International Journal of GEOMATE, July, 2022, Vol.23, Issue 95, pp.112-118
ISSN: 2186-2982 (P), 2186-2990 (O), Japan, DOI: https://doi.org/10.21660/2022.95.3210
Geotechnique, Construction Materials and Environment

EXPERIMENTAL INVESTIGATION ON THE ULTIMATE CAPACITY OF RECTANGULAR REINFORCED HYBRID CONCRETE COLUMNS UNDER AXIAL LOAD

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*Corresponding Author, Received: 09 Jan. 2022, Revised: 06 May 2022, Accepted: 28 May 2022

ABSTRACT: An experimental investigation was conducted on five configurations of reinforced concrete short rectangular columns that were tested until failure under concentric loading. Conventional concrete (CC) and ultra-high-performance concrete (Reactive powder concrete, RPC) were used in the experiments. Two of the columns were considered control specimens, one cast from a CC mix and the other from an RPC mix. The remaining three were; cast by combining the two types of concrete into a hybrid combination having the CC at the centre of the column surrounded by a 40 mm layer of RPC. The research included studying the effect of secondary reinforcement (sizes and spacing). The reinforcement bar diameters studied were 4,6, and 8 mm and the spacings were 100, 140 and 175 mm. The columns studied had dimensions of 100×200×740 mm. The data obtained included: crack and ultimate loads as well as longitudinal and lateral strains. The test results showed that increasing the diameter of the secondary reinforcement was more significant than changing the spacings between them with respect to the CC column. The maximum recorded increase in ultimate capacity resulting from changing the diameters was 203% while that resulting from changing the spacings was 179%.

Keywords: Rectangular concrete columns, Hybrid concrete, Conventional concrete, Concentric loading, Secondary reinforcement.

1. INTRODUCTION

An experimental investigation was performed on five short rectangular reinforced concrete columns with a cross section of 100×200 mm and a height of 740 mm. The studied columns were cast using two kinds of concrete: conventional concrete (CC) and ultra-high-performance concrete (reactive powder concrete, RPC).

Two of the columns were considered control specimens, one from the CC mix and the other from the RPC mix; the remaining three were cast from a combination of both mixes producing hybrid columns, HCs, with the core cast from the CC mix and the surrounding 40 mm layer cast from the RPC mix. Two variables were studied: the effect of tie spacing (100, 140 and 175 mm), and the size of the ties, which were taken from previous research performed by the same researchers [1].

Reinforced concrete columns are important structural members: therefore, knowing their behaviour under the influence of all types of loads is of paramount importance, and has been investigated by many researchers. The development and practice of the concrete industry has helped in increasing the use of stronger concrete in compression members [2 and 3].

Reactive powder concrete (RPC) is one of the most important developments in concrete technology [4]. The use of RPC provides higher strength and improves ductility compared to conventional concrete (CC). Using a hybrid of these types of concrete in casting primary structural members such as columns can achieve economic benefits [5].

The increase in the use of concrete with high strength has helped engineers design columns with smaller sizes that carry the same loads as the loads carried by larger members cast with conventional concrete. Reducing the size of members is beneficial especially in the presence of architectural aesthetic preferences regarding the size of columns. Additional advantages include reducing the cost, by producing durable materials cast in smaller forms [6 and 7]. The superior mechanical properties and durability of ultra-high-performance concrete (UHPC) or RPC have allowed for lo mechanical and durability properties allowing for longer service life and decreased maintenance costs [8 and 9].

Mixing two or more types of concrete within one structural element in a hybrid combination gives more advantages than using either high strength concrete alone or conventional concrete. The high-strength type is used in structural parts subjected to severe environmental conditions to increase the strength of the structure without increasing its dead weight, while the other type, conventional concrete, is used in other parts of the structure, producing a much stronger and economical structural element.

A column is defined as a vertical structural member whose effective length is greater than three times the least lateral dimension (subjected to compressive forces). Columns are said to be short if the ratio between the effective length and the least lateral dimensions is less than 12 [10].

