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BEHAVIOR OF REACTIVE POWDER CONCRETE COLUMNS UNDER ECCENTRIC COMPRESSION LOADING

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ABSTRACT: -The strength of concrete columns is controlled by the strength of the material and the geometry of the cross section. The use of Reactive Powder Concrete RPC technology has proven most popular with superior strength, stiffness and durability being the major advantages. An experimental investigation was carried into the behavior of RPC columns subjected to axial load with initial eccentricity. Twelve columns were prepared with 120mm square section at the midsection and were hunched at the ends to apply eccentric loading. The specimens were tested up to failure to evaluate the effects of the variation of the concrete type (normal or RPC), presence of steel fibers and longitudinal steel ratio. Experimental data on strength, lateral displacement and failure mode was obtained for each test. The comparative analysis of the experimental results showed that the use of RPC caused substantial variation in the ultimate strength and failure modes. Also, inclusion of steel fibers in RPC was an effective way to prevent spalling of the concrete cover and increase the ductility, as well as, high ratio of longitudinal reinforcement delays the buckling of the columns and increases strength.

INTRODUCTION

A reinforced concrete column is a structural member which is used primarily to carry compressive loads, composed of concrete with an embedded steel frame to provide reinforcement. Axially loaded columns exist rarely in practice because some bending is almost always present. The moments introduced by continuous construction, also, inevitable imperfections of construction will introduce eccentricities and consequent bending in the member. The strength of columns is controlled by the strength of the material (especially the compressive strength of concrete) and the geometry of the cross section [1].

High Strength Concrete (HSC) is now being used in many parts of the word which have significant improvements its physical and mechanical properties. Most serious deficiency of concrete is its lack of tensile strength as well as its considered brittle material. Unlike conventional concrete, HSC containing a significant quantity of steel fibers exhibits high ductility and energy absorption characteristics [2]. As construction and material costs escalate, demand has increased for stronger materials that occupy less space. Recently, very high strength cement based composite with high ductility called Reactive Powder Concrete (RPC) has been developed in Bouygues, France [3]. RPC is composed of particles with similar elastic moduli and is graded for dense compaction, thereby, reducing the differential tensile strain and increasing enormously the ultimate load carrying capacity of the material. So, this technology provides many enhancements in properties compared to conventional and high strength concrete. Generally, this composition has high performance properties, such as low permeability, limited shrinkage, increased corrosion and abrasion resistance and increased durability, in addition to its ultra-strength characteristic [4].

2. LITERATURE REVIEW

Many researchers studied the behavior of concrete columns and increasing its axial strength and durability. This idea starts from the characteristics of concrete subjected to compressive stress states [5]. Some studies [6, 7] have demonstrated the economy of using HSC in columns of high-rise buildings, as well as low to mid rise buildings. Tests [8, 9] have shown that the use of steel fibers in the mix design can improve the strength and ductility of HSC columns. The behavior of fiber reinforced polymer FRP confined concrete column has been extensively studied by many researchers [10-13]. Generally, the results show that the columns confinement had higher strength, ductility and energy absorption compared to the conventionally concrete columns.

3. RESEARCH SIGNIFICANCE

From literature, research conducted on RPC columns is still in its infancy and the use of ultra-high compressive strength of RPC needs to be addressed further. So, in the present study, an experimental program were prepared to provide much needed understanding of the behavior of RPC columns under eccentric compression loading. The experimental program was conducted a series of reinforced columns of normal and reactive powder concrete which were casted to illustrate the effect of concrete type, steel fiber content and longitudinal reinforcement ratio.

4. EXPERIMENTAL PROGRAM

The experimental program carried out was intended to study the behavior of columns with a square section and subjected to eccentric axial load. The mechanical description of constituent materials (concrete and steel) was given initially.

4.1 MATERIAL PROPERTIES

Ordinary Portland Cement (Type I) produced in Iraq of (TASLUJA-BAZIAN) was used in this study. The chemical and physical properties indicated that the adopted cement conforms to the Iraqi specification No.5/1984 [14].

Al-Ekhaider natural sand of 4.75mm maximum size was used as fine aggregate in normal concrete. However, for RPC very fine sand with maximum size 600µm was used. Crushed gravel from AL-Nibaey region was used for reference concrete specimens with maximum size of 10mm. Results indicate that grading of these materials (aggregates) within the requirements of the Iraqi specification No.5/1984 [15].

To improve the workability and strength of concrete, high range water reducing admixture used in this study which is known commercially as Viscocrete-PC20. This type of superplactisizer is imported from Sika Company. In the present investigation, silica fume was used which imported from Sika Company. Tap water was used in all mixes and in the curing of the specimens.

Hooked short steel fibers were used throughout the experimental program. This type of steel fibers was manufactured by the SPI Fiberforce Company, Turkey. The properties of the used steel fibers are presented in Table (1).

Four size of deformed steel bars of nominal diameter 6mm for closed stirrups and (10, 12, and 16) mm for longitudinal reinforcement. The tension test of all these bars gave the properties listed in Table (2).

4.2 MIXES AND MIXING PROCEDURE

Three types of Reactive Powder Concrete RPC mixes were used in the present research as listed in Table (3). The variables used in these mixes were the volume ratio of steel fibers (three volume ratios were considered, 0, 0.75 and 1.5) %. The mix type normal concrete NC was adopted as a reference mix.

