0.30	20	8-30
0.15	7	0-10
0.075	4.1	≤ 5
Sulfate content = 0.38		**≤ 0.5**

(*) *All tests were made at the National Center for Construction Laboratories and Researches.*

Table (4) Properties of Superplasticizers*.

Commercial name	GLENIUM 51
Chemical composition	Sulphonated melamine and naphthalene formaldehyde condensates
Subsidiary effect	Increased early and ultimate compressive strength
Form	Viscous liquid
Color	Light brown
Relative density	1.1 g/cm^3 @ 20º C
pH	6.6
Viscosity	128 ± 30 cps @ 20º C
Transport	Not classified as dangerous
Labeling	Not hazard label required
Chlorides	Free from chlorides

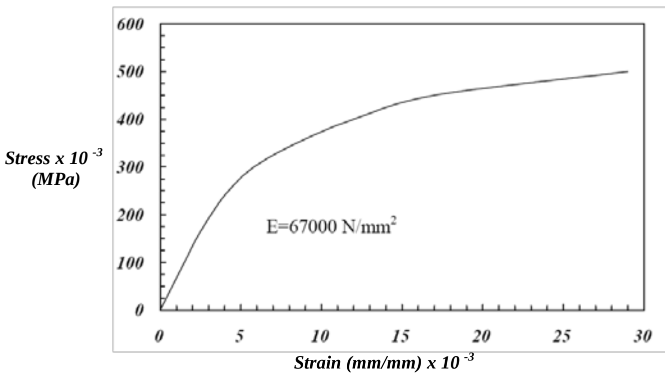
(*)Provided by the manufacturer

Table (5) Chemical Properties of Wire Mesh(12).

Fe%	Cr%	Cu%	Mn%	Ni%	C%	S%	Si%
99.44	0.01	0.05	0.38	0.036	0,055	0.019	0,01

Table (6) Yield Strength, Ultimate Strength and Modulus of Elasticity of Wire Mesh and Smooth Bar.

Properties (MPa)	Wire mesh(12)	Smooth Bar
Yield stress (*fy*) MPa	275	372
Ultimate strength (*fu*) MPa	500	550
Modulus of elasticity (*E*) MPa	67000	198820



Figure(1) Stress–Strain Curve of the Wire Mesh(12)

2-1-6 Mold.

Four rectangular molds of 1 m length and (50x120) cross section were made for casting the 12 ferrocement beam specimens. The molds were made from plywood sheet having a thickness of 15 mm. Each two molds were joined together and consisted of four main parts (base and three similar side parts). The three similar side parts were fastened to with the base part by 6 bolts of 10 mm diameter. Plate (1) shows the mold.

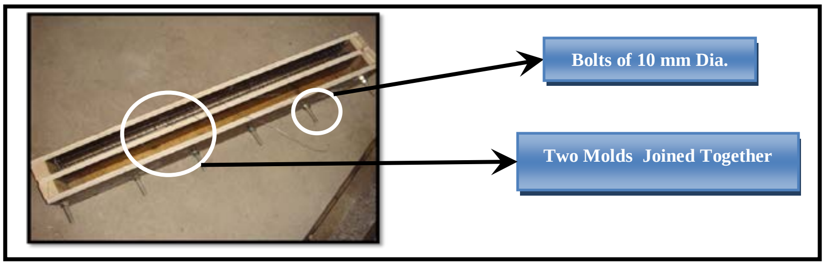


Plate (1) The Plywood Mold.

Mortar Mixes

1:1.5 mix in casting the beam specimens were used by weight (cement: sand) with w/c of 0.32 and superplasticizers at 1.4% the weight of cement. By many trial mixes the optimum dosage of superplasticizers and w/c was obtained. They were fixed on the basis of workability(flow) and compressive strength, and conformed the ASTM C109-05. Table(7) shows some trials mixes.

Table (7) Trial Mixes (Flow Values for Varying Dosages of Superplasticizers, w/c and Compressive Strength for Mortars).

w/c	Superplasticizers (SP) (% weight of cement)	Flow (110±5)mm	Water reduction %	Compressive strength(MPa)*	
				7-days	28-days
0.5	0	112	0	27.93	43.51
0.47	0	106	6	31.27	45.87
0.4	1	High	20	36.10	53.23
0.32	1	98	36	50.29	63.92
0.32	1.2	104	36	49.63	64.10
0.32**	1.4	110	36	47.24	66.44

(*) Each value is an average of three cubes (50 x 50 mm).
(**)The optimize results which compatibility with a flow.

