The influence of RPC thickness on hybrid beams under torsion

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Abstract. This paper deals with the experimental investigation on torsion in hybrid reinforced concrete beams cast with conventional concrete (CC) at the core surrounded by reactive powder concrete (RPC) at the periphery. Hybrid concrete is usually used in structural members to resist flexure, shear and torsion. Four reinforced concrete beams are cast and tested with dimensions: width 100mm, height 200mm and length 1500mm and the cross-sectional areas of the core in the specimen studied were (20x120) mm and (40x140) mm, respectively. All beams were cast and tested to failure by using two opposite cantilevers steel arms, which contribute to transferring the torque to the central part of the beam. One of the beams was of RPC. The second beam was CC only and the others were hybrid beams. Experimental data on ultimate capacity, cracking torsional loads, failure pattern and twisting angle for each of the beams were obtained. The experimental results show that the ultimate torsional strength value of hybrid beams was higher than conventional concrete beams by about (23.7-50.0) % and about (25.8-10.0) % lower than reactive powder concrete beam depending on the thickness of RPC.

1. Introduction

The torsion failure is undesirable as it occurs in a brittle nature. It is necessary to avoid this type of failure in the earthquake areas [1]. Recently hybrid reinforced concrete structures were found to be of great interest by engineers due to their economic and good performance under loading. The concrete of the hybrid section can briefly be explained by using a specific type of concrete in a specific zone of the section [2].

A significant research effort has been made to study the torsional behavior of concrete structural members recently. A diversity of studies on developing analytical models was made to predict the elastic stress distribution and strength limits of concrete beams under torsion. There are many different structures where torsional loading can be a significant loading condition. The most noticeable are bridges and spandrel beams. As is well known, the shear stress developed in the beam flows around the outside surface [3].

2. Beams Details

A comparison between two beams each composing of mix of RPC and CC (incorporated to improve the tensile strength and other properties of concrete) presenting high strength concrete (RPC) cast
around the beam with different thicknesses (20,40)mm with two other beams consisting of only CC or RPC all having other variables as same.

Two mixes of fresh concrete are incorporated (to improve the tensile strength and other properties). These are: high strength concrete (RPC) and CC. These are high strength concrete (RPC) cast around the beam with different thicknesses (20,40) mm to compare and study properties of concrete under torsion with two other mix containing just RPC beam or CC beam respectively, with identical parameters for all the four samples.

In this investigation four torsional tests are reported. Of these tests, two beams containing two mix fresh concrete (hybrid beams), one beam having RPC (1: 1:0.25:6%:0.2) (cement: fine sand: silica fume: super plasticizer percentage: w/c), respectively and other one CC (1:1.5:1.75:0.5), (cement: sand: gravel: w/c). The beams were designed to have the same proportions in the all beams. The beams designed (main reinforcement and stirrups) are presented in figure 1, and change the thickness of RPC is shown in figure 2. The load is applied on steel plate above two steel arms put opposite at the end of the beam to obtain torque.

Figure 1. The beams designed (CC and RPC)(B1 and B4)

Figure 2. The hybrid beams designed (B2 and B3)

Increasing the thickness of RPC at cross section areas from 20mm to 40 mm means increasing the ratio of cross section areas from 52% to 88% of RPC, respectively and decreasing the ratio of CC from 48% to 12%.
### Table 1. The properties of beams.

| Name of Beams | Main steel (Al) | At | Thickness of (RPC) mm | Thickness of (CC) mm | Area of RPC (%) | Area of CC (%) |
|---------------|-----------------|----|-----------------------|---------------------|-----------------|----------------|
| B1            | 4 12            | 6@50 | 0                     | all                 | 0               | 100            |
| B2            | 4 12            | 6@50 | 20                   | 60                  | 52              | 48             |
| B3            | 4 12            | 6@50 | 40                   | 20                  | 88              | 12             |
| B4            | 4 12            | 6@50 | all                  | 0                   | 100             | 0              |

3. Materials

3.1 Cement

Ordinary Portland cement (Almaas) conforming to Iraqi standard [4] for both RPC and CC was used throughout the experimental work.

3.2 Fine Aggregate

Natural sand used throughout this experimental work was for CC mixes only. Fine sand with maximum particles size of $(600 \text{ m})$ is used for RPC mixes. The grading of the natural and fine sand conformed to the Iraqi specification [5].