In the present work, mixing was performed by using 0.19 m^3 capacity horizontal rotary mixer. Firstly, the silica fume powder was mixed in dry state with the required quantity of sand for 5 minutes. Then, cement was loaded into the mixer and mixed for another 5 minutes. The required amount of tap water was added to the rotary mixer within 1 minute. Then all the superplasticizers were added and mixed for an additional 5 minutes. Finally when steel fibers were used, they were introduced, and dispersed uniformly and mixed for an additional 2 minutes. In the present study, a total of four batches of concrete (normal and reactive powder) were used to cast the columns by using three wooden molds. Each batch was used to cast three columns with three cubes of 100mm to determine the compressive strength of concrete. Concrete vibration was performed through a table vibrator.

4.3 DETAILS OF TESTED COLUMNS

The experimental program was included twelve reinforced concrete columns, three of which were casted using NC as controlling specimens. The other nine columns were casted using fibrous RPC with volume percentage. All columns were identical in size and the nominal dimensions.

The prototype selected in the present investigation were a square section of (b=120mm) and a total length of 1000mm. The length between corbels (middle portion) was 500mm. For eccentricity loaded columns, a constant value of eccentricity ***e=b/2*** was assumed herein.

All columns were reinforced longitudinally with four steel bars with nominal diameter of (10, 12 or 16) mm (as variable) which were placed at each corner of specimens. The columns contained the same transverse reinforcement of deformed bars with 6mm nominal diameter and spaced at 120mm to give good confinement effects. The corbels reinforced with additional steel to prevent premature failure at this portion of the specimens during the tests and to concentrate the failure in the middle portion. Figure (1) shows the geometry and reinforcement details of the specimens. The test program and specimen details are summarized in Table (4), where (NC) refers to Normal Concrete , (RPC) refers to Reactive Powder Concrete, the symbol (10, 12 and 16) refers to longitudinal steel bar diameter and symbol (0, 0.75 and 1.5) refers to steel fibers content as a percentage of concrete volume.

4.4 SUPPORT AND LOADING CONDITION

The columns were tested in a (300) ton capacity universal testing machine model (EPP300 MFL) with hydraulic jack and dial gauge for detecting the load. Figure (2) shows a general view of the testing machine. Columns were placed vertically and eccentrically with respect to the vertical axis of the testing machine.

To apply a proper axial compression loading and transmit it's to the column with accurate eccentricity, arrangement of a new loading cap was manufactured based on a loading cap designed by Hadi [11]. The loading cap has rectangular section (120×240) mm, thickness 20mm and can be provided two values of eccentric loading, see Figure (2). However, in the present work, one eccentricity distance of 60mm was used. The loading caps were made of high strength steel and each end of the columns was covered with loading cap. The lower end of the column was attached to the actuator of the machine, while the upper end was supported on the steel reaction cap of the machine. Both end supports were designed as hinged connections with predefined eccentricity by using these loading caps. The equipment and facilities for the manufacturing and testing of columns were all available in the Structures Laboratory of the College of Engineering, AL-Mustansiriya University.

4.5 MEASUREMENTS AND TESTING PROCEDURE

During the test of the columns, the main characteristics of their structural behaviour were measured at every stage of loading. The load at first crack as well as the ultimate failure load with their corresponding lateral displacements at mid-height of the column were all observed and recorded Figure (4) shows the instrumentation and the rig used for testing the columns during the course of this investigation.

Mid-height lateral displacement has been measured by means of (0.01mm/div.) sensitivity dial gauge of 30mm capacity placed at tension face of the test column at mid height. Readings from this gauge were recorded for each load increment.

The columns were tested under static loads, loaded in successive increments, up to failure. The test was stopped when concrete crushed and the concrete cover was spall or bucked away on the compression face. For each increment, the load was kept constant until the required readings were recorded.

Each column was initially exercised by applying a small load, of about (2-4) kN, to ensure that the test set-up and the instrumentation work properly. The column was then unloaded and the datum readings were taken. All columns were loaded to failure. Loading was applied slowly in small increments of 5kN, until the column showed signs of distress, where many cracks appeared along the column, crushing at compression face or spalling of concrete cover, as well as buckling, particularly in the high moment zone. Then, the load was applied until failure, as the column continued to buckle without any increase in the applied load. This amount of incremental loading was allowed sufficient number of loads and corresponding displacements to be taken during the test which gave a good picture for the structural behavior of the column.

5. RESULTS AND DISCUSSION

The general behaviour and experimental observations of twelve columns are reported and discussed, in addition to the effects of various parameters (concrete type, steel fibre volume fraction and longitudinal reinforcement ratio) on the behaviour.

5.1 GENERAL BEHAVIOUR

Photographs of the tested columns are shown in Figures (5)-(8), and the test results are given in Table (5). The general behaviour of the tested columns can be summarized, as follows:

At early stages of loading, the column deformations were initially within the elastic ranges, then the applied load was increased until the first crack occurred which was observed in the maximum moment region (midheight of the column) at the tension face. As the load increased further, usual flexural cracks horizontally initiated at intervals along the columns length. These cracks developed higher under increasing loads, and they increased in depth and extended towards the compression face of the specimens. At about 80% of their ultimate load, more cracks were developed and the specimens were buckled outward of its axis. Near the ultimate load, the concrete cover at compression face was spall and buckle away. However, this phenomenon cannot be noticed in fibrous RPC columns.