Mixing Procedure (6)

The wire mesh units are placed and fixed in the mold, after cleaning and oiling it. Before mixing, all quantities are weighed and placed in clean container. Saturated surface dry sand and cement are mixed for 1 minute in a horizontal rotary mixer. Water is added to the mix; half of the water is added to the mix and mixed for 5 minutes. Then the superplasticizer was added to the residual water and poured into the mixer. The mortar was then mixed for 5 minutes. The mortar is poured on the molds in three layers, and each layer is vibrated on a table vibrator which gives adequate compaction. Mortar control specimens are also taken from the same mix and for each mix, the cylindrical and cubical molds are filled with concrete into three layers; each layer is vibrated on a table vibrator. The surface of the mortar is leveled off and finished with a trowel. Then, all the specimens are covered with a nylon sheet to prevent water evaporation. All specimens are left in the laboratory until they are demolded after 24 hours, and then placed in water bath for (28) days with almost constant laboratory temperature.

Control Specimens

To determine the mortar properties of hardened mortar, the following standard samples (Mortar Control Specimens) were taken directly from the material used for casting beams specimens. All details of mortar tests are given in Table (8).

Table (8) Mechanical Properties of Hardened Mortar (6).

Mortar properties	Average Strength
Compressive Strength f_{cu}	65.65 MPa
Modulus of Rupture fr	6.52 MPa
Modulus of Elasticity f_t	3.86 MPa
Splitting Tensile Strength E	47.10 GPa

Detail of Specimens and Their Reinforcement

In this study the beam specimens were reinforced with layers of wire mesh, each layer called (unit). This unit consists of two layers of wire mesh with skeletal steel, Figure (2). 12 beams were divided into three groups (one group has 2 units, one group has 3 units, and one group has 4 units) as shown in Figure (3). The clear cover of the units was about 10mm. Each group had four beams [one beam without CFRP (reference beam), and three beams with CFRP at different spacing (100,160, 200) mm c/c]. Table (9) shows the experimental test arrangement for ferrocement beams strengthened with CFRP under pure torsion.

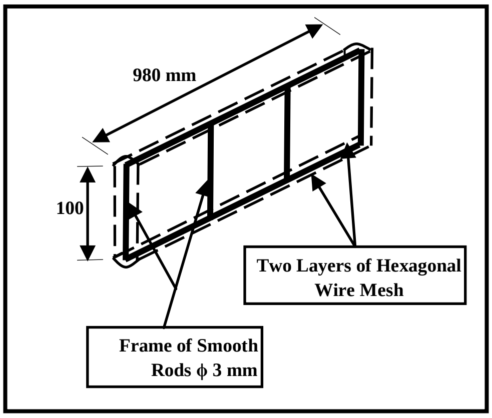


Figure (2) Detail of Wire Mesh Unit.

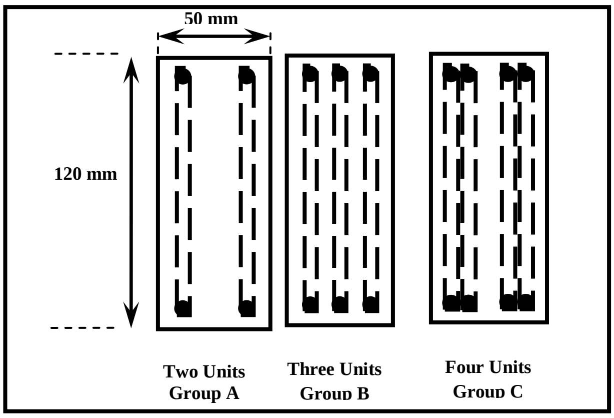


Figure (3) Reinforcement of Cross Section of Beams.

Table (9) Groups and Details of Beams Strengthening with CFRP.

