Flexural performance of conventional and reactive powder concrete built–up beams

Ghazwan K. Mohammed¹, Kaiss F. Sarsam², Iqbal N. Korkess³

¹²³ Civil Engineering Department, University of Technology, Baghdad, Iraq.
Email: 41874@student.uotechnology.edu.iq

Abstract. This paper presents an experimental investigation on the flexural behavior of reinforced concrete beams made from a combination of two types of concrete as a (built-up or composite) member. The experimental program consists of casting and testing of eleven rectangular cross-sections of simply supported reinforced concrete beams. Distribution of the specimens was three beams used as a reference which were fully poured from conventional concrete (CC) and reactive powder concrete (RPC). The remaining were eight (built-up) beams made by incorporation of two types of concrete as an element, about those beams, the RPC is poured as layers different in depth and the effective regions (compression and tension), where they are compatible with CC to complete the beam depth. Experimental results show that a stiffer behavior of load-deflection appears, especially when the RPC is in tension region (the bottom of the beam) with respect to increase of the layer depth and the volumetric ratio of steel fibers (vf). The load-carrying capacity of (built-up) beams increase when the RPC is used in the compression region affected by the increase of the layer depth and the volumetric ratio of steel fibers, with less stiffer behavior compared to the beams where the RPC used in the tension regions. The results can be summarized that RPC utilizing in compression regions is more influential than utilizing it in tension regions.

1. Introduction
RPC (Reactive powder concrete), which is generally known as high or ultra-high-performance concrete (HPC, UHPC) [1]. RPC contain 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 makes possible to adopt water-cement ratio less than 0.20, and special fine fibers [2]. This is a new material had taken the interest of researchers and construction developers from early of the 1990s when it was introduced, owing to its high mechanical properties and good resistance to environmental circumstances (durability). Fibers addition to RPC leads to significant enhancement in the cracking resistance, post cracking strength, and energy dissipation capacity [3]. Although of the many significant features of RPC related to its mechanical properties such as high compressive strength, high ductility, high tensile strength compared to ordinary concrete, the main disadvantage of this material is the high cost of the raw materials like fibers, silica fume, fine sand, superplasticizer, so that from economical view the researchers go to use the RPC in (composite or built-up)reinforced concrete structural sections in order to reduce the cost and get the benefits of combining materials by employing them in appropriate regions in structural members, below example about use of RPC in composite beam.

An experimental study has been reported in the literature by Habel et al. [4] about the flexural behavior of built-up beams. Which were made by ordinary concrete at the compression regions and UHPFRC layers at the tension regions. They concluded that using UHPFRC layer in shape of the built-up beam increases stiffness, reduce disfigurements for applied loads, minimize the widths and spacing
of cracks, and slow down the formation of localized macrocracks when they were compared to original beams, which were made by the ordinary concrete.

2. Aim of the study
This study aimed to experimentally investigate the flexural behavior, the ultimate load capacity, and the deflection at midspan, of (built-up) reinforced concrete beams. To obtain this purpose, eleven beams made individually from CC, RPC, or by combining both materials. All beams were tested under flexural loading.

3. Experimental Program
Eleven beams manufactured from CC, RPC, or by combining both materials are cast, cured, and tested experimentally with respect to the flexural performance relationship. The materials and mixes mechanical properties are selected toward studying the effect of mechanical properties of the two types of concrete on the flexural performance relationship of the built-up beam. Four concrete mixes have been prepared and used to investigate the effects of incorporation of two types of concrete, from sides of the layer depth and the content of steel fibers as a volumetric ratio. The content of the cement and the fine sand are 950 kg/m³ and 900 kg/m³ respectively; superplasticizer content is 70.5 kg/m³, Silica fume content is 225 kg/m³, water/cement plus silica fume ratio is 0.2, used for all mixes of RPC. Steel fibers volumetric ratios are various, for ordinary concrete, the content of cement, sand, crushed gravel was 500 kg/m³, 600 kg/m³ and 1250 kg/m³ respectively, water/cement ratio is 0.42 these materials conforming to the valid standards [5,6,7,8]. Micro copper-coated straight steel fibers straight shape were utilized, with diameter 0.2 mm, length 13 mm, tensile strength (2800 MPa), and aspect ratio 65.

