# Behavior of Reinforced RPC Beams Strengthened by External CFRP in Flexure

**Dr. Kaiss F. Sarsam**
Building and Construction Engineering Department, University of Technology/ Baghdad
Email:kaisssarsam@yahoo.com
**Dr. Raid I. Khalel**
Building and Construction Engineering Department, University of Technology/ Baghdad
**Falah Jarass Aied**
Building and Construction Engineering Department, University of Technology/ Baghdad

## Abstract

This study is an attempt to provide experimental test data for reactive powder concrete (RPC) beams strengthened by externally bonded carbon fiber reinforced polymer (CFRP) in flexure.

The mixing procedure used in this work presents a successful way to produce RPC with a (cylinder 100 x 200 mm) compressive strength exceeding 110 MPa using heat curing.

Seven singly reinforced RPC beams were investigated, one was the control beam (no CFRP was applied) and six were externally strengthened by CFRP. All beams were of the same cross section, length, internal reinforcement, and of the same concrete mix design and were cured in the same way. The experimental variables considered in the test program include, number of CFRP strip layers (1 layer or 2 layers) and the width of CFRP strip, with and without using external anchorages. The experimental results showed that the ultimate loads are increased up to 64.29 % for the beams strengthened with bonded CFRP sheets and external anchorage with respect to the unstrengthened reinforced concrete beam (control beam). Also, these strengthened beams showed an increase in the first cracking load up to 100 %. On the other hand, there is a lower deflection at corresponding loads than the unstrengthened reinforced concrete beam.

**Keywords:** Carbon Fiber Reinforced Polymer, First Cracking Load, Flexure, Reactive Powder Concrete, Ultimate Load.

# سلوك الانثناء للاعتاب المصنعة من خرسانة المساحيق الفعالة المسلحة المقواة خارجيا بألياف الكاربون البوليمرية

## الخلاصة

هذه الدراسة تتضمن تقديم نتائج وبيانات من دراسة عملية لتقوية اعتاب من خرسانة المساحيق الفعالة المقواة باللصق الخارجي لألياف الكاربون البوليمرية في الانثناء. أسلوب الخلط الذي أستخدم في هذه الدراسة نتج عنه

https://doi.org/10.30684/etj.33.7A.1
2412-0758/University of Technology-Iraq, Baghdad, Iraq

الطريق الأفضل لإنتاج خرسانة المساحيق الفعالة ذات مقاومة انضغاط (للأسطوانة) تتجاوز 110 (ن/مم$^2$) باستخدام الإنضاج بالحرارة. تضمنت الدراسة صب سبع اعتاب من خرسانة المساحيق الفعالة. ستة منها تمت تقويتها باللصق الخارجي لألياف الكاربون البوليمرية بينما لم يتم تقوية إحداها وتم اعتبارها المرجع. اما أبعاد المقطع وطول العتبة والتسليح الداخلي ونسب الخلط بالنسبة للخرسانة وكذلك طريقة المعالجة وطريقة تسليط الحمل كانت متشابهة لكل الاعتاب بدون أي تغيير. أن المتغيرات الأساسية التي جرى اعتمادها في الجانب العملي فهي عدد طبقات شرائح ألياف الكاربون البوليميرية المستخدمة (طبقة واحدة أو طبقتان)، عرض شرائح ألياف الكاربون البوليميرية، واستعمال أو بدون استعمال الإرساء الخارجي. لقد أظهرت النتائج العملية أن تقوية الاعتاب الخرسانية باستخدام الياف الكاربون البوليمرية مع استخدام الارساء الخارجي ادت الى زيادة في مقاومة الانحناء للعتبات يصل مقدارها احيانا الى 64.29 % مقارنة مع العتبات الخرسانية غير المقواة وكذلك زيادة في حمل التشق الاولي (First Cracking Load) تصل احيانا الى 100 % إضافة إلى أن الاعتاب الخرسانية المقواة بالألياف الكاربونية تكون اقل عرضة للانحراف (Deflection) مقارنة مع الاعتاب الخرسانية غير المقواة.

## INTRODUCTION

The main objective of the present study is to investigate the behavior of reinforced concrete beams strengthened with externally bonded CFRP strips. CFRP is selected as a strengthening material because of its outstanding tensile strength and stiffness compared to other composite materials [1]. A more recent generation of Ultra High Performance Concrete (UHPC) named RPC has been developed, that offers superior strength, durability and ductility [2]. RPC contains high cement content, silica fume, fine sand (grain size distribution of 150-600 μm as a replacement of natural coarse and fine aggregates), special water reducer so that it is possible to adopt water-cement ratio less than 0.20, and special fine steel fibers [3].

## Experimental Work

During the design phase of the experimental program, the variables included in this study are focused mainly on the number of CFRP strip layers, using different width of CFRP strips, and external anchorage schemes that will influence the flexural behavior of the reinforced concrete beams strengthened externally with CFRP strips. Detailed description of each variable is presented in the section on strengthening scheme.

## Specimens Description

Seven singly reinforced RPC beams with rectangular cross sectional dimensions of 100 mm width by 200 mm height and 1500 mm length were cast. The flexural reinforcement of the beams consisted of 2Φ12 mm tension bottom bars at the tension face, and 2Φ6 mm top bars in the shear spans only at the compression face. To avoid shear failure, the beams were over reinforced for shear with Φ6 mm closed stirrups spaced at 50 mm on center. Figure (1) shows specimen dimensions, reinforcement details, support locations, and location of loading points.

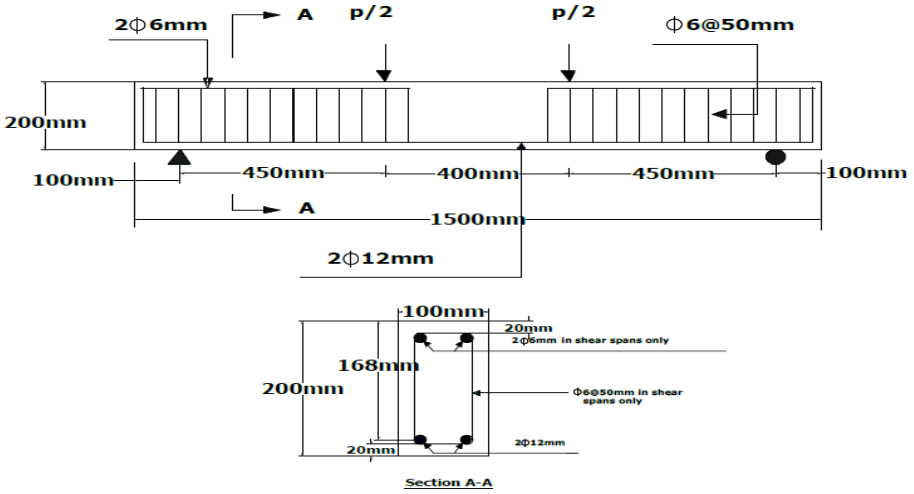


Figure (1) Geometry and reinforcement of la boratory specimens.