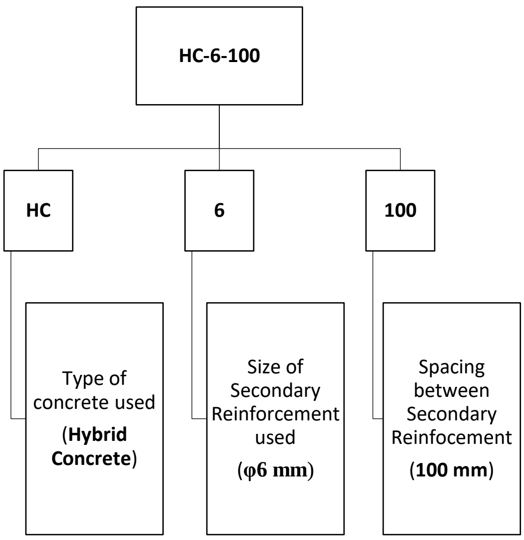
2. RESEARCH SIGNIFICANCE

Limited experimental and theoretical works are available in the literature dealing with hybrid short concrete columns of rectangular sections. The aim of this research is to study the secondary reinforcement of such columns.

The study included showing the effect of the sizes and spacings on the loading capacity of the hybrid columns with respect to the other columns cast solely from the CC or the RPC mixes.

3. MATERIALS AND METHODS

Five 740 mm high reinforced concrete columns in (100×200) mm rectangular section were cast for this work; two of the columns were control specimens, with one cast from the CC mix and the other from the RPC mix. The remaining three were cast from the combination of both mixes producing hybrid columns, with the core cast from the CC mix and the surrounding 40 mm layer cast from the RPC mix. Specimen names included the type of concrete, the diameter of the ties used and amount of spacing between the ties, so the specimen (HC-6-100) represents a hybrid concrete column with 6 mm-diameter ties spaced at 100 mm, as shown in the flow chart below.



The details of the studied specimens are shown in Table 1. The volumetric ratio of steel fibres used in the HC and RPC columns was 1%, and this ratio was selected based on research in the literature [11].

Table 1 Properties of research specimens

No.	Name	As** (No-ϕ) (mm²)	At** (ϕ) (mm²)	Spacing (mm)	Thickness of RPC layer (mm)
1	RPC-6-100	4-10	6	100	100 (Full RPC)
2	HC-6-100	4-10	6	100	40
3	CC-6-100	4-10	6	100	0 (Full CC)
4	HC-6-140	4-10	6	140	40
5	HC-6-175	4-10	6	175	40
6*	HC-4-100	4-10	4	100	40
7*	HC-8-100	4-10	8	100	40

**From reference [1], ** according to references [12 and 13]*

3.1 Properties of Materials

According to international and Iraqi specifications all materials used were tested.

1- Cement: Al-Mass ordinary Portland cement was used for both CC and RPC and according to international limits of Iraq specification No.5, 1984[14]. Portland cement is the most common type of cement used in construction around the world [15].

2- Fine aggregate: Natural sand with a maximum particle size of 4.75 mm was used for CC only, while fine sand with a maximum particle size of 0.6 mm was used for RPC, according to the international limits of Iraq specifications No.5, 1984, zone 2 and zone 4 [16].

3- Coarse aggregate: Natural gravel with a maximum particle size of 10 mm was used for CC. The grading conformed to the international limits of Iraq specification No.5, 1984.[16]

4- Silica Fume: Grey silica fume with 20000 m2/kg fineness was used for RPC to fill the voids and improve the properties.

5- Superplasticizer: Sika Visco Crete-5930-L was used as a superplasticizer for the RPC mix improvement.

6- Steel Reinforcement: Nominal deformed steel bars were used; 10 mm dimeter for longitudinal reinforcement and 6 mm dimeter for tie reinforcement. A tensile test was performed. For each bar, the results obtained included a yield stress of 480 and 507 MPa, respectively.

7- Steel fibres: Straight macro copper golden fibres were used to produce high strength concrete; (length: 15 mm, diameter: 0.2 mm, tensile strength, 2600 MPa, and aspect ratio of 75), as supplied by the manufacturer [17].

3.2 Mix Design

The CC mix included 1 Cement : 1.2 Sand : 1.75 Gravel. The RPC mix included 1 Cement : 1 Fine Sand : 0.25 Silica fume : (0.5%, 1% and 1.5%) Steel fibres); the water cement ratios for the CC and the RPC were 0.5 and 0.22, respectively. The percentage of the superplasticizer used to produce the RPC mix was 6%; the properties of the straight steel fibres were described in Section 3.1.7 mentioned earlier. A 400 kg/m^3 cement content was used for the CC mix and a 900 kg/m^3 cement content was used for the RPC mix.