(1)

Groups	Type of Reinforcement and No. of beams	Symbols	Distance of CFRP c/c (mm)**
A	Two unit* (4 beams)	AR	Without
		A1	@ 100
		A3	@ 160
		A4	@ 200
B	Three unit* (4 beams)	BR	Without
		B1	@ 100
		B2	@ 160
		B3	@ 200

(2) Continued

Groups	Type of Reinforcement and No. of beams	Symbols	Distance of CFRP c/c (mm) **
C	Four unit* (4 beams)	CR	Without
		C1	@ 100
		C2	@ 160
		C3	@ 200

Carbon Fiber Fabric Strengthening System (CFRP)

The components of this system are unidirectional woven carbon fiber fabric SikaWrap-230C/45 and epoxy based impregnating resin Sikadur-330.

CFRP Installation

The specimens were cleaned and loose particles and contaminations from the specimen's surface were removed. The corners of the specimens were rounded to avoid any stress concentration in the CFRP sheets at corners of the beams. The mixed resin Sikadur-330 was applied to the prepared substrate using a trowel or brush in a quantity of approximately (0.7 to 1.5 kg/m2), depending on roughness of substrate. The SikaWrap -230C\45 fabric was cut by scissors to strips at (50 mm) width and for the required length for all the specimens. The SikaWrap -230C\45 fabric was placed onto the resin with gloved hands and the plastic roller until the resin is squeezed out between and through the fiber strands and distributed evenly over the whole fabric surface. (50 mm) overlapping the SikaWrap -230C\45 fabric. As a covering layer an additional resin layer of approximately (0.5 kg/m2) broadcast with the brush is added, which will serve as a bonding coat for following cementitious coatings. After allowing the sheets to cure for 7 days until the resin (Sikadur-330) was dry, the specimens will be ready to test. All apparent concrete surface beams were painted white so that crack propagation can be easily detected. Plate (2) shows the beams strengthened with CFRP.

Testing Procedure

A hydraulic universal testing machine (MFL system) was used to test the beam specimens. This machine was calibrated by the "Iraqi Central Organization for Standardization and Quality Control". The normal load can just be applied by this machine on the specimen at several points and the supports should be remaining fixed without rotating around the longitudinal axis. In this research the applied loads outside the bed of the universal machine are needed in order to get torsional movement. The experimental requirements were applied to move the supports circularly (ball bearing) and transmitting the load from the center of the universal machine to the two external points that represent the moment arm (6).

The special clamping loading frame on each end of the beam used in this research is shown in Plate (3). This frame consists of two large steel clamps which work as arms for applied torque with separated faces to connect them over the sample by large bolts; four bolts (10 mm dia.) are used for each arm. This frame is made of steel sections; they have cross section of U shape attached by welding. The final shape is similar to a bracket. These arms were capable of providing a maximum eccentricity of (600 mm) with respect to the longitudinal axis of the beam. In order to get pure torsion the center of support should coincide with the center of the moment arm. The steel box girder of (3 m) length is used to transmit the loads from the center of the universal machine to the two arms (pure torsion). This girder was set above the two arms as shown in Plate (3). A strengthened group of beams was tested under monotonically increasing torque up to failure; the load was applied gradually. At each load increment (500 N), readings were acquired manually. In addition, at each load stage, cracks were recorded according to their occurrence. The torque increased gradually up to failure of the beam.

Angle of Twist Measurements

A simple method was used to estimate the angle of twist by using two dial gages (right and left side) attached the bottom fiber of the end of beam at a point (20 mm) from the center of the longitudinal axis of the beam as shown in Plate (3). The two dial gages on the right and left side recorded readings to find the twist angle in radians.

Plate (2) Beams Strengthened with CFRP.