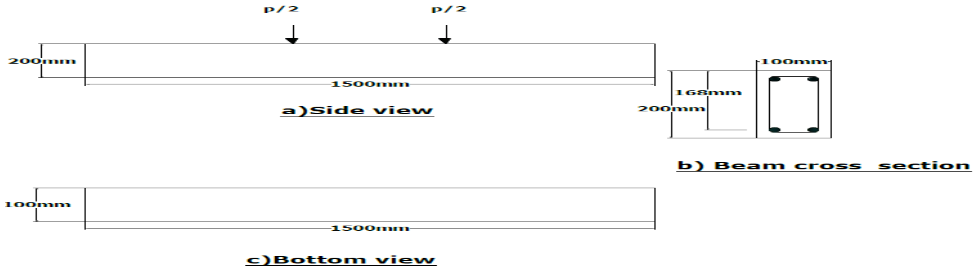
## Specimens Identification and Strengthening Schemes

Strengthening schemes were chosen carefully based on the practical needs and the field conditions. Six RPC beams were strengthened with externally bonded CFRP sheets and all the external anchorages used in this work were made from the same CFRP sheets. The test specimens details are listed in Table (1). The details of all beam specimens are shown in Figure (2).

Table (1) Test specimens details.

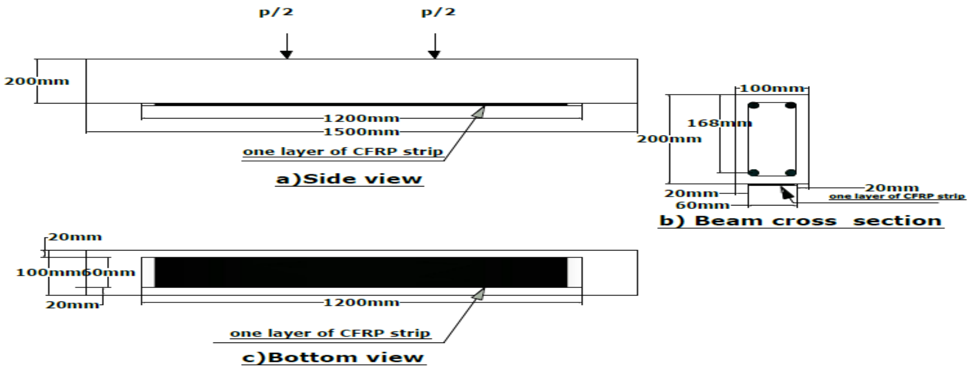
| **Beam No.** | **Details of strengthening** | | |
|---|---|---|---|
| | **CFRP strip dimensions at bottom face (mm)** | **No. of CFRP layers** | **No. of U-shape CFRP anchors** |
| B1 | --- | --- | --- |
| B2 | 1200x60x0.166 | 1 | --- |
| B3 | 1200x60x0.166 | 2 | --- |
| B4 | 1200x60x0.166 | 2 | 4 |
| B5 | 1200x100x0.166 | 1 | --- |
| B6 | 1200x100x0.166 | 2 | --- |
| B7 | 1200x100x0.166 | 2 | 4 |

*U –shape CFRP anchor dimensions are (400x100x0.166) mm.



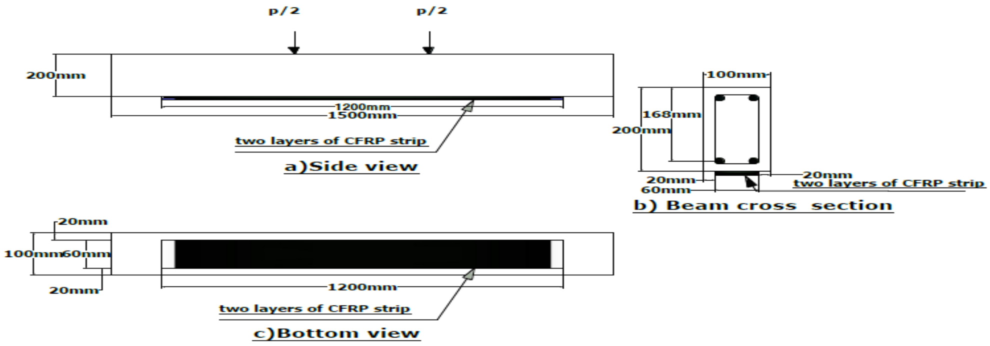
(a) Schematic of specimen B1.

https://doi.org/10.30684/etj.33.7A.1
2412-0758/University of Technology-Iraq, Baghdad, Iraq

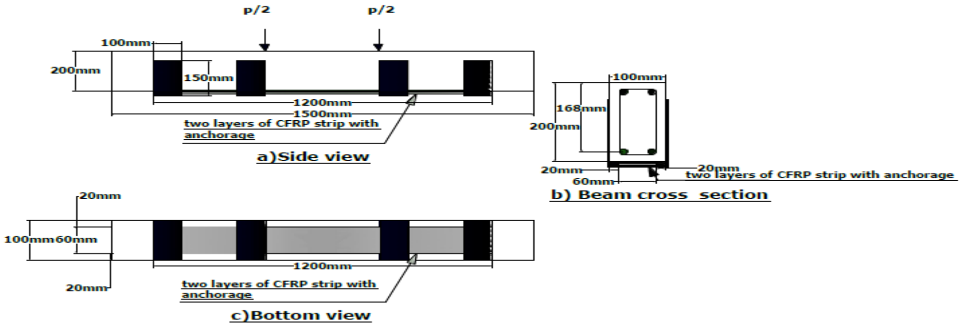


(b) Schematic of specimen B2 with bonded CFRP strip.

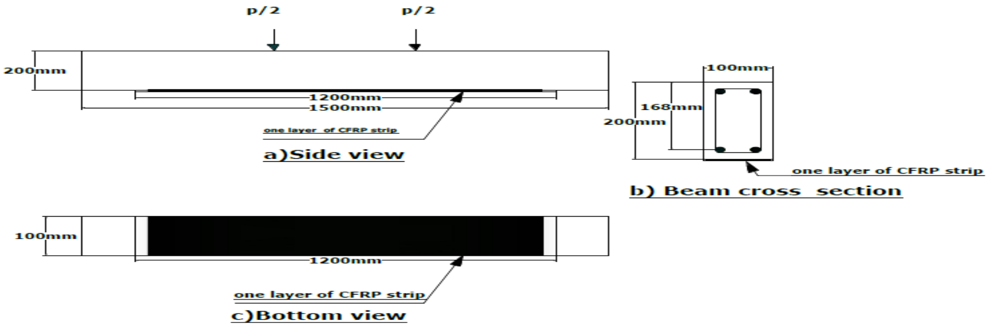
Figure (2) Details of beam specimens.