3.3 Coarse Aggregate

The coarse aggregate used was natural aggregate with maximum size (10 mm) of aggregate. Coarse aggregate is used for CC mixes only. RPC in this research has been made without coarse aggregate to obtain its homogeneity. The grading of the used coarse aggregate conformed to the Iraqi specifications [5].

3.4 Silica Fume

Silica fume grey in colour has been used with RPC mixes to improve its properties. Used silica fume had $20000 \text{ m}^2/\text{kg}$ fineness and the percentage used was 25% as partial replacement of cement weight.

3.5 superplasticizer

A superplasticizer commercially called Sika Visco Crete – 5930-L was used as an admixture to improve RPC in this work.

3.6 Steel reinforcement

Two nominal deformed steel diameters were used: 6mm as stirrups reinforcement at 50 mm spacing and diameter of 12 mm as longitudinal reinforcement. The yield stresses $(fy)$ are 416.6 MPa and 519.2 MPa respectively.

3.7 Steel fiber

Straight brass coated gold color short steel fibers were used: 15mm long with radius of 0.2 mm and aspect ratio of 75 and tensile strength of 2600 MPa.

4. Casting the Hybrid Beams

The procedure for casting these beams is: the first layer is cast RPC only in the bottom of the mould to 20mm height and the other is 40mm height, as shown in figure 2. The two hybrid beams were: One beam had 60X160 mm CC and the other 20X120mm CC. After 10 minutes of final cast, the plates were pulled out of the hybrid beams from the side of the mould, as shown in the figure 3.
a. The plates with 60mm width.

b. The plates with 20mm width.

c. The RPC at 20mm high.

d. The RPC at 40mm high.

e. The CC at the middle.

f. The last layer RPC to the top of mold.

g. The completed hybrid beams.

**Figure 3.** The procedure of casting the hybrid beams.

5. **Discussion of Results**

5.1 **Compressive Strength of Concrete (f_c')**

The compressive strength tests were performed according to ASTM C39/C39M-01[6] on three cylinders (100X200) mm for both RPC and CC. The average of three specimens for concrete compressive strength was (89.6 MPa and 30.1 MPa) for RPC and CC mixes, respectively on the testing day. The test is shown in figure 4.

5.2 **Splitting Tensile Strength (f_t)**

The splitting tensile strength tests were performed according to ASTM C496/ C 496M-04[7] on three cylinders (100X200) mm for both RPC and CC. The average of three specimens for splitting tensile
strength were (10.22 MPa and 2.84 MPa) for RPC and CC mixes, respectively. The test sample is shown in figure 5.

![Figure 4. The compressive strength of concrete.](image1)

![Figure 5. The splitting tensile test.](image2)

5.3 Modulus of Elasticity Test
The modulus of elasticity tests were performed according to ASTM C469/C-02[8] on three cylinders (150X300) mm of each RPC and CC. The average modulus of elasticity of three specimens were (49.34 and 27.9) GPa for RPC and CC mixes, respectively.

5.4 Cracking torsional capacity
The capacity of cracking torsion is defined as the load at which the tensile stress at the beams reaches the tensile strength of the concrete[7]. The capacity of cracking torsion for hybrid beams is shown in table 2.

The capacity of cracking torsion increases with the increase in the thickness of RPC from B1 (containing CC mix) to B4 (containing RPC mix) solely. The capacity of cracking torsion for hybrid beams B2 (20mm thickness of RPC) & B3 (40mm thickness of RPC) showed an increase about 11.9 % & 19.9 % above B1 and a decrease of 12.5% & 6.3 % respectively in comparison with B4. As shown in figure 6.

5.5 Ultimate torsional capacity
The ultimate torsional capacity (can be defined as the test machine reading when load drops [9]) as deformation continues. The RPC thickness is a major part in strengthening. The relative percentage (Tu/Tcr) increases when the thickness of RPC increases. The residual torsion concluded after the appearance of cracks in hybrid beams is larger than in CC beam and lower than of RPC beam. The capacities of ultimate torsion for hybrid beams are shown in table 2 and figure 6.
Figure 6. The cracking and ultimate torsional capacity.

Figure 7. The rate of torsional capacity increasing.
Note: 50 mm presented to RPC only

Figure 7 showed the effect of presence of RPC on the surrounding of the beams and the thickness of this layer in increasing the proportion of the torsional capacity. The rate of increase will decrease by increasing the thickness of RPC, especially of the cracking torsion capacity, the proportion of increasing from CC beam about (11.87%) but became about (8%) with increasing the thickness of RPC. But the proportion of this increase is more severe in the ultimate torsional capacity than the cracking torsional capacity, the increasing proportion nearly (24%) and decrease to (16.66%).