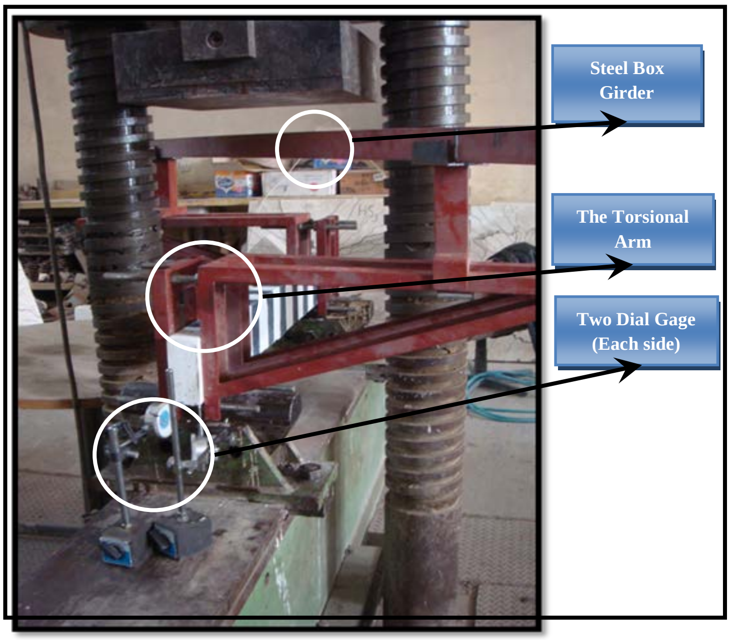


Plate (3) Testing Setup.

RESULTS AND DISCUSSIONS

Water Reduction

The physical properties and microstructure of mortar depend on the chemical composition of the cement, the nature of the sand, the w/c ratio, and the curing conditions of the finished product. Since the matrix represents approximately 95 percent of the ferrocement volume, its properties have a great influence on the final properties of the product (1) . A superplasticizer, GLENIUM 51, was used to reduce the w/c ratio while maintaining workability (flow) to reference mix. From trial mixes, results of the maximum water reduction attained at optimum dosage of superplasticizers (1.4% of weight of cement) is (36 %) as shown in Table (7). Higher cement contents and lower water contents have produced higher strengths (13). There is considerable improvement in strength of mortars compared to their reference mixes as shown in Figure(4). The results of average compressive strength of mortar of 12 ferrocement beams are (65.65 MPa).

Parameters Affecting the Torsional Strength

The results obtained from experimental work are presented in Table (10).

Table (10) The Results of Ferrocement Beams Strengthened with CFRP.

Beams Symbols	Ultimate Torque (N.m)	Ultimate Rotation (rad/m) [10^{-3}]
AR	1100	65
A1	4250	60
A2	3350	146
A3	2550	177
BR	1150	50
B1	4250	59.5
B2	3500	135
B3	2550	174
CR	1250	45
C1	5150	56
C2	3850	120
C3	2650	125

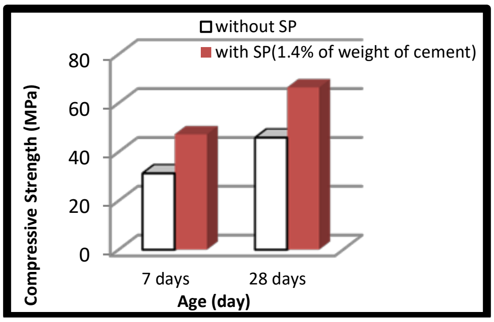


Figure (4) Improvement of Average Compressive Strengths of Mortar Mixes of Beams.

First, effect the number of wire mesh(units). The ultimate torque increases when the number of units is increased. **Table (11)** presents a comparison between groups that had different number of units, group A with B and C.

Table (11) Relative Increase in Torsional Strength: Effect of Increasing Number of Units.

Reinforcement	Beams symbols	Ultimate Torque (N.m)		Increase in Torque(%)	Average Increase in Torque (%)
		Group A	Group B&C		
Two units(A) with Three units(B)	AR with BR	1100	1150	4.55	3.24
	A1 with B1	4250	4250	0	
	A2 with B2	3350	3500	4.48	
	A3 with B3	2550	2650	3.92	
Two units(A) with Four units(C)	AR with CR	1100	1250	13.64	13.44
	A1 with C1	4250	5150	21.18	
	A2 with C2	3350	3850	14.93	
	A3 with C3	2550	2650	4.00	