(c) Schematic of specimen B3 with bonded CFRP strips.

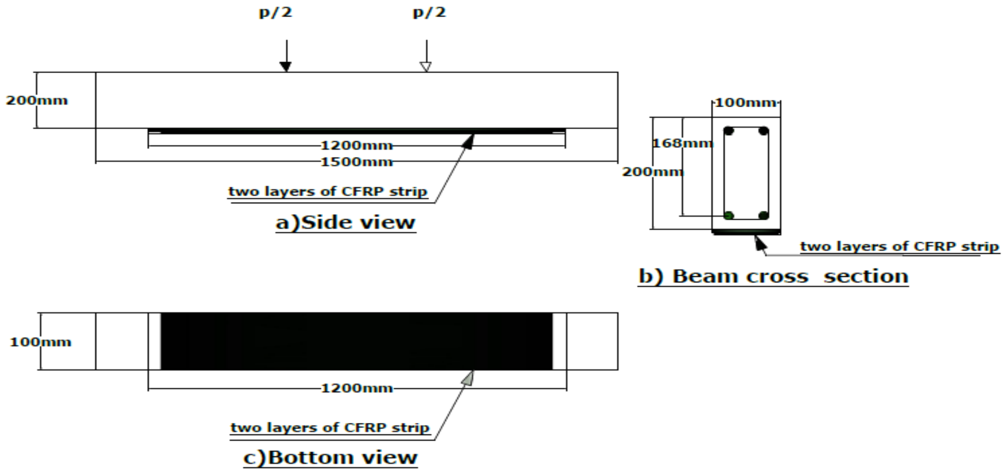


(d) Schematic of specimen B4 with bonded CFRP strips and external anchorages.

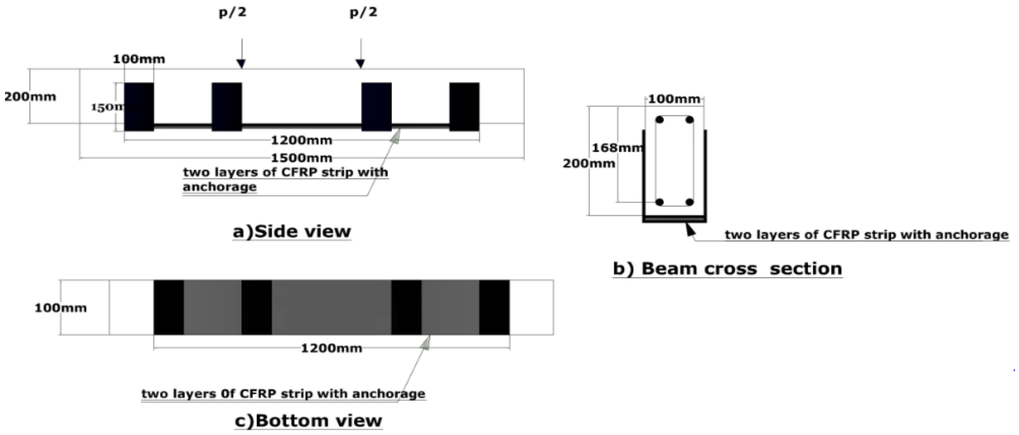


(e) Schematic of specimen B5 with bonded CFRP strip.

**Figure (2) Continued.**



**(f) Schematic of specimen B6 with bonded CFRP strips.**



**(g) Schematic of specimen B7 with bonded CFRP strips and external anchorages.**

**Figure (2) Continued.**

## Construction Materials

### 1. Cement

Ordinary Portland cement manufactured by United Cement Company commercially known as (CARASTA) was used throughout this study which conforms to Iraqi Specification No.5/1984 [4].

### 2. Fine Aggregate

Al- Ekhaider natural sand of 4.75 mm maximum size, was used as fine aggregate. For RPC, very fine sand with maximum size of 600 µm was used. This sand was separated by sieving. Its fine grading is in accordance with the Iraqi Specification No.45/1984 [5].

### 3. Silica Fume

A gray densified silica fume (which is a byproduct from the manufacture of silicon or ferro-silicon metal) was used, which was imported from Sika company. The used silica fume conforms to the chemical and physical requirements of ASTM C1240-04 [6].

## 4. Superplasticizer (S.P.)

A high performance concrete superplasticizer (also named High Range Water Reducing Agent-HRWRA) based on polycarboxylic technology, which is known commercially as SikaViscocrete®-5930, is used in this study. SikaViscocrete®-5930 is free from chlorides and complies with ASTM C494/C494M-04 type a [7].

## 5. Steel Fibers

The RPC contains small steel fibers, each steel fiber has a diameter about 200 μm, length of approximately 15mm and aspect ratio of 75. The steel fibers used in this test program were straight according to ASTM A820/A820M-04 [8].

## 6. Steel Rebars and Stirrups

For all beams, two sizes of steel reinforcing deformed bars are used. Bars of size Φ12 mm with 596 MPa yield stress were used as longitudinal tension reinforcement, and bars of size Φ6 mm with 633 MPa yield stress were used as transverse reinforcement (closed stirrups).

## 7. Water

Tap water was used in all mixes and in the curing of the specimens.

## 8. Carbon Fiber Reinforced Polymer (CFRP)

In the last years, CFRP composites have been used for strengthening structural members of reinforced concrete structures [9]. CFRP of type SikaWrap®-300 C/60 was used to externally strengthen the reinforced concrete beams. CFRP when loaded in tension, does not exhibit any plastic behavior before rupture. The tensile behavior of CFRP is characterized as a linearly elastic stress-strain relationship up to failure, which is sudden and can be catastrophic. The mechanical properties of CFRP sheet are given in Table (2) according to manufacturing specifications of Sika Company.

**Table (2) Technical properties of CFRP sheet.***

| **Properties** | **Tensile strength (MPa)** | **E (GPa)** | **Elongation At break (%)** | **Width (mm)** | **Density (g/cm³)** | **Thickness (mm)** |
|---|---|---|---|---|---|---|
| SikaWrap®-300 C/60 | 3900 | 230 | 1.5 | 600 | 1.79 | 0.166 |

*Provided by manufacturer.

## 9. Bonding Materials

The building and construction industries represent some of the largest users of adhesive materials. Many applications were non-structural in the sense that the bonded assemblies were not used to transmit or sustain significant stresses (e.g. crack injection and sealing, skid-resistant layers, bonding new concrete to old). Sikadur®-330 was used in this work for the bonding of CFRP sheet. The product data is listed in Table (3).