This increasing between cracking and ultimate torsion is important for safety.

5.6 Angle of twist
For measurement of the angle of twist two LVDTs were attached to the plate steel in the end of beams. The conventional concrete beam B1 reached maximum torque 6.30 kN.m at maximum rotation 0.029 rad/m, while the first cracking torsion was 4.38 kN.m at rotation (0.025 rad/m), the beam had larger angle of twist at failure. The RPC beam B4 had rotation of (0.008 and 0.109) rad/m at cracking and ultimate torsional capacity respectively. The values furthermore of half of the torsion capacity are the angle of twist almost closely in hybrid beams and RPC beam. The hybrid beams had smaller angle of twist (\( \phi \)) as well as RPC beam. There is a clear and significant increase in the value of the cracking and ultimate torsional capacity with less increase in the angle of twist (\( \phi \))The hybrid beams B2 and B3 had
maximum rotation of (0.039 and 0.0647) rad/m at ultimate torsional capacity. As shown in figure 8 and 9.

![Image](image-url)

**Figure 8.** The LVDT and steel arms.

![Graph](graph-url)

**Figure 9.** Angle of Twist ($\phi$).

6. Testing procedure
All beams including control specimens were removed from water curing after 60 days. Drying lasted about 30 days, and then all have been cleaned and painted white in order to obtain clear observation of cracks and their spreading patterns. Steel arms were placed at both ends of each beam in opposite ways. A load has been applied. With load increment (at low loads), hairline cracks have formed in the areas between supporting arms. With further increase in load, multiple cracks with wider propagation began to form in diagonal orientation. These cracks continued to propagate with increasing load until reaching failure point.
Table 2. The capacity of cracking and ultimate torsion.

| Name of Beams | Cracking torsion kN.m | Percent of increase% | Angle of twist (rad/mm) | Ultimate torsion kN.m | Percent of increase% | Angle of twist (rad/mm) | Tu/Tcr |
|---------------|-----------------------|----------------------|-------------------------|-----------------------|----------------------|-------------------------|--------|
| B1            | 4.38                  | 0                    | 0.424                   | 6.30                  | 0                    | 0.493                   | 1.44   |
| B2            | 4.90                  | 11.87                | 0.063                   | 7.79                  | 23.65                | 0.34                    | 1.59   |
| B3            | 5.25                  | 19.86                | 0.063                   | 9.45                  | 50                   | 0.497                   | 1.80   |
| B4            | 5.60                  | 27.85                | 0.145                   | 10.50                 | 66.67                | 1.132                   | 1.88   |

7. Failure of beams
All beams failed in torsion as the inclined cracks were about 45 degree to the beam axis. This cracking angle appeared in the surface of beams led to redistribution of internal stresses. The failure in CC beam was beyond just cracking and reached to crushing into cover concrete, which is more dangerous than the other beams at failure. While in other beams failure is represented by cracks on the surface of the beams. Thus, hybrid beams are more reliable in terms of failure. Two mix procedures used in this research present a successful way to produce hybrid beams with different thicknesses of RPC. The beams B1, B2, B3 and B4 are shown in figures 10, 11, and 12.

8. Conclusions
A total of four beams are tested under pure torsion, in order to determine the effect of the thickness of RPC on the strength of beams. Comments are given below:

1- Unlike practically all codes (except the BS code [10]), this work indicates that concrete strength has a significant influence on torsional strength.
2- The ultimate torsional capacity compared to the CC beam was increased by 23.65%, 50% and 66.67% respectively, depending on increasing RPC thickness to 20mm, 40mm and all RPC.
3- The cracking torsional capacity increases with increasing thickness of RPC by 11.87%, 19.86% and 27.85% respectively percentage to conventional concrete (CC).
4- In general, the cracking and ultimate torsion capacities of hybrid beams are larger than CC and less than RPC beam.
5- The angle of twist decreased in hybrid beams at cracking torsion when compared with normal concrete beam (CC).
6- In CC beam the failure was beyond just cracking and reached to crushing into cover concrete, which is more dangerous than the other beams at failure. While in other beams failure is represented by cracks on the surface of the beams. Thus, hybrid beams are more reliable in terms of failure.
7- The gap (figure 6) between cracking and ultimate torque is greater for beams where RPC increased.

Figure 10. Show the B1 (CC) & B4 (RPC)
Figure 1. Show the B2 (20mm thickness of RPC)

Figure 2. Show the B3 (40mm thickness of RPC)

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