5.2 MODES OF FAILURE

For all columns, the failure mechanism was by yielding of longitudinal steel reinforcement which can be seen from buckling and cracking at tension face of the specimen, as well as crushing and debonding of the concrete cover at compression face. Generally, this was dependant on the longitudinal steel reinforcement ratio, concrete type (compressive strength) and steel fibre content. The buckling was noticed clearly for normal concrete column reinforced with longitudinal bars of Ø10 (ρ=2.2%) and became lower for specimens of RPC and reinforced with Ø16 (ρ=5.5%). Steel fibers affect the failure mode of columns, where specimens without fibers failed suddenly under loading with an exploding and spalling of concrete cover. While the failure of columns with steel fibers was much more ductile and occurred in a gradual manner with large deformations taking place before the load drops, also, these fibers showed an arresting and confining effect in preventing concrete cover from exploding and spalling even after failure, see Figures (5)–(8). Thus the effect of fibers randomly anchored into the concrete core and spanning across the crack planes is to delay premature spalling of the concrete cover until the crushing strength of concrete is occurred [11].

5.3 CRACK PATTERN

Crack patterns for test specimens were shown in photographs of Figures (5)-(8). From these figures, it can be seen, columns reinforced with high ratio of longitudinal bars, a crack was initiated at the corners of the columns and propagated towards its compression face, thereby, crushing and debonding of concrete cover was occurred at this face. This can be explained as the high stress concentrations at these locations, where, the column became stiff due to presence this ratio of reinforcement.

The cracks ware developed in the concrete when the tensile stress at the cover-core interface reaches its strength limit. Once cover-core interface cracks have developed, the cover concrete was free to spall or buckle away. Generally, the influence of the steel fibres content on the development of the cracks is really good, where cracking was more diffuse and the opening of the crack was less. The possible reason was the contribution of steel fibres to improvement the properties of RPC as well as these fibres were delay the development and propagation of the cover-core cracks due to the fact that they bridging the crack. The orientation of fibers across the initiating cracks restricted their propagation and transmitted the tensile stresses uniformly to the concrete media surrounding the crack instead of being concentrated at its tip.

5.4 STRENGTH CHARACTERISTICS

First crack and maximum failure loads were measured experimentally in all the tested columns, these loads are given in Table (5).

The experimental first crack loads for columns in this study were observed visually with a magnifying glass, while the load was increased gradually. In all specimens, the first crack appeared at tension face in midheight of the column (maximum moment region). It can be seen from Table (5), this load was increased with increasing reinforcement ratio, compressive strength of concrete, and steel fiber content. For RPC columns with steel fibers, the first crack load was increased up to four times as compared to those of normal concrete reinforced with similar longitudinal reinforcement. This can be explained that the composition of RPC gives tensile strength higher than of conventional concrete. Also, the steel fibers are used in order to improve the concrete tension, splitting and rupture strength [4].

Table (5) lists the experimental failure loads of the tested columns in the current investigation. Test results show that RPC specimens gain an increase in strength over that of the normal concrete, with same ratio of longitudinal reinforcement, up to 180%. The percentage of increasing was dependent on the steel fiber content and longitudinal reinforcement ratio, see Table (5). Generally, the ultimate load capacity increases with the additional longitudinal reinforcement ratio. Also, results show that the ultimate failure loads of RPC columns were increased substantially with use of steel fibers and its volume fraction. Figure (9) shows the variation of the steel fibers content, with increasing in ultimate load of RPC columns with respect to the normal concrete column. In reference to this figure, it can be seen that, as the steel fibers content has been increased, the ultimate strength of RPC columns was increased, also. This may be due to that the composition of RPC and presence of steel fibers in concrete are improved its properties, especially the compressive strength [4, 16]. This can be noticed clearly from Table (5), where the results shown that the improvement in compressive strength has far exceeded the results achieved with conventional concrete.

5.5 LOAD-DISPLACEMENT CHARACTERISTICS

The load-displacement characteristics for the tested columns, measured at their midheight, were constructed and shown in Figures (10) through (16). Generally, at the initial stage of loading (i.e. before the first crack load), the response was linear. As the load increased, the stiffness slightly decreased from the first stage due to the appearance of first crack. However, longitudinal reinforcement ratio, concrete type (NC or RPC) and presence steel fibres affect the load-displacement curves of the columns and this effect was summarized in these figures. It can be shown that RPC columns have less displacement during the loading stages than the reference columns NC, reinforced with same longitudinal steel ratio, but still the ultimate deflection (at failure) in RPC was higher than the reference columns due to the use of steel fibers. Similar behavior can be noticed when the longitudinal steel ratio increased. Also, it can be seen from these figures that, the presence of steel fibres had a distinct effect on stiffening the column, reinforced with same longitudinal reinforcement ratio, which reduced the deflection. The ultimate deflection was reduced between (11-47) % depending on concrete type, presence of steel fibres and longitudinal reinforcement ratio. This improves the compliance of the RPC columns with the serviceability limits. Generally, all RPC columns showed significant increase in stiffness and ultimate capacity, as compared with the normal concrete column.

5.6 DUCTILITY

The area under the load-displacement curves can be expressed good indicator for ductility [13]. From the load-displacement curves presented in this study, it was clear that the RPC columns performed better than reference columns. Also, it can be noticed that an increase in ductility was produced for specimens due to the inclusion of the steel fibres and its volume ratio, as well as this increasing in their ductility depending upon the ratio of longitudinal reinforcement. This can be explained as during tensile cracking the large number of small fibre together with the good bond between fibre and matrix which provided high resistance to fibre pull out and greatly increase the toughness of the material. This behaviour and ductility of RPC with steel fibres is a very desirable feature for safer design.