4. Reinforcement and Details of Tested Beams
Three sizes of deformed steel reinforcing bars with nominal diameter (Ø16, Ø8, and Ø4) were utilized in all beams. They were matching to the requirements of ASTM A615[9]. For the main reinforcement deformed bars of nominal diameter (Ø16), and to resist the shear forces, lateral reinforcement (stirrups) deformed steel bars with nominal diameter (Ø8) with spacing of 70 mm are will be constant in all beams with enough quantity to get guarantee that all beams will fail in flexure mode. The, (Ø4) deformed steel bar was utilized in the upper reinforcement, which only employs to support the stirrups as shown in figure (1). The yield strength of steel with diameters of Ø16, Ø8 and Ø4 are 520 MPa, 438 MPa, and 415 MPa, respectively. Figure (2). Show details and setup of the tested beams. Table (1) gives details about tested beams.

![Figure 1. Steel reinforcement details.](image1.png)

![Figure 2. Details and setup of the tested beams](image2.png)
Table 1. Discerption of tested beams.

| Beams     | HL (cm) | R  | Vf  (% of RPC) | Description of test beams                      |
|-----------|---------|----|---------------|------------------------------------------------|
| BEAM-1    | 0       | 0  | 0             | CC beam                                         |
| BEAM-2    | 20      | 1  | 1%            | RPC beam                                       |
| BEAM-3    | 20      | 1  | 2%            | RPC beam                                       |
| BEAM-4    | 5       | 1/4| 1%            | Built-up beam with RPC in tension region        |
| BEAM-5    | 10      | 1/2| 1%            | Built-up beam with RPC in tension region        |
| BEAM-6#   | 5       | 1/4| 1%            | Built-up beam with RPC in compression region    |
| BEAM-7#   | 10      | 1/2| 1%            | Built-up beam with RPC in compression region    |
| BEAM-8    | 5       | 1/4| 2%            | Built-up beam with RPC in tension region        |
| BEAM-9    | 10      | 1/2| 2%            | Built-up beam with RPC in tension region        |
| BEAM-10#  | 5       | 1/4| 2%            | Built-up beam with RPC in compression region    |
| BEAM-11#  | 10      | 1/2| 2%            | Built-up beam with RPC in compression region    |

# RPC in compression

5. Tests Results and Discussion

5.1 Mixes Mechanical Properties:
Table 2 illustrates the results of the mixes mechanical properties such as, $(f'c)$ compressive strength, $(f_r)$ flexural strength, $(f_{ct})$ splitting tensile strength, and $(E_c)$ modulus of elasticity for both types of concrete. The Results indicate that increment in volumetric ratio of steel fibers from 1% to 2%, leads to significant development in the mechanical properties of RPC comparing with RPC, which was made without steel fibers. These developments are shown obviously in properties related to tensile force resistance such as flexural and splitting tensile strength more than compressive strength and modulus of elasticity.

Table 2. Mechanical properties of CC and RPC.

| Mix          | Compressive strength $(f'c)$ MPa | Splitting tensile strength $(f_{ct})$ MPa | Modulus of rupture $(f_r)$ MPa | Modulus of elasticity $(E_c)$ GPa |
|--------------|----------------------------------|------------------------------------------|-------------------------------|---------------------------------|
| CC           | 39.355                           | 3.501                                    | 3.986                         | 29.835                          |
| RPC 0%*      | 75.541                           | 4.981                                    | 6.035                         | 37.920                          |
| Increasing ratio (%) | 0                              | 0                                        | 0                             | 0                               |
| RPC 1%*      | 86.637                           | 10.520                                   | 11.508                        | 42.003                          |
| Increasing ratio (%) | 14.68                          | 111.2                                    | 90.68                         | 10.76                           |
| RPC 2%*      | 99.825                           | 12.038                                   | 15.143                        | 44.477                          |
| Increasing ratio (%) | 32.14                          | 141.67                                   | 150.91                        | 17.29                           |

