Behavior of hybrid reinforced concrete columns

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Abstract. This paper involves an experimental investigation to study the behavior of short rectangular columns cast with hybrid concrete, to compare the strength, stiffness and toughness provided by the hybrid structural system and the results collected may be used as basic data for future development of design models for this combination of materials.

Seven columns were cast and tested under concentric loading; the variables studied included the diameter of steel bars for both longitudinal and lateral reinforcement. The dimensions of rectangular columns were: 100 mm x 200 mm x 740 mm high. Two columns were cast as full conventional concrete and full reactive powder concrete columns acted as control specimens. The remaining five were cast as hybrid columns having the conventional concrete at the core and surrounded by a 40 mm thickness of reactive powder concrete, with 1% micro steel fiber.

The combination of these two types of concrete into the hybrid concrete columns was very useful because it enhanced the ultimate capacity of the columns with respect to the conventional concrete in about 179% compared to the enhancement produced due to using the reactive powder concrete alone which was 203%, therefore, it was concluded that using this hybrid concrete combination in concrete industry would be more economical than the use of reactive powder concrete; moreover, based on the mode of failure observed, it would be safer to use the hybrid structural system because of the destructive type of failure for columns cast with conventional concrete. Increasing the diameter of the main reinforcement gave an average increase in the percentage of the failure load with respect to the conventional concrete column of about 179% compared to the increase in the diameter of the ties which gave an average increase of 185%; which leads to the conclusion that the effect of lateral reinforcement was more pronounced than the effect of the longitudinal reinforcement in hybrid columns, due to the increase in confinement produced by both the reactive powder concrete cover in the hybrid concrete columns and the ties represented by the lateral reinforcement.

Keywords
hybrid concrete, short rectangular columns, reactive powder concrete, RPC, conventional concrete, CC, concentric loading.

1. Introduction:
The field of High-Performance Concretes (HPC) has been introduced in the construction industry in last decade. This type along with the next generation of cementitious materials concrete, referred to as Ultra-High Performance Concrete (UHPC), showed both tensile and compressive strength
characteristics that make the (UHPC) a well suited material for use in important structures such as highway bridges because of the enhancement in their performance and durability [1].

Cement matrix in these cementitious materials has low tensile strength (as compared to compressive strength), a low capacity of deformation and almost no strength immediately after the appearance of first crack. Therefore, the addition of steel fibers (with high tensile strength and ductility), contributes in improving the post peak load carrying capacity and deformation of the cement matrix [2].

Advanced cementitious materials such as Ultra-High Performance Fibre Reinforced Concretes (UHPFRC), sometimes are referred to as reactive powder concrete, (RPC), are promising in structures and belong to the group of High Performance Fibre Reinforced Cement Composites (HPFRCC) shown in figure 1, that produce strain-hardening under uniaxial tension.

Moreover, UHPFRC are identified by a dense matrix that has low permeability when compared to HPFRCC and normal strength concretes [1].

Due to the high material cost of advanced cementitious materials compared with conventional materials led engineers to take advantage of the excellent properties in each of its constituents, and allows the optimum use of both materials [3].

The UHPFRC is the most expensive and the strongest material among others, therefore it is possible to use this expensive type in parts of the structure, where their advantageous material properties are used, while the remaining parts may be constructed of conventional concrete, in a composite structural element usually referred to as Hybrid Concrete element.

(Bentur and Mindes, 1990) [4] stated that the steel fibers are not as efficient as the longitudinal reinforcement to support tensile forces, however, they participate in controlling the crack propagation in the concrete leading to modifying the mechanical behavior of the concrete (after rupture) as well as improving its toughness.

Figure 1. Definition of UHPFRC [1].
The present research represents an experimental investigation to study the behavior of short rectangular columns cast with hybrid concrete and subjected to concentric loading, to compare the strength, stiffness and toughness provided by the hybrid structural system.

For this purpose, seven columns were cast and tested under concentric loading and the results collected may be used as basic data for future development of design models for this combination of materials.

2. Research significance
The experimental, analytical, and numerical studies on hybrid concrete columns are mainly concentrated on circular and/or square columns, whereas limited data are available on rectangular columns. Few experimental data is available for the development of models for rectangular hybrid columns constituting of RPC and CC.