Table (11) shows that the 4-units (reinforcement near the surface) average increase in torque is significantly greater in this case where the average increase is (13.44 %) versus 3-units (uniformly distributed reinforcement arrangement) average increase in torque is (3.24 %). This is due to the circulatory nature of the torsion induced shear stresses in the beam which is based on a thin-walled tube and space truss analogy. The beams cross section under torsion is idealized as a tube with the core concrete cross section (solid beams) being neglected [(14)]. In addition, increasing the number of units tends to increase the number of cracks because the reinforcement in ferrocement has higher percentage of reinforcement of smaller diameter than the conventional reinforcement. Thus, instead of immediate loss of strength associated with the onset of cracking for plain concrete or mortar within the tension zone, the inclusion of mesh layers results in bridging the cracks and transmitting force across the cracks. So, increasing the number of units restricts the width of the crack and with increasing loads, another crack appears in order to release the strain energy and to allow the beam to rotate. Plate (4) to Plate (6) show an increase in the number of cracks when the number of units increases. Figures. (5) to (8) show that the slopes of torque-rotation curves were increased by increasing the number of units, hence, more units were useful in arresting the rotation of the beam thus, exhibiting some sort of toughness.

Plate (4) Failure of Beam AR (2units, without CFRP)

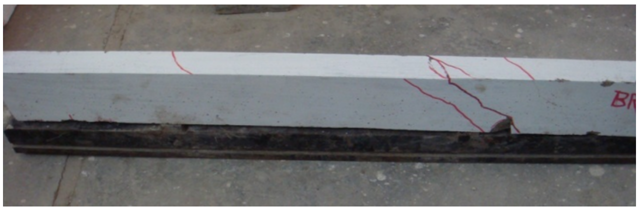


Plate (5) Failure of Beam BR (3units, without CFRP)

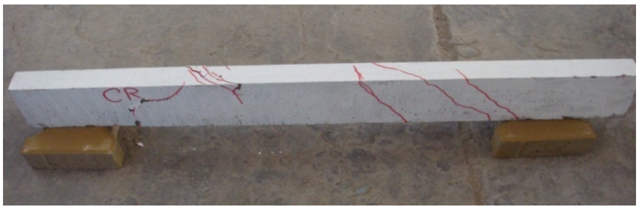


Plate (6) Failure of Beam CR (4units, without CFRP)

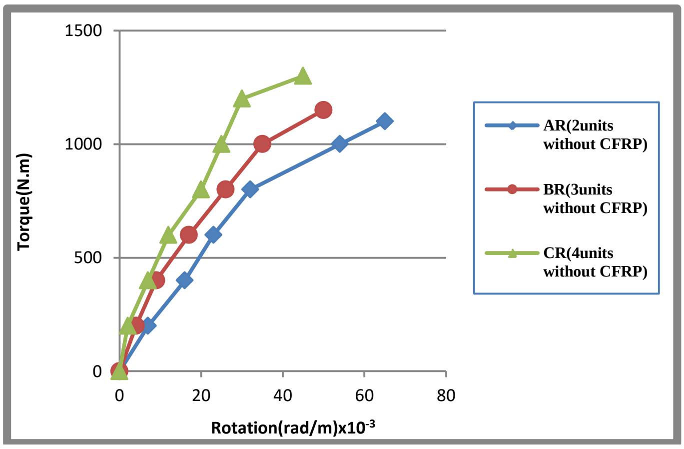
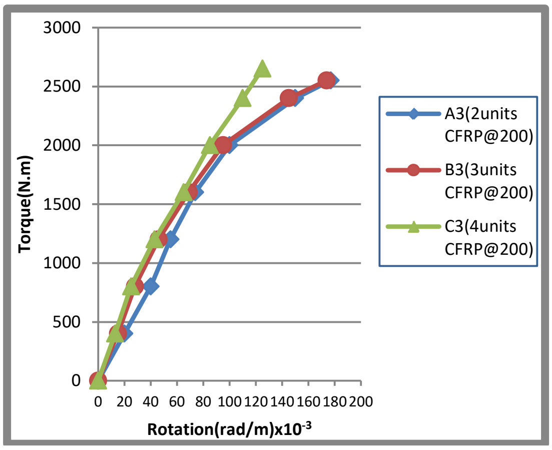


Figure (5) Torque-Rotation Relationships (Effect Number of Units).