Table 3 illustrates results (maximum deflections with maximum failure loads) of the tested beams. As a rule, the increment of RPC layer depth and the volumetric ratio of steel fibers $V_f$, has an affirmative influence on the behavior of the tested beams, toward a considerable increase of the load-carrying capacity and deflections when RPC used in compression regions, with a slightly increment when RPC used in tension regions, if they were compared with (BEAM-1) that was made from CC.
Table 3. Maximum (midspan deflections, loads) of the tested beams.

| Beams   | Pu (kN) | Δmax (mm) | Pu/ Pu (BEAM-1) % | Δmax/ Δmax (BEAM-1) % |
|---------|---------|-----------|-------------------|-----------------------|
| BEAM-1  | 118     | 12        | -                 | -                     |
| BEAM-2  | 183.3   | 21        | +55.33            | +75                   |
| BEAM-3  | 196.13  | 23.71     | +66.21            | +97.58                |
| BEAM-4  | 122.58  | 10.45     | +3.88             | -12.91                |
| BEAM-5  | 137.29  | 9.62      | +16.34            | -19.83                |
| BEAM-6# | 152     | 16.31     | +28.81            | +35.91                |
| BEAM-7# | 161.8   | 18.92     | +37.11            | +57.66                |
| BEAM-8  | 127.48  | 10        | +8.03             | -16.66                |
| BEAM-9  | 143.17  | 9.18      | +21.33            | -23.5                 |
| BEAM-10#| 158     | 17.95     | +33.89            | +49.58                |
| BEAM-11#| 174.55  | 20.21     | +47.92            | +68.41                |

5.3 Effect of RPC Layer Depth Ratio (R):

In general, RPC beams (BEAM-2,3) display a high stiffer behavior comparing with CC beam (BEAM-1). This performance is attributed by RPC high mechanical properties such as (compressive strength, flexural, splitting tensile strength and modulus of elasticity) which may be caused by fine ingredients, steel fiber and the absence of coarse aggregate. Maximum midspan deflections of these beams are(21,23.71mm) respectively, which are higher than that of (BEAM-1), since these beams endured a high ultimate load which leads them to resist more deflections with a high capacity of energy dissipation as shown in Fig. (3). Obviously increment in stiffness behavior of built-up beams with RPC in tension region with maximum midspan deflection (10.45mm of BEAM-4) compared with CC beam (BEAM-1), when the layer depth ratio (R) and steel fibers volumetric increased from (0.25-0.5,1-2%) respectively. This behavior affected by the high tensile features of RPC, as shown in Figures (4 to 5). Built-up beams with RPC in compression region also showed a slight increase in stiffness behavior compared with CC beam (BEAM-1), maximum midspan deflection of these beams (20.21mm of BEAM-11#) is higher than deflection of CC beam (BEAM-1) because of thy sustained high ultimate load. This performance attributed by high compressive strength and high modulus of elasticity, as shown in figures (6 to 7).
Figure 3. Reference beams

![Reference beams graph](image)

Figure 4. Built-up beams. RPC in tension (vf=1%).

![Built-up beams graph](image)

Figure 5. Built-up beams. RPC in tension (vf=2%).

![Built-up beams graph](image)
Figure 6. Built-up beams. RPC in compression (vf=1%).

Figure 7. Built-up beams. RPC in compression (vf=2%)

5.4 The Effect of Volumetric Ratio of Steel Fibres (vf\%):
Generally, the increase in a volumetric ratio of steel fibers from 1% to 2%, leads to stiffer behavior with respect to the same layer depth, as shown in the above figures. This effect is less pronounced in built-up beams with RPC in compression regions, with increased in a volumetric ratio of steel fibers for the same layer depth. Built-up beams with RPC in tension regions show maximum midspan deflections lower than CC beam (BEAM-1) for different volumetric ratios of steel fibers, while Built-up beams with RPC in compression show higher maximum deflections than CC beam since they were sustained a higher load.

5.5 Modes of Failure and Crack Patterns:
Modes of failures and crack patterns of the tested beams are shown in figures (8 to 11) as examples. All beams were designed to fail in flexure by yielding of the main reinforcement followed by compressive crushing of concrete. Several cracks began in the tension face at the region of maximum moment, the middle third of the beam. During over loading, these cracks outstretched upwards and turn to be wider, while other cracks started to extended at the each of the adjoining shear spans, especially for built-up beams with RPC in compression region and reference beams (BEAM-2,3).