3.3 Preparing Moulds and Specimens

Horizontal steel moulds were prepared to cast all specimens. The concrete mixes for both types of concrete used in this research were prepared.

The casting started with pouring the RPC mix into a mould up to a height of 40 mm. Then two steel plates were inserted along the mould to separate the two types of concrete poured (the CC within the centre of the column and the RPC surrounding it). Finally, the 40 mm layer of RPC was poured to complete the casting of the specimen. Then, the plates were removed.

According to the ASTM standards [18, 19, 20 and 21], control specimens were cast from each batch.

The moulds and cast specimens are shown in Fig. 1.

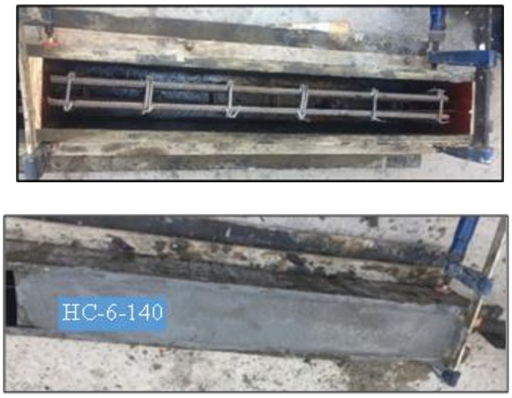


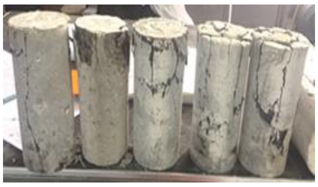
Fig.1 The moulds with the HC-6-140 cast specimen

3.4 Curing Procedure

All specimens were cured for 28 days. After leaving them for a week to dry (at room temperature) all specimens were ready for testing. [22].

3.5 Control Specimens Tests

Compressive strength and splitting tensile strength tests were conducted according to ASTM [18,19]. Three standard cylinders were used for each test of both the CC and RPC mixes. The tested control specimens are shown in Fig. 2. The results of the destructive tests for CC were as follows: compressive strength, 28 MPa, tensile strength, 4 MPa, whereas for RPC concrete the compressive strength was 84 MPa and the tensile strength was 16 MPa.



(a) Compressive strength

(b) Tensile strength

Fig.2 Compressive and splitting tensile strength for RPC and CC.

3.6 Columns Tests

The test setup (Fig. 3) represents the method of testing all columns using an Avery testing machine at the University of Technology Civil Engineering Department structural laboratory.

The load was applied vertically on the top of the column; the load is distributed with the help of a steel bearing plate. The crushing of concrete under those plates was reduced by applying steel rings at the edges of the columns (top and bottom). The test setup for some of the specimens is shown in Fig.4.

Fig.3 Photo of the test setup on the Avery Testing Machine.

Fig.4 Picture of tested specimens

To record the vertical and horizontal displacements for the tested columns, two LVDTs were used at the centre of each column, and the locations of these LVDTs are shown in Fig.5.

Fig.5 LVDTs locations on specimens

4. RESULTS

Five specimen columns and a standard number of control specimens were tested in this work to obtain the properties of the hybrid concrete columns. The load was applied concentrically on all specimens until failure. The data obtained are listed in Table 2.

Cracking loads and displacements were recorded optically (based on eye vision) along with the accompanying voices during the test; therefore, they were assumed to be almost true.

Table 2 Test results of columns tested in work

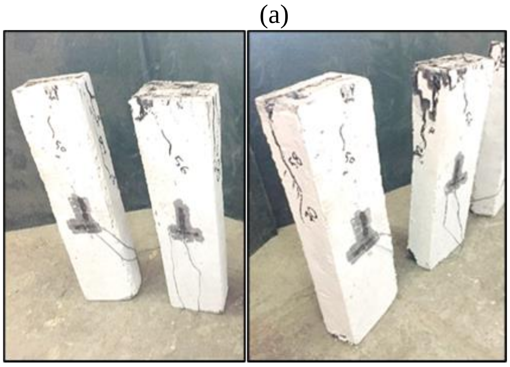
No.	Name	Pcr (kN)	Δcr (mm)	Pu (kN)	Δu (mm)	%Inc. wrp CC
1	RPC-6-100	600	0.130	1030	0.240	203
2	HC-6-100	540	0.178	950	0.370	179
3	CC-6-100	220	0.242	340	0.310	-
4	HC-6-140	640	0.278	720	0.340	112
5	HC-6-175	400	0.090	560	0.123	65
6*	HC-4-100	500	0.260	930	0.362	174
7*	HC-8-100	650	0.196	1030	0.372	203