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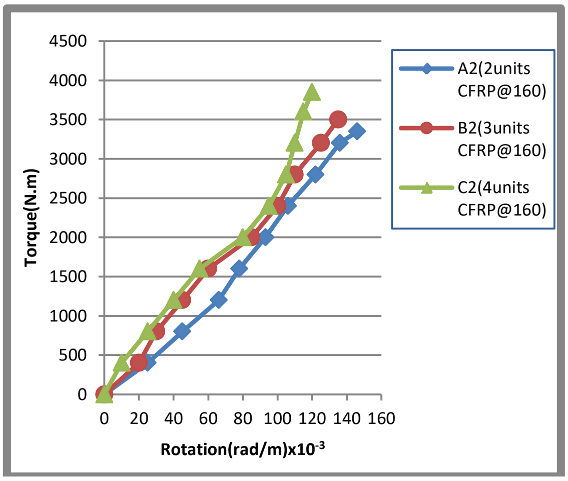


Figure (7) Torque-Rotation Relationships (Effect Number of Units).

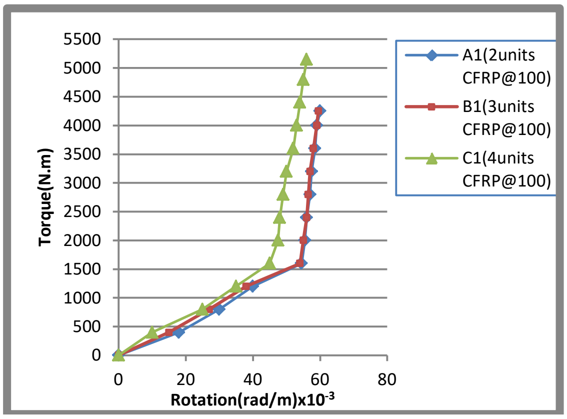


Figure (8) Torque-Rotation Relationships (Effect Number of Units).

Second, effect the spacing of CFRP. Table (12) indicates the lowest and highest increase in torque is 112 % and 312 %, respectively**.** The CFRP contribution (TU FRP) to torsional capacities of all the strengthened beams of the three groups (A, B, and C) is determined by (TU FRP = TU beam –TUR) and listed in the sixth column of Table(12). In general, Table (12) shows that CFRP contribution to torsional strength increases with the number of units. Groups C has the highest increase of CFRP contribution(3900 N.m) because they have the highest number of units (4 units). In addition, this table shows CFRP contribution in one group became more clear when spacing of CFRP strips decreases. From the above, CFRP contribution to torsional strength depended on the variables investigated in this study. It is increased when number of units(reinforcement) increases, and spacing of CFRP strips decreases. The ultimate torque of beams with CFRP strips @ 100 mm and 160 mm is greater than beams with CFRP strips @ 200 mm as shown in Table(13). The cracks of strengthened beams occurred between the strips and then they opened up. These cracks were few in number but wide in size, in the case of large spacing between CFRP. While this applied to the 200 mm spacing, in contrast for the 100 mm spacing cracking was restrained from propagation and opening up, where they were greater in number but smaller in size. Plate(7)to Plate(15) show failure mode photos and details of cracks .That means, the spacing of CFRP strips should not be so wide as to allow the full formation of a diagonal crack without intercepting a strip.

Table (12) Relative Increase in Torsional Strength: Effect of Spacing of CFRP Strips.

Reference of Groups (without CFRP)	Ultimate Torque of Reference Beam (T_{UR})(N.m)	Beam Symbol and Distance of CFRP c/c (mm)	Ultimate Torque of Beams (T_U)(N.m)	Increase in Torque (%)	CFRP Contribution to Ultimate Torque ($T_{U\,FRP}$) (N.m)
AR	1100	A1 @100	4250	286.36	3150
		A2 @160	3350	204.55	2250
		A3 @200	2550	131.82	1450
BR	1150	B1 @100	4250	269.57	3100
		B2 @160	3500	204.35	2350
		B3 @200	2550	121.74	1400
CR	1250	C1 @100	5150	312	3900
		C2 @160	3850	208	2600
		C3 @200	2650	112	1400

Table (13) Increase in Ultimate Torque (Compared with CFRP Strips @200 Spacing)