The significant benefit of the research is to investigate the effect of longitudinal and lateral reinforcement on the loading capacity of short rectangular hybrid columns, as well as the toughness of these columns compared to the full RPC or CC columns.

3. Experimental program
Seven short rectangular columns (100 mm × 200 mm × 740 mm long) were cast for this investigation. Out of seven, two were cast as full CC and full RPC columns to act as control specimens and the remaining five were cast as hybrid columns having the CC at the core and surrounded by a 40 mm thickness of RPC, with 1% micro steel fiber. The weaker concrete type was chosen to be the core of the specimens and the strongest was placed on the peripheral to improve the confinement of the weakest type of concrete.

Specimen designation included three categories, the first category referred to the type of concrete used, CC for conventional concrete, RPC for reactive powder concrete and HC for hybrid concrete.

The second and third categories referred to the diameter of the steel bars used for longitudinal and lateral reinforcement, respectively.

For example, the specimen (HC10-6) refers to a hybrid concrete column with φ10 bars for longitudinal reinforcement and φ6 bars for lateral reinforcement.

The variables studied included the diameter of steel bars for both longitudinal and lateral reinforcement; details of specimens are shown in Table 1.

3.1. Properties of Materials Used:
The mixture used was (1: 1.2: 1.75) (Cement: Sand: Gravel) with water cement ratio of 0.5 for CC; while for the RPC, the mixture was (1: 1: 0.25: 0.01) (Cement: Fine Sand: Silica Fume: Steel Fiber) with water cement ratio of 0.22 and super plasticizer of 6%; straight steel fibers were used in the RPC mixture; their properties are described in Table 2. The quantity of cement was 400 kg/m$^3$ for the CC mix and 900 kg/m$^3$ for the RPC mix.
Table 1. Details of Specimens Studied in Present Research.

| No. | Name     | % V_f | Thickness (mm) | ϕ_A_s (mm) | ϕ_A_t (mm) | Spacing (mm) | Variables       |
|-----|----------|-------|----------------|------------|------------|--------------|-----------------|
| 1   | CC-10-6  | 0     | Full CC, 100   | 4 ϕ 10     | 6          | 100          | Control Specimens |
| 2   | RPC-10-6 | 1     | Full RPC, 100  | 4 ϕ 10     | 6          | 100          |                 |
| 3   | HC-10-6  | 1     | RPC, 40        | 4 ϕ 10     | 6          | 100          |                 |
| 4   | HC-8-6   | 1     | RPC, 40        | 4 ϕ 8      | 6          | 100          | Longitudinal Reinforcement, ϕ_A_s |
| 5   | HC-12-6  | 1     | RPC, 40        | 4 ϕ 12     | 6          | 100          |                 |
| 6   | HC-10-4  | 1     | RPC, 40        | 4 ϕ 10     | 4          | 100          | Lateral         |
| 7   | HC-10-8  | 1     | RPC, 40        | 4 ϕ 10     | 8          | 100          | Reinforcement, ϕ_A_t |

Table 2. Properties of Steel Fibers*.

| Description | Length, mm | Diameter, mm | Tensile Strength, MPa | Aspect Ratio |
|-------------|------------|--------------|------------------------|--------------|
| Straight    | 15         | 0.2          | 2600                   | 75           |

*Supplied by the manufacturer

3.2. Molds and Casting Procedure:
All columns were cast in horizontal steel molds manufactured for the purpose of the research. Both CC and RPC mixes were prepared earlier then the casting was performed in three stages, the first stage was pouring the RPC into the molds in a 40 mm thick layer, then two steel plates were inserted to allow a space for the CC in the core of the specimen. Stage two starts by pouring both the CC in the core and the RPC in the space outside the plates. Finally, stage three starts by pouring the RPC to complete the casting up to the top of the mold; then the plates are pulled out carefully from the molds.

From each batch several control specimens were cast for destructive tests according to the ASTM standards [5, 6, 7 and 8]. Figure (2) shows the molds used in casting the research specimens along with the casting procedure.

Figure 2. Photos of the Mold and the Cast Column.