6. CONCLUSIONS

The specific aims of the experimental program in the present study were to determine the strength and ductility characteristics RPC under static eccentric axial loading. From the discussion carried out in the previous sections and other observations during the experimental tests, the following conclusions are worth noting.

1. The use of RPC technology can improve significantly the behaviour of the columns and their efficiency as compared to normal concrete because of the compressive strength and homogeneity of this type of concrete.
2. RPC columns had higher stiffness, as compared with normal concrete columns, and consequently reduced the deformation at corresponding load.
3. Almost in tested columns, the crack patterns and modes of failure were similar by buckling of the column with cracks at its tension failure. Failure occurred suddenly in the tested columns without steel fibres by debonding and spalling the concrete cover.
4. Columns reinforced with high ratio of longitudinal reinforcement became stiff, so, a crack was initiated at its corners (at hunched) due to the high stress concentrations at these locations.
5. The inclusion of steel fibres in RPC columns resulted in an enhanced stiffness, reduced crack width and preserving the whole section together after reaching failure. So, all RPC specimens with steel fibres were failed without exploding and spalling the concrete cover.
6. The presence of steel fibres and its volume fraction in the RPC columns increased the ultimate load failure to a significant value, up to 180%, as compared to conventional concrete specimens. However, this percentage became 1.27% when longitudinal steel ratio increased.
7. The inclusion of steel fibres in RPC columns resulted in a significantly enhanced ductility which made the columns fail gradually in a ductile manner, unlike nonfibrous RPC and conventional concrete specimens which showed lesser ductility at failure.

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Table (1): Properties of the used steel fibers*

Property	Specifications
Relative Density	7860 kg/m^3
Ultimate strength	2000 MPa
Modulus of Elasticity	$200x10^3$ MPa
Strain at proportion limit	$5650\ x10^{-6}$
Poisson's ratio	0.28
Average length (L_f)	13 mm
Nominal diameter (D_f)	0.2 mm
Aspect ratio (L_f/D_f)	65

*According to the certificate of conformity.

Table (2): Properties of the steel bars*

Nominal diameter (mm)	6	10	12	16
Yield stress (MPa)	435	482	532	528
Ultimate strength (MPa)	535	573	715	707

*Carried out at the College of Engineering, Al-Mustansiriya University

Table (3): Properties of the different types of (RPC and NC) mixes.

Mix Type	Cement kg/m^3	Sand kg/m^3	Gravel kg/m^3	Silca fume * %	Silica fume kg/m^3	w/c	Viscocrete PC20* %	Steel fiber content** %	Steel fiber content kg/m^3
RPC0	900	990	0	25	225	0.18	5	0	0
RPC0.75	900	990	0	25	225	0.18	5	0.75	78
RPC1.5	900	990	0	25	225	0.18	5	1.5	156
NC	400	600	1200	0	0	0.45	0	0	0

*Percent of cement weight. **Percent of mix volume.

Table (4): Details of tested columns.

Column designation	Concrete type	Longitudinal* reinforcement	Longitudinal reinforcement ratio (ρ) %	Steel fiber (%)
NC-10-00	Normal	4 Ø10	2.2	0
NC-12-00		4 Ø12	3.2	
NC-16-00		4 Ø16	5.5	
RPC-10-00	Reactive Powder	4 Ø10	2.2	0
RPC-12-00		4 Ø12	3.2	
RPC-16-00		4 Ø16	5.5	
RPC-10-0.75	Reactive Powder	4 Ø10	2.2	0.75
RPC-12-0.75		4 Ø12	3.2	
RPC-16-0.75		4 Ø16	5.5	
RPC-10-1.5	Reactive Powder	4 Ø10	2.2	1.5
RPC-12-1.5		4 Ø12	3.2	
RPC-16-1.5		4 Ø16	5.5	

*All specimens have closed stirrups of **Ø6@120.**

Table (5): Strength characteristics of tested columns.

Column designation	Compressive strength f_{cu} (Mpa)	Ultimate load (kN)	Maximum lateral displacement (mm)	First crack load (kN)
NC-10-00	39	83	8.05	6
NC-12-00		92.5	3.88	7
NC-16-00		102.5	5.02	13
RPC-10-00	89	122	9.15	17.5
RPC-12-00		137.5	6.25	24
RPC-16-00		157.5	5.6	32
RPC-10-0.75	107	168	8.67	26
RPC-12-0.75		172	5.91	35
RPC-16-0.75		192	5.35	50
RPC-10-1.5	120	227	14.6	32.5
RPC-12-1.5		254	8.4	40
RPC-16-1.5		287	6.9	53