**Table (3) Technical properties of bonding materials.***

| **Properties** | **Sikadur®-330** |
|---|---|
| Tensile strengths (MPa) | 30 |
| Bond strengths | Concrete fracture on sandblasted substrate: >1 day |
| E-modulus (MPa) | 4500 |
| Elongation at break (%) | 0.9 |
| Open time (minute) | 30 minutes at +35°C |
| Full cure (days) | 2 days at +35°C |
| Mixing ratio | part A : part B = 4 : 1 by weight |

*Provided by manufacturer.

### Concrete Trial Mixes

Four types of RPC trial mixes were tested in the present work, as listed in Table (4). The variable used in these mixes was w/cm ratio. For RPC, The mix B from Table (4) is used to cast the main beam specimens in the present investigation as well as their control specimens.

**Table (4) Properties of the different types of RPC mixes.**

| **Parameter** | | **Concrete mixes** | | | |
|---|---|---|---|---|---|
| | | **Mix A** | **Mix B** | **Mix C** | **Mix D** |
| Cement (kg/m$^3$) | | 900 | 900 | 900 | 900 |
| Fine aggregate (kg/m$^3$) | | 990 | 990 | 990 | 990 |
| Silica fume (%)* | | 25 | 25 | 25 | 25 |
| Silica fume (kg/m$^3$) | | 225 | 225 | 225 | 225 |
| Water to cementitious ratio w/cm | | 0.14 | 0.16 | 0.18 | 0.2 |
| Water (L/m$^3$) | | 157.5 | 180 | 202.5 | 225 |
| Admixtures (Sika® ViscoCrete-5930) (%)** | | 6 | 6 | 6 | 6 |
| Admixtures (Sika® ViscoCrete-5930) (kg/m$^3$) | | 67.5 | 67.5 | 67.5 | 67.5 |
| Steel fibers (%)*** | | 2 | 2 | 2 | 2 |
| Steel fibers (kg/m$^3$) | | 156 | 156 | 156 | 156 |
| Cube compressive strength (MPa) | 7 days | 119.7 | 107.4 | 91.7 | 76.8 |
| | 28 days | 126.2 | 115.3 | 103.6 | 91.9 |

* Percent by weight of cement.

** Percent by weight of cementitious materials (cement + silica fume).

*** Percent of mix volume.

### Mixing Procedure

RPC was mixed by using a horizontal rotary mixer with (0.1) m$^3$ capacity. The mixing sequence was as follows: the desired quantity of silica fume was mixed in dry state with the required quantity of cement. This operation was continued for 3 minutes to ensure that silica fume powder was thoroughly dispersed between cement particles. Then, fine sand was loaded into the mixer and mixed for 5 minutes. The superplasticizer was dissolved in water and the solution of water and superplasticizer was added to the rotary mixer and the whole mix ingredients were mixed for a sufficient time. The mixer was stopped and mixing was continued manually especially for the portions not reached by the blades of the mixer. The mixer then was operated for 5 minutes to attain reasonable fluidity. Fibers were uniformly distributed into the mix slowly in 5 minutes during mixing process, and then the mixing process continued for additional 3 minutes. In total, the mixing of one batch requires approximately 30 minutes.

### Casting and Curing Procedure

Before casting, all molds, cylinders, and cubes were well cleaned and steel reinforcement was placed on the bottom face of the beam's mold. The concrete was placed in the molds in three equal layers, each layer was compacted by using electrical vibrating table for one minute.

All specimens were demolded after 24 hours, and then they were heat cured at about $90^0$ C for 48 hours in a water tank. After that they were left to be cooled at room temperature, and then they were placed in water and left until the end of water curing at 28 days.

### Surface Preparation

1. Grinding the concrete surface by scraper machine at the location of gluing the CFRP on the concrete to remove the weak surface.
2. Rounding the edges of the beam (approximately 15 mm) to prevent stress concentration in the CFRP sheets.
3. Cleaning and removing the dust from the concrete surface by water.

### CFRP System Installation

First of all, the CFRP was cut into the required lengths. According to manufacturer technical data, the two-part adhesive (white and black) (comp. A and comp. B, respectively) was mixed first separately each one alone with an electrical mixer (here slow speed electrical drill was used) and mixed in 4:l proportion, for approximately 3 minutes until the color was a uniform gray. Apply a thin layer of mixed epoxy on the concrete surface (approximately 1.5 mm). This will impregnate the carbon fiber sheet after they were placed on the concrete element. The adhesive was also applied to the sheet with the same thickness. The sheet was then placed on the concrete, epoxy to epoxy, and a rubber roller was used with direction of the sheet to remove air bubbles that are trapped behind the carbon fiber sheet and to properly seat it by exerting enough pressure so the epoxy was forced out on both sides of the sheet.

### Testing of Beams

All beam specimens were tested under a static two- points load to study their flexural behavior and to compare the experimental results with the analytical predictions. A hydraulic jack with a capacity of 2000 kN is used. The universal testing machine is a closed loop servo hydraulic testing system controlled manually. The machine was calibrated by "Iraqi Central Organization for Standardization and Quality Control" in 2014. It was used to apply the load to the test beam through a spreader steel beam, the frame has a high degree of stiffness and can be modified to accommodate different configurations of beams as well as other structural elements.

The experiments were executed in load control with manual data monitoring, standard steel supports with 200 mm wide contact plates were used to support the beam ends. The load was applied at a load rate of 4 kN/min.

### Control Specimens

The control specimens were cast from the same concrete batch used for casting the beams. The control specimens were tested immediately after the beam test, consisting of:

1. Three 100 mm cubes for compressive strength test according to B.S: 1881: part 116 [10].
2. Three 100 x 200 mm cylinders for compressive strength test according to ASTM C 39/C 39M-05 [11].
3. Three 100 x 200 mm cylinders for splitting tensile strength test according to ASTM C 496/C 496M-04 [12].
4. Three 100 x 200 mm cylinders for modulus of elasticity test according to ASTM C 469-02 [13].
5. Three 100 x 100 x 500 mm prisms for flexural strength test (modulus of rupture) according to ASTM C 78-02 [14].

The mechanical properties for the control specimens are shown in Table (5).