**Data collected from reference [1]*

All tested specimens are presented in Fig.6. CC-6-100, RPC-6-100 and HC-6-100 represent the control specimens (Fig.6 (a)), while the remaining hybrid columns HC-6-140 and HC-6-175 are shown in Fig.6 (b).

The test results showed that using hybrid columns was very effective and economical for bearing higher loads with lower cost compared to the high- performance concrete columns.

(a)



(b)

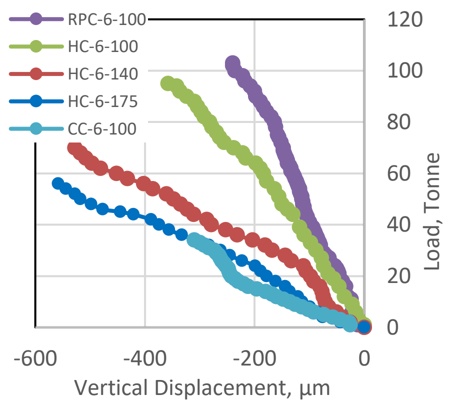
Fig.6 Pictures of tested specimens

4.1 Load-Displacement Curves

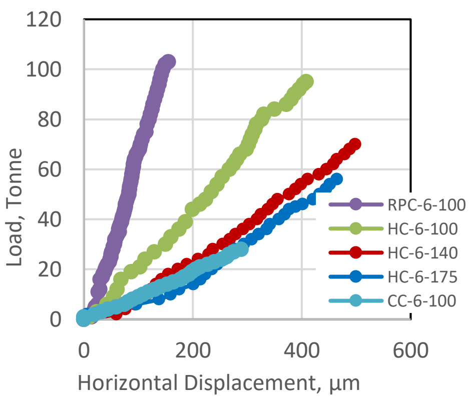
The load-displacement (vertical and horizontal) curves are shown in Fig.7 (a and b). These curves show the behaviour of each type of column tested throughout this research. In these figures, it was obvious that the RPC columns were stiffer than the CC columns. The HC columns were moderate in behaviour between the two types of concrete used. HC-6-100 was stiffer than the other HC columns (it approached the RPC column in behaviour). Increasing the spacing between ties decreased the failure load, leading to a direct load-displacement relationship.

For the same spacing the hybrid columns approached the RPC column in behaviour; this was most significant in vertical displacement rather than the horizontal displacement.

Increasing the spacings between ties in hybrid columns from 100 mm to 140 mm and 175 mm led to an increase in failure load (with respect to the CC column) of 179%, 112% and 65% respectively; this behaviour almost approached that of the CC column with 100 mm spacing.



(a)



(b)

Fig.7 Load versus displacement curves

4.2 Load-Strain Curves

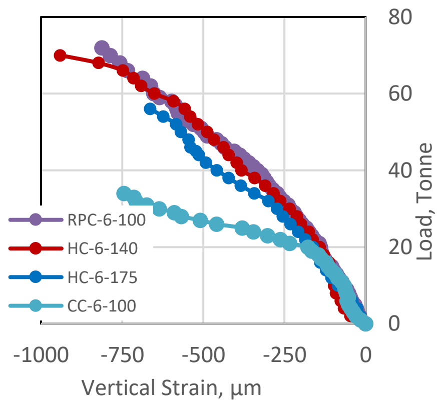
The load–strain (vertical and horizontal) curves are shown in Fig.8 (a and b). The figures show that the behaviour of the HC columns was between those of the RPC column and the CC column.

For the vertical strain curves, since the strain gauges were attached to the outer layer surface of the HC columns (RPC-layer), the behaviour was expected to approach that of the RPC column.