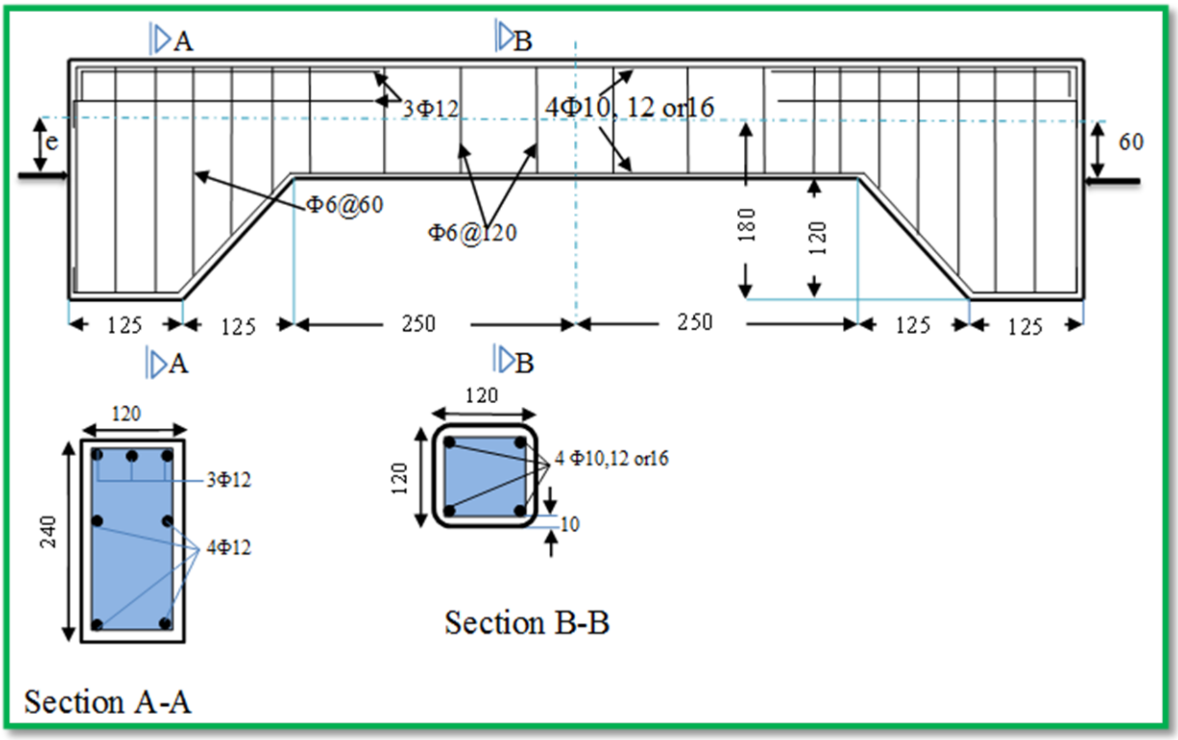

Figure (1): Details of specimen (All dimensions in mm).

Figure (2): Testing machine.

Figure (3): Loading cap with two grooves for eccentricity distance.

Figure (4): Test set-up and instrumentation.

Figure (5): Modes of failure and crack patterns for normal concrete columns.

Figure (6): Modes of failure and crack patterns for RPC columns without steel fiber.

Figure (7): Modes of failure and crack patterns for RPC with 0.75% steel fibers.

Figure (8): Modes of failure and crack patterns for RPC with 1.5% steel fibers.