**Table (5) Properties of tested control specimens.**

| **Beam No.** | **Compressive strength, $f_{cu}$ (MPa)** | **Compressive strength $f'_c$ (MPa)** | **$f'_c/f_{cu}$** | **Tensile strength, $f_{ct}$(MPa)** | **Modulus of rupture $f_r$(MPa)** | **Modulus of elasticity $E_c$(MPa)** |
|---|---|---|---|---|---|---|
| B1 | 117.50 | 108.95 | 0.93 | 14.35 | 19.17 | 48994 |
| B2 | 117.50 | 108.95 | 0.93 | 14.35 | 19.17 | 48994 |
| B3 | 117.50 | 108.95 | 0.93 | 14.35 | 19.17 | 48994 |
| B4 | 123.95 | 110.20 | 0.89 | 14.80 | 20.20 | 49510 |
| B5 | 123.95 | 110.20 | 0.89 | 14.80 | 20.20 | 49510 |
| B6 | 123.95 | 110.20 | 0.89 | 14.80 | 20.20 | 49510 |
| B7 | 124.56 | 111.35 | 0.89 | 15.40 | 20.85 | 49741 |

### Beams Result

The evolution of the crack width of the first appearing crack and the load-deflection curves for different load stages of the seven tested beams were obtained and studied extensively. The cracks pattern for all beam specimens is shown in Figure (3). Figures (4 to 9) compare the crack width of the first appearing crack for beam specimen B1 and other beams. Figures (10 to 15) compare load versus midspan deflection of beam specimen B1 and other beams.