3.3. Curing of Specimens
24-48 hours after casting all specimens were stripped and placed in curing tanks for 28 days. After curing, the specimens were removed from the curing tanks and left at dry room temperature for a week then they were ready for testing.

3.4. Testing of Specimens
All specimens were tested by the Avery testing frame system, one of the apparatus of the structural laboratory of the Civil Engineering Department at the University of Technology, as shown in Figure 3.
Figure 3. Photo of the Avery Testing Frame System.

The test set-up was as shown in figure 4. All specimens were tested in the same way by applying the load on the top of the column on a steel bearing plate to distribute the load. Before placing the column for testing, steel rings were applied at the top and bottom of the column in order to reduce concrete crushing under bearing plates.

Vertical and horizontal displacements along the columns were recorded through two LVDTs replaced at the center of the column, as shown in figure 4 (a and b).

Figure 4. Locations of LVDT used in Testing.

4. Test results
Seven columns were tested along with the standard number of control specimens to figure out the properties of the concrete used to construct the hybrid columns, the average results of destructive tests for all control specimens regarding the cylindrical compressive strength and splitting tensile strength, at test date are illustrated in Table 3.
Table 3. Test Results of Control Specimens.

| No. | Type of Test                  | Conventional Concrete, CC* | Reactive Powder Concrete, RPC* |
|-----|------------------------------|----------------------------|--------------------------------|
| 1   | Cylindrical Compressive Stress, $f_{c}$ (MPa) | 28                         | 84                             |
| 2   | Splitting Tensile Strength, $f_{ct}$ (MPa)  | 4                          | 16                             |

* The values are the average of three standard specimens for each property

All columns were loaded concentrically until failure. Test results for all specimens are shown in table 4.

Table 4. Test Results of Specimens Studied in Present Research.

| No. | Name  | $P_{cr}$ (kN) | $\Delta_{cr}$ (mm) | $\%$ Inc. in $P_{cr}$ w/r CC | $P_{u}$ (kN) | $\Delta_{u}$ (mm) | $\%$ Inc. in $P_{u}$ w/r CC |
|-----|-------|---------------|--------------------|-------------------------------|--------------|-------------------|-------------------------------|
| 1   | CC-10-6 | 220           | 0.121              | 0                             | 340          | 0.155             | 0                             |
| 2   | RPC-10-6 | 600           | 0.065              | 173                           | 1030         | 0.12              | 203                           |
| 3   | HC-10-6  | 540           | 0.089              | 146                           | 950          | 0.185             | 179                           |
| 4   | HC-8-6   | 470           | 0.109              | 114                           | 900          | 0.245             | 165                           |
| 5   | HC-12-6  | 750           | 0.085              | 241                           | 1000         | 0.129             | 194                           |
| 6   | HC-10-4  | 500           | 0.26               | 127                           | 930          | 0.362             | 174                           |
| 7   | HC-10-8  | 650           | 0.196              | 196                           | 1030         | 0.372             | 203                           |

* w/r = with respect to

4.1. Cracking Loads and Displacements ($P_{cr}$ and $\Delta_{cr}$):
Cracking loads and displacements recorded throughout this research work were based on eye vision and the voices that accompanied the test procedure; therefore they were not exact values, this may be referred to the cracks that may be produced within the core of the specimens, in the CC, that could not be seen by the researchers; but were assumed to be almost true.

4.2. Ultimate Load ($P_u$):
The ultimate load (failure load) for each column is shown in Table 4. It is obvious that there is an enhancement in the failure load for RPC columns (1030 kN) with respect to the CC columns (340 kN); the percentage of increase was about 203%.

The combination of RPC (with volumetric ratio of 1%) and CC into the HC columns enhanced their ultimate capacities. The failure load for HC-10-6 was recorded to be 950 kN, the percentage of increase was about 179%. This result was closer to the RPC column than the CC column; which makes the usage of this combination in construction industry very useful and more economical than using full RPC specimens.

It was also obvious that the enhancement in the failure load was more significant with increasing the size of the lateral reinforcement; this enhancement was due to the increase in the confinement that the lateral reinforcement offers to the column.