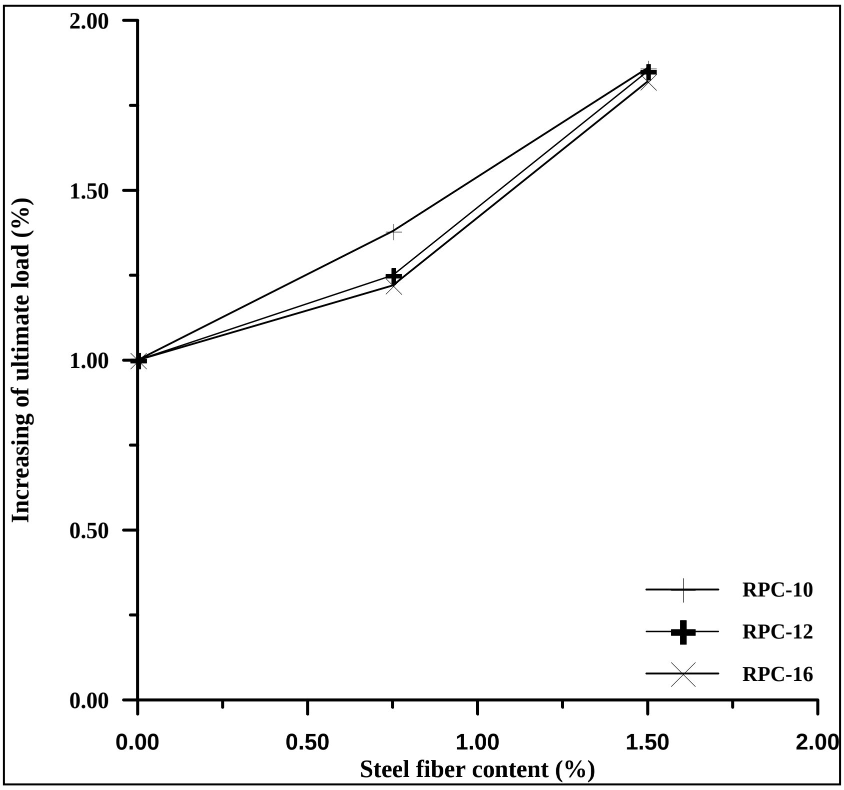

Figure (9): Relationship between steel fibers content and increasing in ultimate

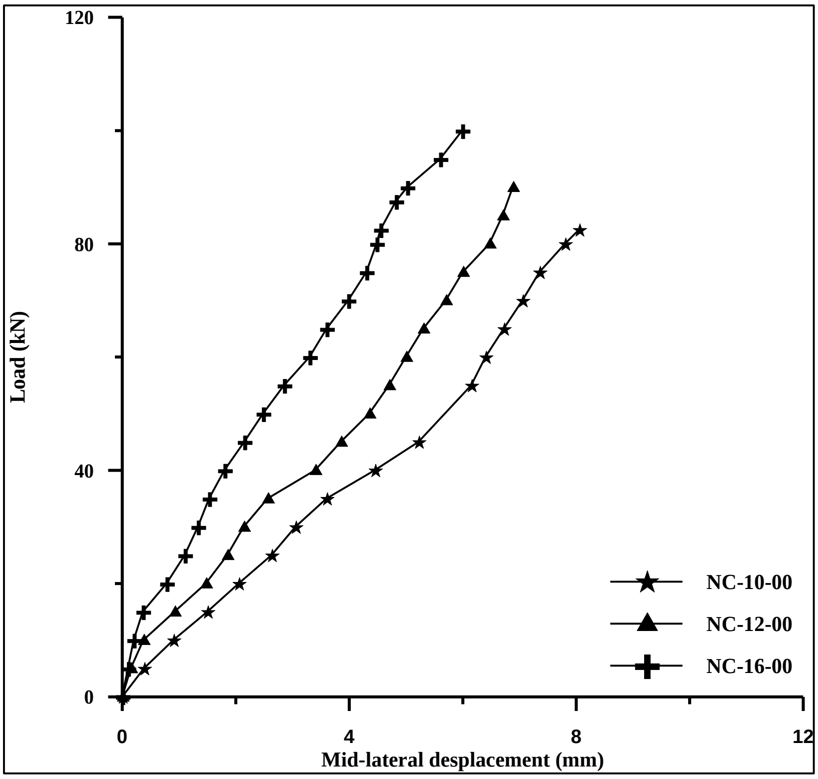

Figure (10): Load – displacement curve for normal concrete columns.

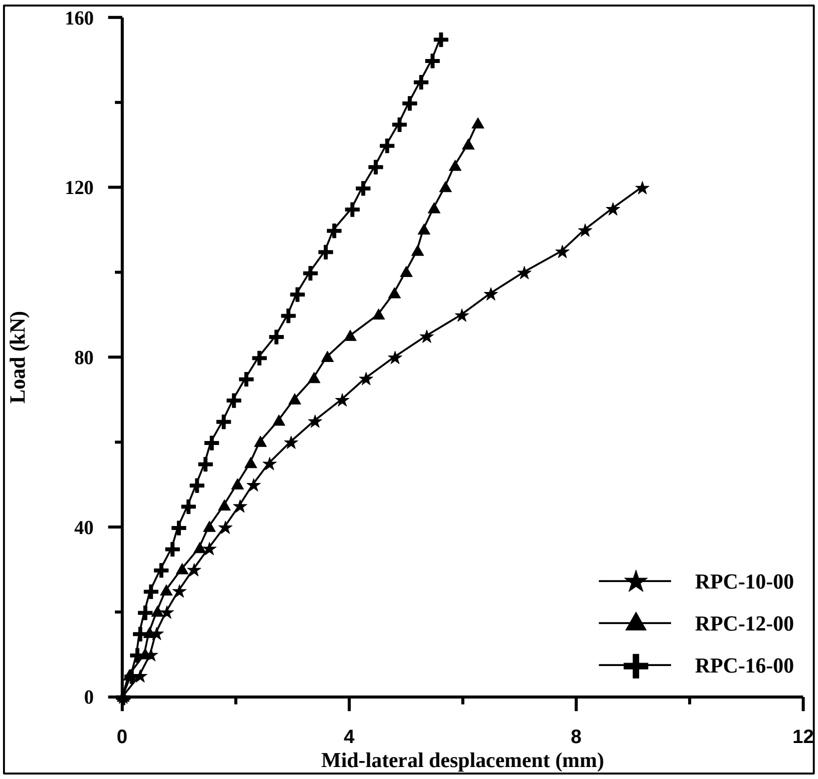

Figure (11): Load – displacement curve for RPC columns without steel fibers.

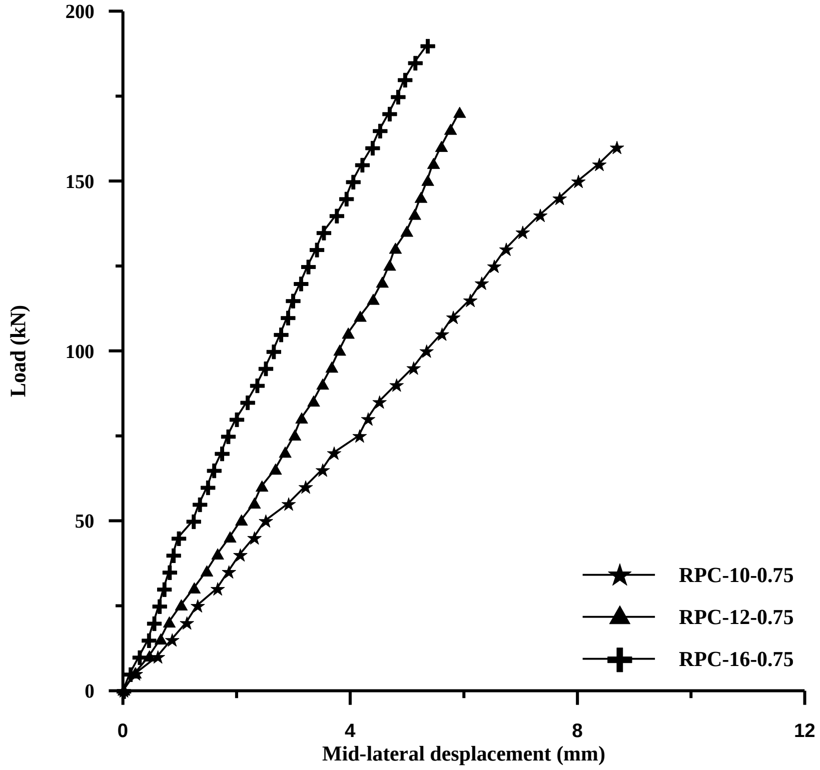

Figure (12): Load – displacement curve for RPC columns with steel fibers of 0.75%.