**Figure (3) Cracks pattern for all tested beams.**

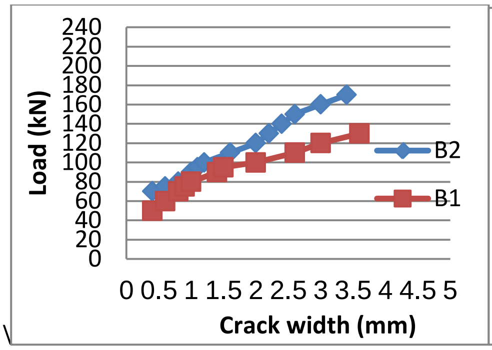


Figure (4) Cracks width evolution of beams B2&B1

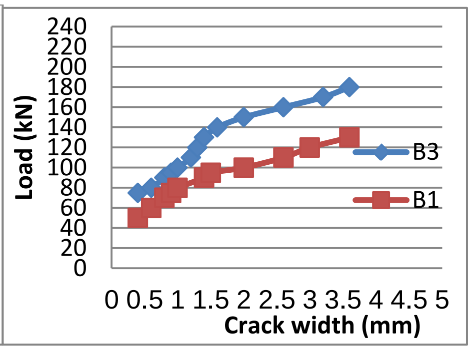


Figure (5) Cracks width evolution of beams B3&B1

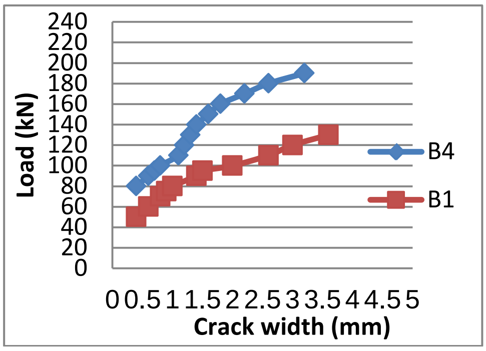


Figure (6) Cracks width evolution of beams B4&B1

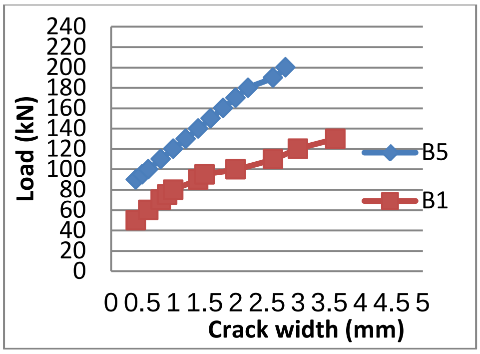


Figure (7) Cracks width evolution of beams B5&B1

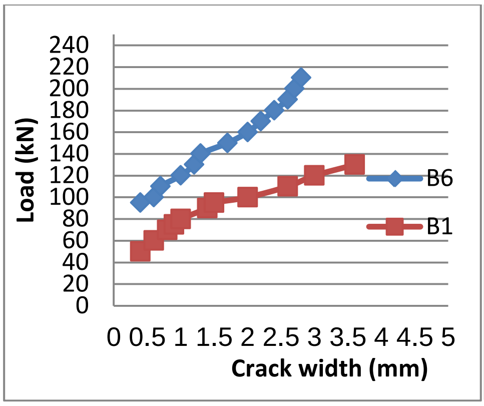


Figure (8) Cracks width evolution of beams B6&B1

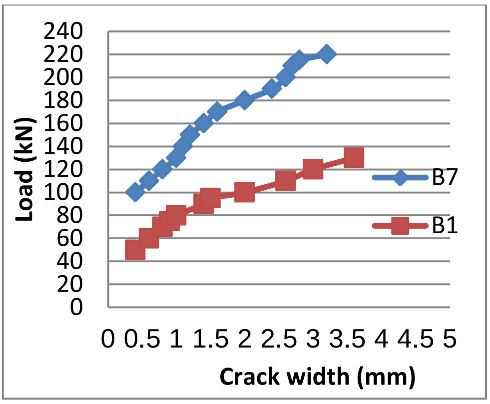


Figure (9) Cracks width evolution of beams B7&B1

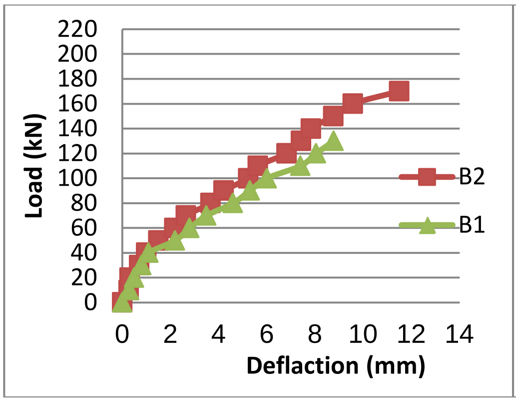


**Figure (10) Load-midspan deflection of beams B3&B1**

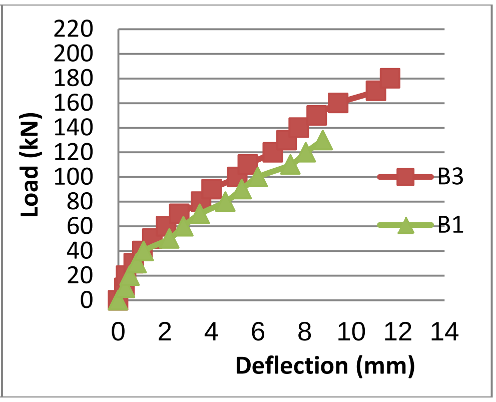


**Figure (11) Load-midspan deflection of beams B2&B1**

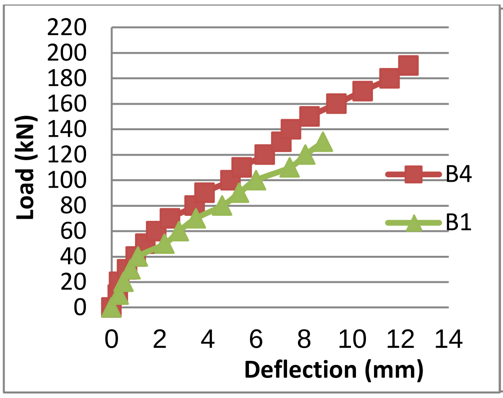


**Figure (12) Load-midspan deflection of beams B4&B1**

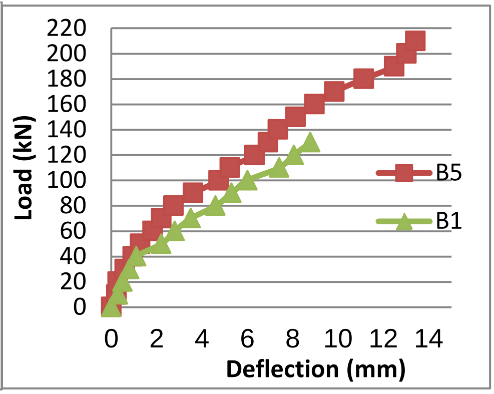


**Figure (13) Load-midspan deflection of beams B5&B1**

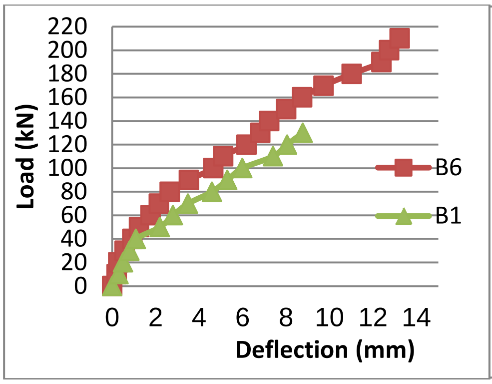


**Figure (14) Load-midspan deflection of beams B6&B1**

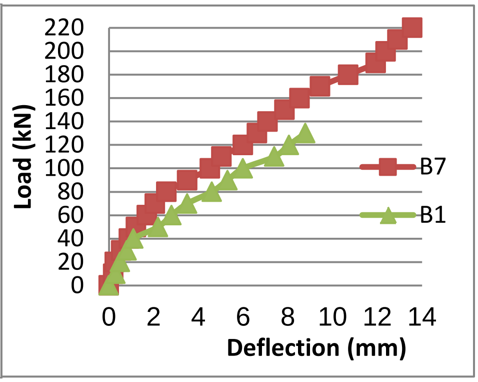


**Figure (15) Load-midspan deflection of beams B7&B1**

Table (6) shows the cracking, ultimate loads, increase in the cracking and ultimate loads percentages and $P_{cr} / P_u$ percentages for all the tested beams as a summary of the results obtained.

**Table (6) Percentage increase in the cracking and ultimate loads.**

| Beam No. | Cracking load $P_{cr}$ (kN) | Percent of increase (%) | Ultimate load $P_u$ (kN) | Percent of increase (%) | $P_{cr}$ / $P_u$ (%) | mode at ultimate loa Failure mode at ultimate load |
|---|---|---|---|---|---|---|
| B1 | 50 | - | 140 | - | 35.71 | yielding of the tension steel reinforcement |
| B2 | 70 | 40 | 177 | 26.43 | 39.55 | steel yielding followed by CFRP rupture |
| B3 | 75 | 50 | 188 | 34.29 | 39.89 | steel yielding followed by CFRP rupture |
| B4 | 80 | 60 | 201 | 43.57 | 39.80 | steel yielding followed by CFRP rupture |
| B5 | 90 | 80 | 213 | 52.14 | 42.25 | steel yielding followed by FRP rupture |
| B6 | 95 | 90 | 222 | 58.57 | 42.79 | steel yielding followed by FRP rupture |
| B7 | 100 | 100 | 230 | 64.29 | 43.48 | steel yielding followed by FRP rupture |

Figure (16) shows the first cracking load and the ultimate load for all tested beams.

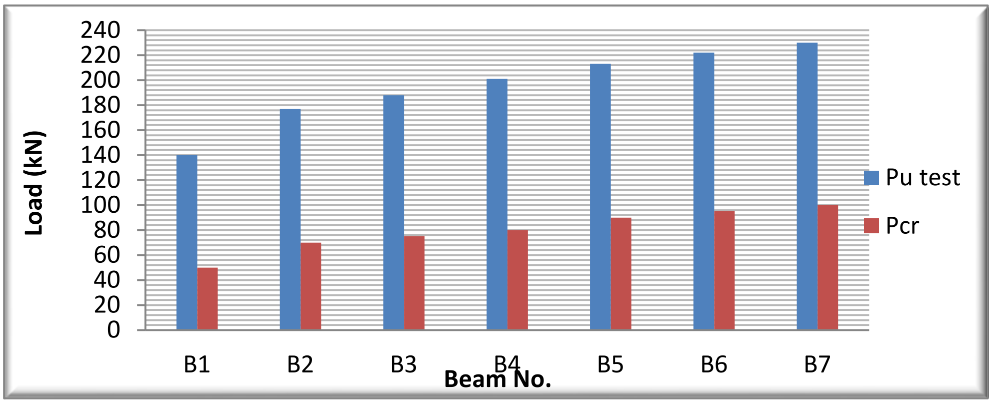


**Figure (16) Cracking & ultimate tested loads.**

## Load Capacity

To predict the nominal bending moment capacity of a singly reinforced rectangular RPC section strengthened with CFRP sheets, the proposals presented by Aied [15], which essentially are close to the proposals of Danha [16], were adopted. Figure (17) shows a rectangular RPC section reinforced in the tension zone with steel bars and strengthened with CFRP sheets at the bottom tension face. The section is subjected to a positive bending moment (M*)* such that at ultimate stage the strain and actual stress distributions are as shown in the same figure. The figure also shows a conversion of the actual stress blocks to equivalent bi-linear stress blocks for both compression and tension.