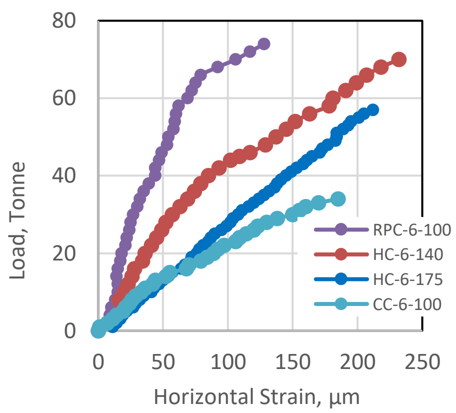
For the horizontal strain curves, the RPC layer mostly worked as a confinement to the CC core of the hybrid columns: therefore, the effect on the horizontal strain was less significant than that on the vertical strain. Moreover, increasing the spacing between ties improved the behaviour of HC columns compared to that of the CC column with 100 mm spacing.

Note that the strain records (both vertical and horizontal) for most of the tested specimens did not reach the failure load. With increasing load capacity, the specimens suffered from surface cracks that propagated underneath the strain gauges causing them to stop recording, which forced us to exclude their readings from our study.

Moreover, for specimen HC-6-100, the strain gauge malfunctioned in the early minutes of the test, registering illogical values that cannot be excepted; therefore, these records were excluded from the study as well.



(a)



(b)

Fig.8 Load – strain curves

4.3 Effect of Secondary Reinforcement

The effect of secondary reinforcement used in this research was studied. This effect is shown in Table 3 and Fig.9. Test results showed that increasing the diameters of the bars was more significant than changing the spacings between them. Increasing the diameter from 4 mm to 8 mm decreased the ratio for Pu/At from 5.3 to 1.5. Increasing the spacing between them from 100 mm to 175 mm gave almost the same ratio (2.5). Studying the test results with respect to RPC and CC showed that the ratio of Pu to At for the HC columns was similar to the ratio obtained for the RPC column.

Table 3 Effect of secondary reinforcement with respect to failure load

Specimen	Pu (kN)	At (mm^2)	Pu/At (kN/mm^2)
RPC-6-100	1030	396	2.6
HC-6-100	950	396	2.4
CC-6-100	340	396	0.9
HC-6-140	720	283	2.5
HC-6-175	560	226	2.5
HC-4-100	930	176	5.3
HC-8-100	1030	704	1.5

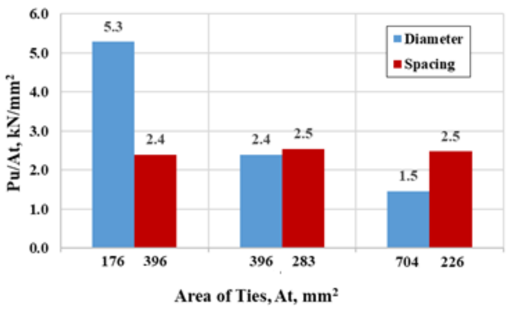


Fig.9 Effect of secondary reinforcement

5. CONCLUSIONS

Five columns were tested under concentric loading to determine the effect of secondary reinforcement on the strength of hybrid columns. The following conclusions were obtained from this investigation:

• Mixing two types of concrete in a hybrid combination successfully strengthened reinforced concrete columns.

• For the same reinforcement, the hybrid column (HC-6-100) approached the RPC column in behaviour; the percent decrease with respect to the RPC column was (8%), while the percent increase with respect to the CC column was (179%).

• For the horizontal strain curves, the RPC layer mostly worked as a confinement to the CC core of the hybrid columns; therefore, the effect on the horizontal strain was less significant than that on the vertical strain.

• Increasing the spacing between ties in the hybrid columns from 100 mm to 175 mm decreased the failure load, although this decrease was higher than the capacity of the CC column; eventually, it improved the behaviour of HC columns compared with the CC column (cast with 100 mm spacing).

It is recommended that CC columns can be strengthed by using the hybrid combination rather than increasing the steel reinforcement of the CC column.

• Based on data obtained from previous research performed by the authors, the results showed that increasing the secondary reinforcement diameters from 4 mm to 8 mm decreased the ratio for Pu/At from 5.3 to 1.5. Increasing the spacing between them from 100 mm to 175 mm gave almost the same ratio (2.5).

• Increasing the diameter of the secondary reinforcement was more significant than changing the spacings between them with respect to the CC column. The maximum recorded increase in capacity resulting from changing the diameters was 203% while that resulting from changing the spacings was 179%.

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