Figure 8. Failure Mode and Crack Pattern of BEAM-1
Figure 9. Failure Mode and Crack Pattern of BEAM-3

Figure 10. Failure Mode and Crack Pattern of BEAM-4

Figure 11. Failure Mode and Crack Pattern of BEAM-11#

6. Conclusions
Depending on the above results, which were obtained from the experimental tests the following conclusions can be drawn:

1. RPC mixes mechanical properties affected by the increment of the volumetric ratio of steel fibers. Where the increment of this ratio from 0% to 2%, leads the compressive strength, and modulus of elasticity, to increase by 32.14%,17.29% respectively. On the other hand, this effect has become higher on the tensile strength features since the flexural strength and splitting tensile strength increase by 141.67%,150.91% respectively. This emphasizes the concept of improving the tensile strength features of RPC fundamentally by the addition of fibers, further than other compressive properties.

2. The maximum midspan deflections at the failure loads of beams which were made from RPC (21mm-23.71mm), were higher than of CC beam (12mm) for different volumetric ratios of steel fibers, caused by their larger stiffness, with an increment of the load-carrying capacity 55.33%,66.21% respectively.
3. Built-up beams with RPC in tension regions displayed a stiffer behavior than BEAM-1 which was made from CC obviously when the volumetric ratio of steel fibers reach to 2% and layer depth ratio (R) is 0.5. The maximum midspan deflections of these beams (10.45mm-9.18mm) were lower than of CC beam (12mm) with an acceptable increment on the load-carrying capacity from 3.88 to 21.33%.

4. A slight stiffness performance is shown by the built-up beams with RPC in compression region with respect increase of steel fibers ratio and layer depth. Significant increment in the load-carrying capacity varied from 28.81% to 47.92% especially with steel fiber ratio is 2% and layer depth ratio (R) is 0.5 comparing with CC beam, with maximum midspan deflections (16.31mm-20.21mm) were higher than of CC beam (12mm) because beams sustained higher ultimate load and this allows them to withstand further deflections. This leads to the fact that utilizing of RPC in compression regions is more useful than using it in tension regions.

References

[1] Wille K, Naaman A E and Montesinos G J 2011 Ultra-High Performance Concrete with Compressive Strength exceeding 150 MPa (22 ksi): A simple way ACI Materials Journal, Vol. 108, No. 1, pp 46-54

[2] Richard P and Cheyrezy M H 1994 Reactive Powder Concretes with High Ductility and 200-800 N/mm² Compressive Strength ACI Special Publication, Vol. 144, No. 24, 1994, pp 507-518

[3] Wille K, Naaman A E and El-Tawil S 2011 Optimizing Ultra-High-Performanc Fiber-Reinforced Concrete”, Concrete International, September 2011, pp 35-41

[4] Habel K, Denarie E and Bruhwiler E 2007 Experimental investigation of Composite Ultra High Performance Fiber Reinforced Concrete and Conventional Concrete Members ACI Structural Journal, Vol. 104, No. 1, pp 93-101

[5] Iraqi Specification, No. 5/1984, Portland Cement. Ministry of Planning, Central Organization for Standardization and Quality Control.

[6] Iraqi Specification, No.45/1984, Aggregate from Natural Sources for Concrete and Construction. Ministry of Planning, Central Organization for Standardization and Quality Control.

[7] ASTM C 1240-05 2005 Standard Specification for the use of Silica Fume as a Mineral Admixture in Hydraulic Cement Concrete, Mortar and Grout Vol. 04.02, pp. 1-7

[8] ASTM C 494 /C 494M-05a 2005 Standard Specification for Chemical Admixtures for Concrete. Vol. 04.02, pp. 1-11

[9] ASTM A615/615M-05a 2005 Standard Specification for Deformed and Plain Carbon Structural Steel Bars for Concrete Reinforcement Annual Book of ASTM Standards, Vol.01.02