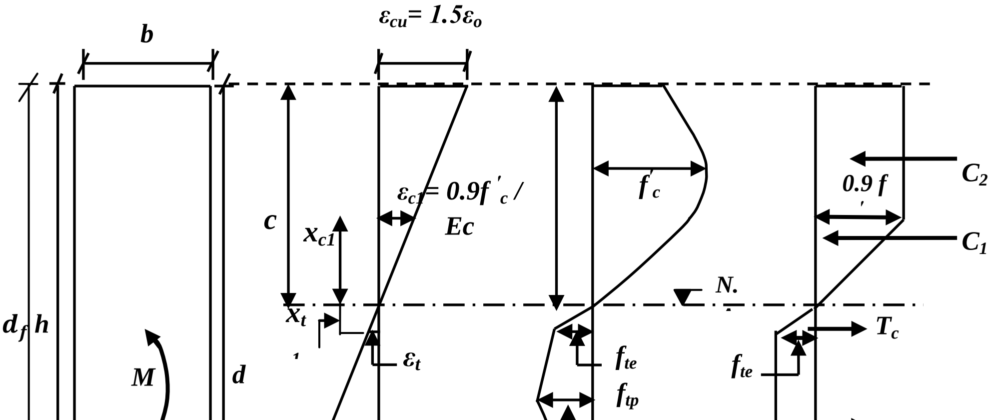


**Figure (17) Actual and proposed equivalent stress distributions at ultimate stage through a singly reinforced rectangular RPC section with CFRP subjected to pure bending moment** [15]**.**

The location of the neutral axis measured from top compression fiber is calculated from the following equation:

$$c = \frac{\left(f_{te}\, b\, h + A_s f_y + A_f f_{fe}\right) \varepsilon_{cu}}{f'_c\, b\, (0.9\, \varepsilon_{cu} - 0.45\, \varepsilon_{c1}) + f_{te}\, b\, (\varepsilon_{cu} + 0.5\, \varepsilon_{te})} \qquad \ldots\ldots \quad (1)$$

Where:

$$\varepsilon_{c1} = \frac{0.9 f'_c}{Ec} \qquad \ldots\ldots \quad (2)$$

$\varepsilon_o = 1.17\times10^{-5}(f'_c) + 4.59\times10^{-4}(V_f) + 1.92\times10^{-3}$ ……
(3)

$$\varepsilon_{cu} = 1.5\ \varepsilon_o \qquad \ldots\ldots \quad (4)$$

$f_{te} = 0.0243(f'_c) + 1.848(V_f)$ ……
(5)

$\varepsilon_{te} = 2.17*10^{-5}(f_{te}) + 1.75*10^{-5}$ ……
(6)

$$\varepsilon_{fd} = 0.41\sqrt{\frac{f'_c}{nE_f t_f}} \leq 0.9\varepsilon_{fu} \qquad \ldots\ldots \quad (7)$$

$$\varepsilon_{fe} = \varepsilon_{cu}\left(\frac{d_f - c}{c}\right) \leq \varepsilon_{fd} \qquad \ldots\ldots \quad (8)$$

$$f_{fe} = E_f . \varepsilon_{fe} \qquad \ldots\ldots \quad (9)$$

$$x_{c1} = \frac{\varepsilon_{c1}}{\varepsilon_{cu}}\ c \qquad \ldots\ldots \quad (10)$$

$$x_{t1} = \frac{\varepsilon_{te}}{\varepsilon_{cu}}\ c \qquad \ldots\ldots \quad (11)$$

Then, the nominal ultimate bending moment capacity of a singly reinforced rectangular RPC section can be determined by summing up the moments around the neutral axis caused by all the compressive and tensile forces on the section such that;

$$M_n = M_{c1} + M_{c2} + M_{Tc1} + M_{Tc2} + M_s + M_f \qquad \ldots\ldots \quad (12)$$

$$M_n = 0.45 f'_c\, b\left(c^2 - \frac{{x_{c1}}^2}{3}\right) + 0.5 f_{te}\, b\left(h^2 + c^2 - 2hc - \frac{{x_{t1}}^2}{3}\right) + A_s f_y (d - c) + A_f f_{fe}\left(d_f - c\right) \qquad \ldots\ldots \quad (13)$$

Where:

$A_f$ = area of FRP external reinforcement, mm$^2$.

$A_s$ = area of longitudinal steel bars, mm$^2$.

$b$ = width of compression face of member, mm.

$c$ = distance from extreme compression fiber to the neutral axis, mm.

$C_1$ = compressive force in concrete for triangular part of equivalent stress distribution, N.

$C_2$ = compressive force in concrete for rectangular part of equivalent stress distribution, N.

$d$ = distance from extreme compression fiber to centroid of longitudinal tension reinforcement, mm.

$d_f$ = effective depth of FRP flexural reinforcement, mm.

$E_c$ = modulus of elasticity of concrete, MPa.

$E_f$ = tensile modulus of elasticity of fiber, MPa.

$f'_c$ = specified compressive strength of concrete cylinder, MPa.

$f_{fe}$ = effective stress in the FRP; stress level attained at section failure, MPa.

$f_{te}$ = first cracking tensile strength of concrete, MPa.

$f_y$ = specified yield strength of steel reinforcement, MPa.

$h$ = height of beam cross section, mm.

$M_n$ = nominal flexural strength, N.mm

$n$ = number of plies of FRP reinforcement.

$T_{c1}$ = tensile force in concrete for triangular part of equivalent stress distribution, N.

$T_{c2}$ = tensile force in concrete for rectangular part of equivalent stress distribution, N.

$T_f$ = tensile force in CFRP, N.

$t_f$ = nominal thickness of one ply of FRP reinforcement, mm.

$T_s$ = tensile force in steel reinforcement, N.

$V_f$ = volumetric steel fibers ratio.

$\varepsilon_o$ = concrete compressive strain corresponding to $f'_c$

$\varepsilon_{cu}$ = ultimate compressive strain of concrete.

$\varepsilon_f$ = strain level in FRP reinforcement.

$\varepsilon_{fd}$ = debonding strain of externally bonded FRP reinforcement.

$\varepsilon_{fu}$ = design rupture strain of FRP reinforcement.

$\varepsilon_s$ = strain level in the steel reinforcement.

$\varepsilon_{te}$ = concrete tensile strain corresponding to $f_{te.}$

The ultimate load for all tested beams and the load capacity of the proposed method are given in Table (7) and shown in Figure (18).

**Table (7) Tested and proposed ultimate loads for all beam specimens.**

| **Beam No.** | **Tested ultimate load $P_{u(\text{test})}$ (kN)** | **Proposed ultimate Load $P_{u(\text{prop.})}$ (kN)** | **$P_{u(\text{prop.})}$ / $P_{u(\text{test})}$ (%)** |
|---|---|---|---|
| B1 | 140 | 116.04 | 82.88 |
| B2 | 177 | 139.51 | 78.82 |
| B3 | 188 | 162.60 | 86.49 |
| B4 | 201 | 162.60 | 80.90 |
| B5 | 213 | 154.95 | 72.75 |
| B6 | 222 | 192.81 | 86.85 |
| B7 | 230 | 192.81 | 83.83 |
| Mean | --- | --- | 0.818 |
| SD | --- | --- | 0.049 |
| COV % | --- | --- | 5.990 |

Where: SD = Standard deviation, COV = Coefficient of variation.