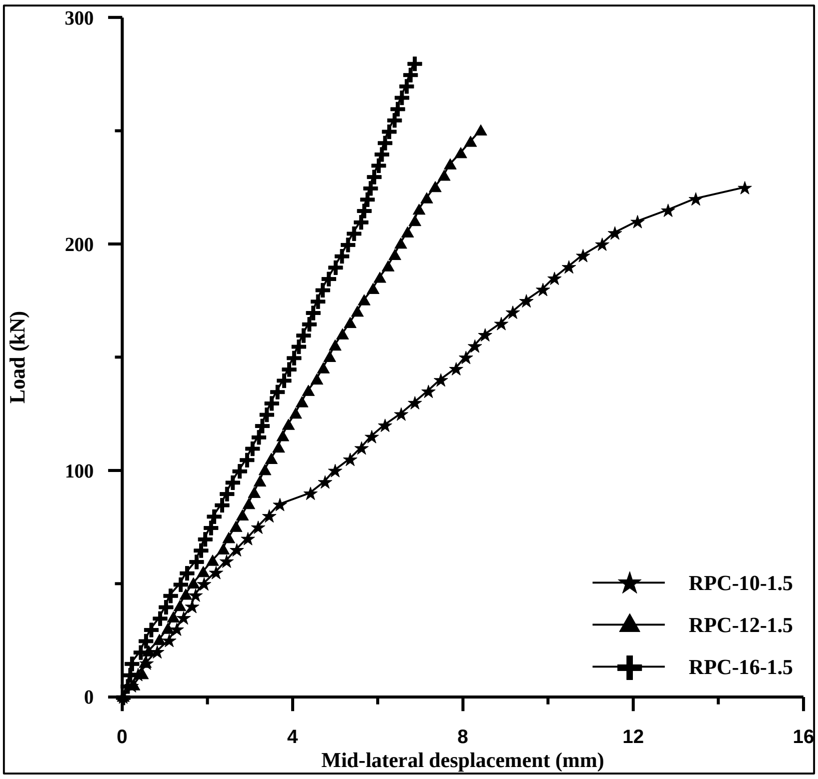

Figure (13): Load – displacement curve for RPC columns with steel fibers of 1.5%.

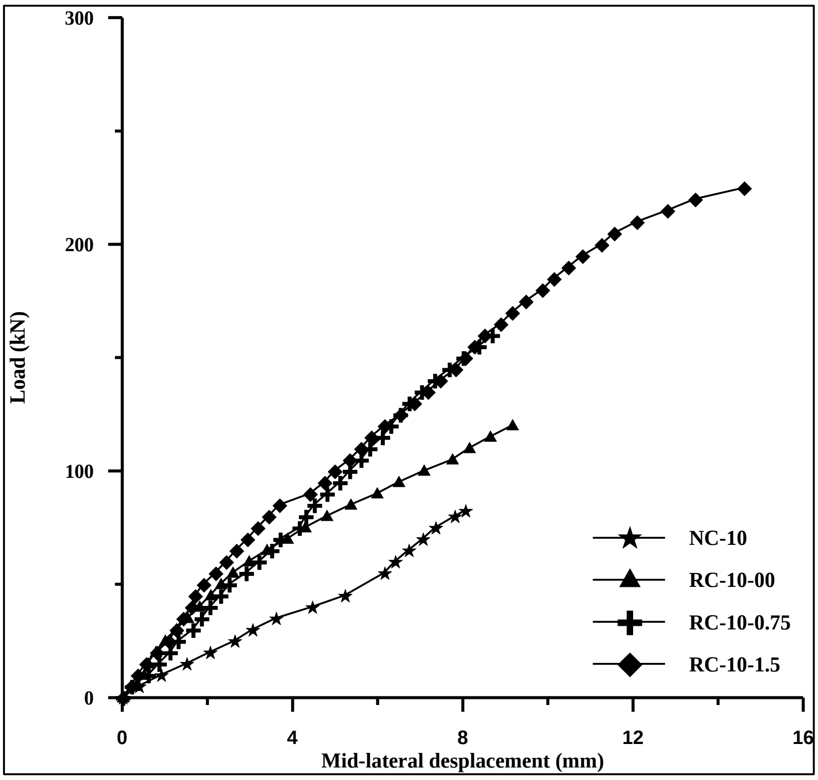

Figure (14): Load – displacement curve for columns with variable steel fibers content.