Groups	Increase in Ultimate Torque %	
	CFRP Strips @160	CFRP Strips @100
A(2-unit)	31.37	66.67
B(3-unit)	37.25	40.00
C(4-unit)	45.28	94.34

Plate (7) Failure of Beam A3

Plate (8) Failure of Beam A2

Plate (9) Failure of Beam A1

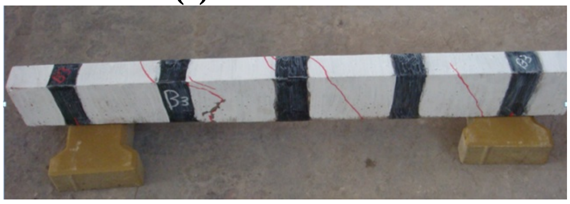


Plate (10) Failure of Beam B3

Plate (11) Failure of Beam B2

Plate (12) Failure of Beam B1

Plate (13) Failure of Beam C3

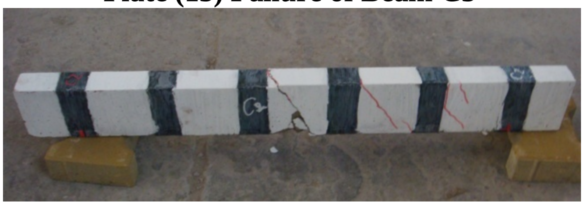


Plate (14) Failure of Beam C2

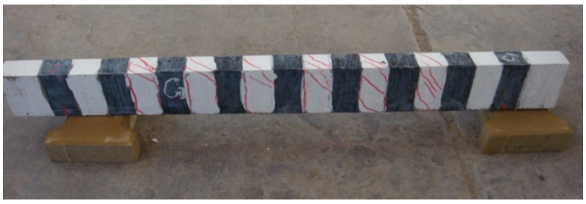
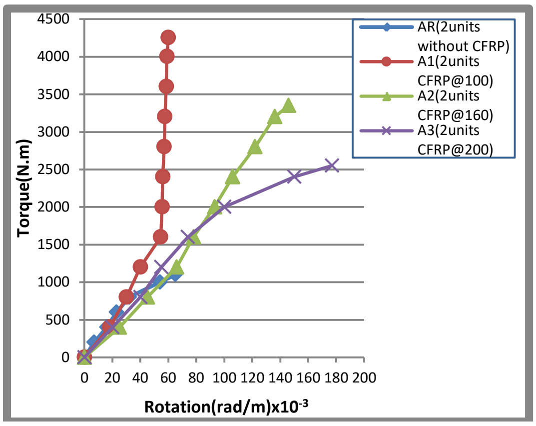


Plate (15) Failure of Beam C1

Figures (9) to (11) show that, while strength increases for strengthened beams considerably, the ductility of behavior drops as CFRP spacing is decreased. For example group C, ultimate rotations are (45, 56, 120, and 125)[10^{-3}] rad/m for CR(without CFRP), C1 (@100 mm), C2 (@160 mm), and C3 (@200 mm), respectively, Table (10) shows ultimate rotation for all beams. As the spacing of the strips becomes smaller, the post-cracking stiffness was increased and consequently the rotation was decreased because the restraining action of CFRP will be greater. This difference is very clear at beams with CFRP spacing @100 mm.



Figure(9) Torque-Rotation Relationships for Group A(Effect of Spacing of CFRP Strips).