Table (7) leads to COV of 6 percent and a mean value of 0.82 for the ratio $P_{u(\text{prop.})}$ / $P_{u(\text{test})}$ .This low value is proposed for safety, because of the limited number of tests. Further tests in the future may lead to a modification in $P_{u(\text{prop.})}$.

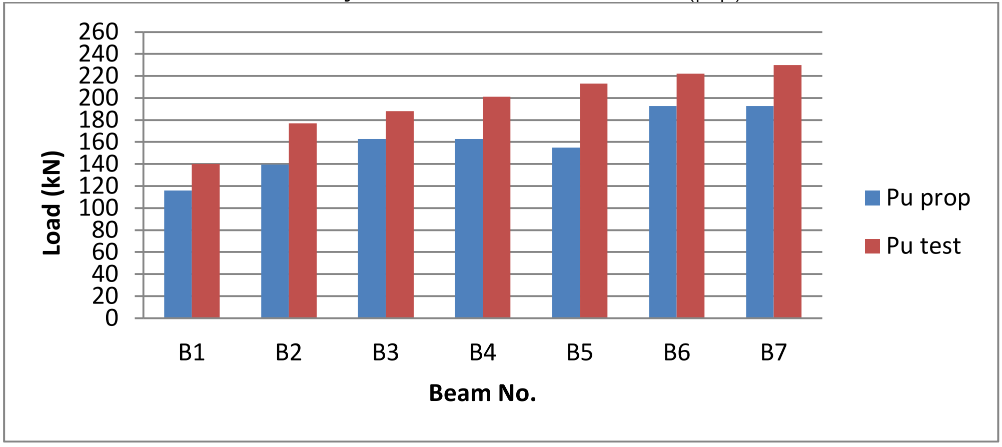


**Figure (18) Tested & proposed ultimate load.**

## Conclusions

Based on the experimental and theoretical investigation of this study, the following remarks can be concluded:

1. The mixing procedure used in this work presents a successful way to produce RPC with a cylinder compressive strength exceeding 110 MPa with heat curing.
2. Using CFRP sheets to strengthen reinforced RPC beams is significantly effective in increasing the first cracking load. The increase was up to 100 % for reinforced concrete beams externally strengthened with CFRP sheets having external anchorages at shear spans compared with the unstrengthened beam.
3. The externally strengthened reinforced concrete beams with bonded CFRP sheets generally showed a significant increase in the ultimate loads. This increase reached up to 64.29 % for reinforced RPC beams externally strengthened with two layers of CFRP strip having external anchorages at shear spans compared with the unstrengthened beam.

4. The reinforced RPC beams strengthened with CFRP sheets showed a lower deflection at corresponding loads compared to the unstrengthened beam due to the presence of CFRP sheets.
5. An increase in the number of CFRP layers from one layer to two layers led to an average increase of 6.3 % & 5.2 % in the first cracking and ultimate loads respectively.
6. Increasing of CFRP sheet width from (60 to 100 mm) led to an average increase of 26.7 % & 17.6 % in the first cracking and ultimate loads respectively.
7. The external anchorages are very effective in increasing the interaction between the CFRP and the RPC section. External anchorages improve the structural behavior of the strengthened beams (increasing first cracking load-6%, increasing ultimate load-5.3%, and reducing beam deflection-9.4%).
8. A yielding of steel reinforcement followed by CFRP sheets rupture failure mode was the dominant mode for all RPC beams strengthened with CFRP.

## References

[1]. Meier, U., "Carbon Fiber- Reinforced Polymers: Modern Materials in Bridge Engineering", Structural Engineering International, 1992, pp. 7-92.

[2]. Al- Hassani, H.M., Khalil, W.I., and Danha, L.S., “Proposed Model for Uniaxial Tensile Behavior of Ultra High Performance Concrete”, Engineering & Technology Journal, Vol. 33, Part (A), No. 1, 2015, pp. 61-77.

[3]. Richard, P., and Cheyrezy, M.H., "Reactive Powder Concretes with High Ductility and 200-800 N/mm$^2$ Compressive Strength", ACI Special Publication, Vol. 144, No. 24, 1994, pp. 507-518.

[4]. Iraqi Specification, No. 5/1984, “Portland Cement”, وزارة التخطيط، الجهاز المركزي للتقييس والسيطرة النوعية.

[5]. Iraqi Specification, No. 45/1984, “Aggregate from Natural Sources for Concrete and Constriction”, وزارة التخطيط، الجهاز المركزي للتقييس والسيطرة النوعية.

[6]. ASTM C 1240-04, “Standard Specification for the Use of Silica Fume as a Mineral Admixture in Hydraulic Cement Concrete, Mortar and Grout”, Vol. 4.2, 2004, 6 pp.

[7]. ASTM C 494/C 494M-04, “Standard Specification for Chemical Admixtures for Concrete”, Vol. 4.2, 2004, 9 pp.

[8]. ASTM A 820/A 820M-04, “Standard Specification for Steel Fiber for Fiber - Reinforced Concrete”, 2004, 4 pp.

[9]. Assi, N.S., “The Effect of Carbon Fiber Reinforced Polymer Length on the Strengthened of Concentrically Loaded Reinforced Concrete Beams : Finite Element Analysis”, Engineering & Technology Journal, Vol. 32, Part (A), No. 7, 2014, pp. 1671-1683.

[10]. B.S. 1881, part 116, "Method of Determination of Compressive Strength of Concrete Cubes", British Standards Institution, 1989.

[11]. ASTM C 39/C 39M-05, "Standard Test Method for Compressive Strength of Cylindrical Test Specimens", Vol. 04.02, 2005, 9 pp.

[12]. ASTM C 496/C 496M-04, "Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens", Vol. 04.02, 2004, 5 pp.

[13]. ASTM C 469-02, "Standard Test Method for Static Modulus of Elasticity and Poisson's Ratio of Concrete in Compression", Vol. 04.02, 2002, 5 pp.

[14]. ASTM C 78-02, “Standard Test Method for Flexural Strength of Hydraulic - Cement Mortars”, Vol. 04.02, 2002, 6 pp.

[15]. Aied, F.J., “Flexural Strengthening of RPC Beams with External CFRP”, MSc Thesis, Building and Construction Engineering Department, University of Technology, Baghdad, Iraq, Jan. 2015, 140 pp.

[16]. Danha, L.S., “Tensile Behavior of Reactive Powder Concrete”, MSc Thesis, Building and Construction Engineering Department, University of Technology, Baghdad, Iraq, August 2012, 124 pp.