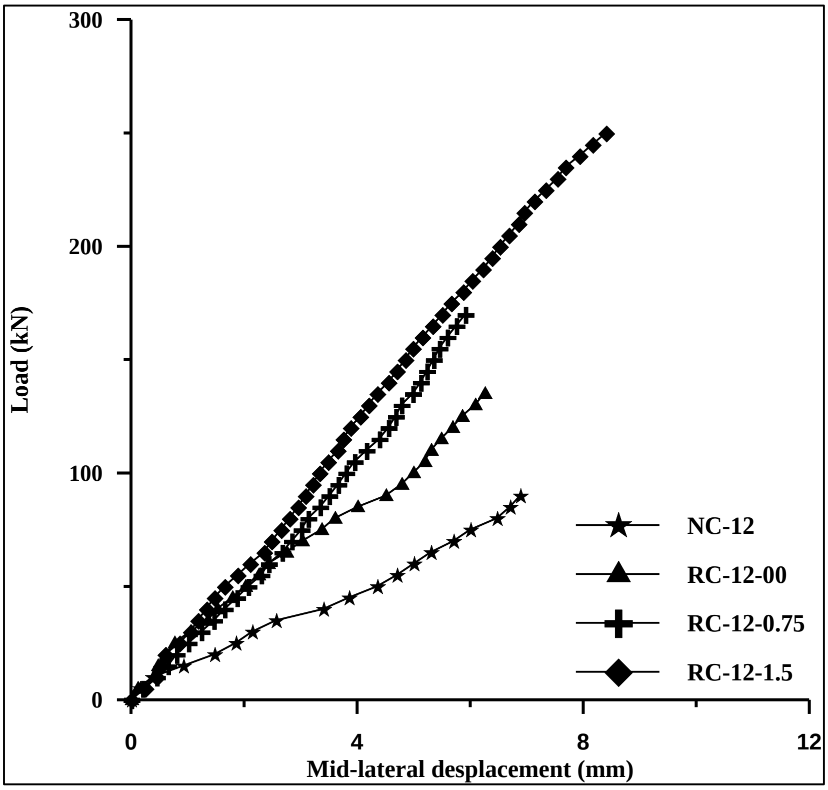

Figure (15): Load – displacement curve for columns with variable steel fibers content.

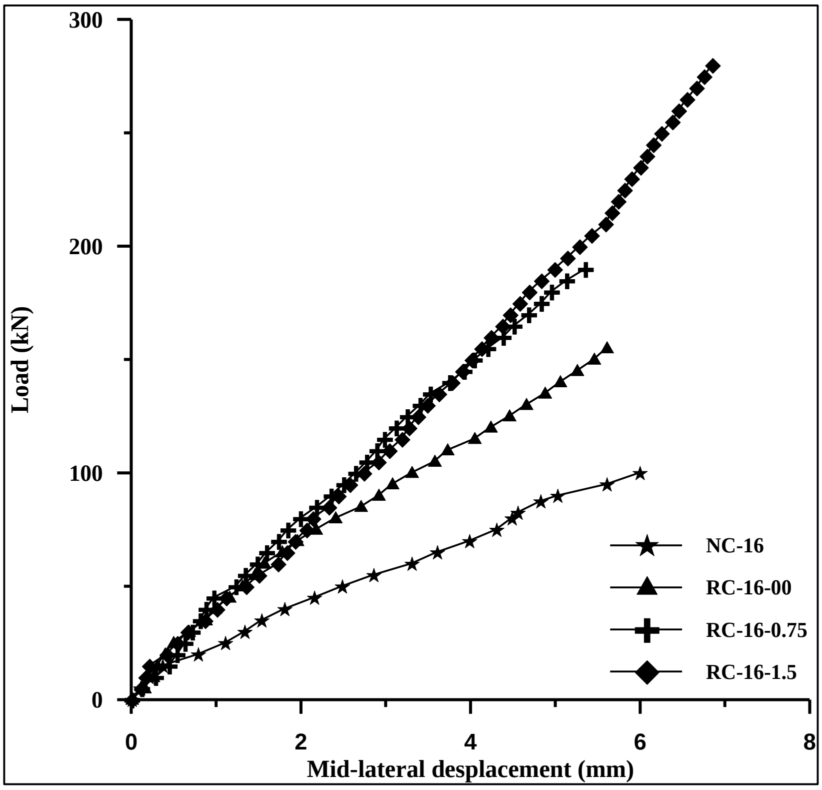

Figure (16): Load – displacement curve for columns with variable steel fibers content.

سلوك اعمدة خرسانة المساحيق الفعالة تحت تاثير احمال الانضغاط اللامركزية

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مدرس / كلية الهندسة / الجامعة المستنصرية

الخلاصة:

ان مقاومة الاعمدة الخرسانية تتحكم بها مقاومة المواد المستخدمة وشكل المقطع. استخدام تقنية خرسانة المساحيق الفعالة اصبحت شائعة لمقاومتها الفائقة, صلادتها وديمومتها. تم اجراء دراسة عملية على اعمدة من خرسانة المساحيق الفعالة والمعرضة الى احمال لامركزية. اثنى عشر عمود تم تجهيزها بمقطع مربع 120 ملم في وسط العمود مع تحدب في نهاياته لتسليط الحمل اللامركزي. النماذج فحصت لحد الفشل لتقييم تاثيرات نوع الخرسانة المستخدمة، وجود الالياف الحديدية ونسبة حديد التسليح الطولي فيها. نتائج عملية على المقاومة, التشوهات الجانبية وشكل الفشل تم الحصول عليها من خلال كل فحص. تحليل النتائج العملية اظهرت بان استخدام خرسانة المساحيق الفعالة سببت اختلاف في المقاومة القصوى وشكل الفشل. كذلك وجود الالياف الحديدية فيها يعتبر طريقة فعالة لمنع تقشر الغطاء الخرساني وزيادة في المطيلية كما وان الزيادة في نسبة التسليح الطولي تعرقل انبعاج النموذج وتزيد من مقاومته.