4.3. Ultimate Displacement, ($\Delta_u$):


The ultimate displacements are shown in table 4. It was obvious that using RPC concrete decreased the ultimate displacement of the columns, (0.12 mm), with respect to the CC columns, (0.155 mm).

For the HC columns, the ultimate displacement, (0.185 mm), was higher than those of the CC columns, (0.155 mm), which is expected because of the increase in the load carrying capacity with respect to the CC column.

4.4. Load-Displacement Curves:
Figure (6) shows the load-displacement curves for columns cast with different longitudinal reinforcement and same lateral reinforcement. Both vertical and horizontal displacements were recorded using LVDTs. The vertical and horizontal displacements for the CC column were much significant than the displacement of the RPC column. On the other hand the RPC column suffered less values in displacement compared with all other columns.

The load-displacement curves for the HC columns were moderate between the CC and the RPC columns but their behaviors were closer to that of RPC column especially for the columns cast with longitudinal reinforcement having largest diameters (HC-12-6).

![Figure 5. Load-Displacement Curves for Columns with Different Longitudinal Reinforcement and Same Lateral Reinforcement (φ 6 mm).](image)

The same behaviour was observed for the columns cast with different lateral reinforcement and same longitudinal reinforcement, as shown in figure (6).

To maintain the LVDT from breaking it was removed before ending the test, therefore most of the results recorded for the horizontal displacement for most types of the tested columns were missing.
Figure 6. Load-Displacement Curves for Columns with Different Lateral Reinforcement and Same Longitudinal Reinforcement ($\phi$ 10 mm).

4.5. Mode of Failure:
Photos of tested specimens are shown in figure (7). The control specimens represented by the CC, RPC and HC-10-6, as well as the Hybrid column HC-8-6 and HC-12-6 are shown in figure (7-a); while figure (7-b) includes the remaining hybrid columns HC-10-4 and HC-10-8.

The failure of most of the columns tested throughout this research work was due to minor cracks up to failure except the column cast with CC which past beyond the cracks and suffered severe demolishing which make the use of RPC and HC concrete much safer in concrete industry.

Figure 7. Photos of Tested Specimens.

4.6. Effect of Longitudinal Reinforcement:
Increasing the size of longitudinal bars enhanced the load carrying capacity of the hybrid columns with respect to the CC column (with a failure load of 340 kN); the highest failure load recorded was 1000 kN for the column cast with longitudinal reinforcement having largest diameter, $\phi$12, (HC-12-6).

The maximum size of bar used in this research gave results, behaviour and failure mode very close to those of RPC column. The effect of Longitudinal Reinforcement is illustrated in figure (8).
4.7. **Effect of Lateral Reinforcement:**
The same behaviour was observed with respect to the size of lateral reinforcement used, as illustrated in figure (9).

The enhancement in the load carrying capacity, in hybrid columns, gained from increasing the lateral bars was more pronounced than increasing the longitudinal bars, therefore in the researcher’s point of view it is suggested that increasing the size of ties in rectangular hybrid columns will be more beneficial than increasing the size of longitudinal bars.

5. **Conclusions:**
From the experimental work performed throughout this research the following conclusion may be obtained:

1) The combination of RPC and CC into the HC columns was very useful because it enhanced the ultimate capacity of the columns with respect to the CC in about 179% compared to the enhancement produced due to using the RPC alone which was 203%, therefore, in the researchers’ point of view, it was concluded that using HC in concrete industry would be more economical than the use of RPC.

2) Due to the type of failure of the columns tested throughout this research work it was concluded that the use of RPC and HC in concrete industry is much safer than the use of CC.

3) Increasing the diameter of the main reinforcement from 8 to 10 and 12 mm gave an increase in the percentage of the failure load with respect to the CC column of 165%, 179% and 194%, respectively.
4) Increasing the diameter of the ties from 4 to 6 and 8 mm gave an increase in the percentage of the failure load with respect to the CC column of 174%, 179% and 203%, respectively.

5) The effect of lateral reinforcement was more pronounced than the effect of the longitudinal reinforcement in hybrid columns, due to the increase in confinement produced by both the RPC cover in HC columns as well as the ties represented by the lateral reinforcement.

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