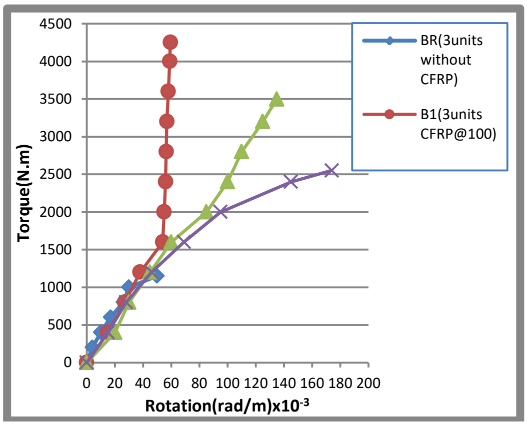
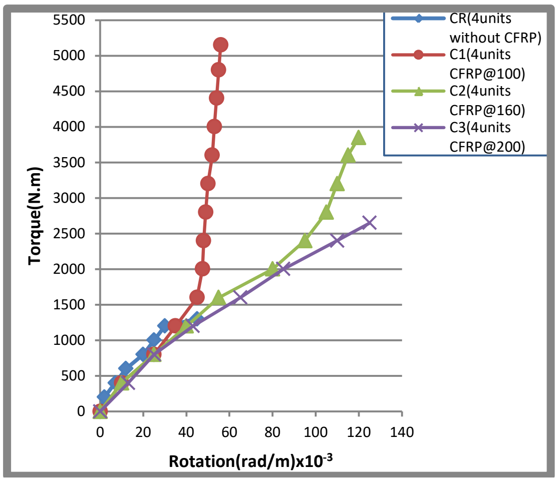


Figure (10) Torque-Rotation Relationships for Group B(Effect of Spacing of CFRP Strips).



Figure(11)Torque-Rotation Relationships for Group C(Effect of Spacing of CFRP Strips).

Torque-Rotation Curves

Figures (5) to (11) show the behavior of 12 ferrocement beams subjected to pure torsion and the following general conclusions may be drawn:

1- Torque-rotation curves are initially linear. Depending on the CFRP spacing, the specimens behaved differently after cracking.

2- Torque-rotation relationships for the specimens strengthened with CFRP @100 mm (A1,B1,C1) show special behavior. The initial stage is similar to other specimens, while wide difference occurs at other specimens at later stages. With significant contrast with 160 mm and 200 mm spacing of CFRP, the ones with 100 mm spacing show major stiffening as their CFRP becomes more effective.

CONCLUSIONS

1- Using optimum dosage of superplasticizers (1.4 % of weight of cement) led to water reduction of (36 %). This water reduction improved clearly the properties of mortar leading to improved torsional strength. The average compressive strength(f_{cu}) values of mortar of the 12 ferrocement beams is (65.65) MPa. With this result, the produced mortar is similar to HSC in strength.

2- Increasing the number of wire mesh layers(units) of beams tends to increase the ultimate torque, torsional stiffness of ferrocement beams and consequently the rotation dropped under the same torque. In addition, more units led to an increase in the number of cracks, with the crack size being smaller.

3- The average increase in ultimate torque of the ferrocement beam having 4-units (reinforcement near the surface of beam section) is greater by (13.44 %) when compared with having 2-units. Because of the distribution of the 3-unit case (uniformly distributed reinforcement throughout beam section), for the 3-unit case, the increase in ultimate strength is only (3.24 %) compared to the 2-unit case. This shows that the reinforcement near the surface will be more efficient, as in the 4-unit case.

4- Strengthening of rectangular ferrocement beams with CFRP strips exhibited greater stiffness and higher increases in the ultimate strength in torsion. The results showed the lowest and highest increase in torque at 112 % (4-units,@200 spacing) and 312 % (4-units,@100 spacing).
5- The ultimate torque of beams with CFRP strips @ 100 mm and 160 mm is greater than beams with CFRP strips @ 200 mm by (94.34%,45.28%), respectively for the group C having 4-units. Consequently, as CFRP spacing decreased, the rotation dropped under the same torque.
6- The CFRP contribution to torsional strength is increased when compressive strength increases, number of units(wire mesh) increases, and spacing of CFRP strips decreases- where the highest and lowest CFRP contribution of strengthened beams are (3900, 1400) N.m, respectively.
7- The spacing of CFRP strips should not be so wide as to allow the full formation of a diagonal crack without intercepting a strip. From the experimental results, the optimum spacing of CFRP strips occurs when d/s ratio (beam depth/ spacing) is equal to /or higher than 1, significantly better strengthening occurs. This is evidenced when comparing the 100 mm CFRP spacing versus the other two: 160 mm and 200 mm.
8- The post-cracking stiffness increased when the CFRP spacing became smaller, as shown in Table (13).
9- Using CFRP strips increases energy absorption when compared with reference beams (without CFRP).
10- The ductility of behavior drops as CFRP spacing is decreased. So, special attention should be paid to the amount of CFRP to avoid brittle failure.

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