Behavior of Axially Loaded Reactive Powder Concrete Columns

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Abstract

In this research the behavior of reactive powder concrete short (RPC) columns with and without reinforcement was reported. Eight specimens of RPC short columns with reinforcing steel and without reinforcing steel are examined and compared with eight specimens of high strength reinforced concrete (HSC) short columns. The columns samples are divided into two groups. The dimensions of the first group are (100 *100* 400) mm and the dimensions of the second group are (70*70*400) mm. The lateral reinforcing steel, which are used in the reinforced concrete short columns, that are tied or spirally reinforced. Experimental data for strength, lateral and axial deformation, ductility and the failure mode were obtained for each test. The failure load of RPC short columns without reinforcing steel is more than the failure load of RPC short columns with reinforcing steel by about 1.222 time for the two groups. The failure mode of RPC short columns without reinforcing steel is shear failure, while the failure mode of RPC short columns with reinforcing steel is rupture of some ties. The carrying capacity of RPC columns with and without reinforcing steel as compared to corresponding HSC columns is about 3.6 and 4.4 times respectively.

Keywords: Concentric load, Ductility, High strength concrete, Reactive powder concrete, Short columns.

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سلوك الاعمدة المصنوعة من خرسانة المساحيق الفعالة والمحملة محوريا

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الخلاصة
في هذا البحث تم دراسة سلوك الاعمدة القصيرة المصنوعة من خرسانة المساحيق الفعالة الحاوية على حديد التسليح والخالية منه حيث تم فحص ثمانية عينات من خرسانة المساحيق الفعالة (RPC)لأعمدة قصيرة حاوية على حديد التسليح وخالية من حديد التسليح و مقارنة النتائج مع ثماني عينات من اعمدة قصيرة مصنوعة من الخرسانة المسلحة عالية المقاومة (HSC). تم تقسيم هذه الأعمدة إلى مجموعتين: أبعاد المجموعة الأولى هي (١٠٠ * ١٠٠ * ٤٠٠) ملم وأبعاد المجموعة الثانية هي (٧٠ * ٧٠ * ٤٠٠) ملم وباستخدام التسليح العرضي من نوع الاطواق اوالحلزون. وقد تم الحصول على النتائج العملية للتحمل، والتشوه المحوري والعرضي، والمطيلية وشكل نموذج الفشل. وقد وجد ان الحمل الاقصى للأعمدة القصيرة من خرسانة المساحيق الفعالة بدون حديد التسليح أكثر من الأعمدة القصيرة لخرسانة المساحيق الفعالة الحاوية على حديد التسليح بنحو ١.٢٢٢ مرة للمجموعتين. كما ان نوع الفشل للأعمدة القصيرة من خرسانة المساحيق الفعالة بدون حديد التسليح هو فشل القص، في حين ان نوع الفشل للأعمدة القصيرة من خرسانة المساحيق الفعالة الحاوية على حديد التسليح هو فشل في بعض الاطواق. كما ان نسبة تحمل اعمدة خرسانة المساحيق الفعالة الحاوية على حديد التسليح و الخالية من حديد التسليح مقارنة بمثيلاتها من الخرسانة المسلحة العادية تقدر بحوالي ٣.٦ و ٤.٤ مرات على التوالي.

1.Introduction

The introduction of reactive powder concrete **(RPC)** in civil engineering structures has progressed at a rapid rate in recent years. RPC is a relatively new cementinious material. It is main features include a high percentage ingredient of Portland cement, very low wat er-to-binder (cement + silica fume) ratio which ranges from 0.15 to 0.25, a high dosage of superplasticizer, and the presence of very fine crushed quartz and silica fume. **RPC**, represents one of the most recent technological leaps witnessed by the construction industry. Among already built outstanding structures, **RPC** structures lie at the forefront in terms of innovation, aesthetics and structural efficiency. The unique properties for **RPC**, make it extremely attractive for structural applications. Column is enlarging of foundation so using RPC will reduce the weight of column cause reduce settlement of foundation.[1]

As construction and material costs escalate, demand has increased for stronger materials that occupy less space, provided the small initial capital cost of the structure is offset by the more significant economic benefit of increased rental

space. **RPC** is an ultra-high-strength, low porosity cement-based composite with high ductility. Unlike conventional concrete, **RPC** containing a significant quantity of steel fibers exhibits high ductility and energy absorption characteristics[2,3]. Conventional concrete is a heterogeneous material with components from fine cement to coarse aggregates each having different strengths and moduli of elasticity. Under a system of forces, all of these component materials deform at different rates. **RPC** is composed of particles with similar elastic module and is graded for dense compaction, thereby reducing the differential tensile strain and enormously increasing the ultimate load carrying capacity of the material. Interest in ultra-high-strength cement-based materials is not solely because of their increased strength. They possess other high-performance properties, such as low permeability, limited shrinkage, increased corrosion and abrasion resistance, and increased durability.[4,5] These are all valuable characteristics used in the construction industry for concrete structures. The technology offers the possibility to build structural elements without passive reinforcement (for example, conventional steel ties in columns) in structural elements and combines innovation, lightness, and high durability. RPC may also be used from the standpoint of weight reduction, for its architectural aspects, or for its high resistance to blast and impact loadings.[6]

The objective of this research is to examine the behavior of RPC short columns with and without conventional reinforcement and to determine any increase in the magnitude of strength and ductility provided by RPC columns, with and without conventional reinforcement compared with HSC columns. Sixteen columns were cast and tested under concentric loading (two column specimens for each type) used in this study and the results are reported herein. The test results form an important data set for future development of design models for RPC columns.

2.Experimental Program

The experimental program consists of casting and testing four column models of dimensions (70*70*400) mm with aspect ratio 5.714 and four columns models of dimensions (100*100*400) mm with aspect ratio 4 of RPC with and without reinforcing steel to investigate the behavior of these models when subjected to axial loading. The program included two column specimens for each type of short column used. Also the experimental program involvs three cylinders of diameter 100 mm and height 200 mm of RPC to know the compressive strength. The experimental program consists of casting and testing four column models (70*70*400)mm and four columns models (100*100*400) mm of HSC to compare these columns' behavior when subjected to axial loading with RPC columns models.

2.1.Detail of Specimens

The RPC column models are classified into two groups. The first group consists of four specimens. The dimensions of every specimens are 100*100*400 mm. The first two specimens are cast of RPC with volume fraction of steel fiber 2% and without reinforcing steel. While the second two specimens are cast of RPC with volume fraction of steel fiber 2% with longitudinal reinforcing steel 0.0113 of cross section area and lateral ties of 4 mm at 60 mm spacing. The second group consists of four specimens. The dimensions of every specimen are (70*70*400) mm. The first two specimens of this group are cast of RPC with steel fiber 2% of cement weight and without reinforcing steel. The second two specimens are cast of RPC with volume fraction of steel fiber 2% and with longitudinal reinforcing steel of 0.0103 of cross sectional area and lateral ties of 4mm at 60 mm spacing. The HSC specimens are classified into two groups. The first group consists of four specimens of dimensions (100* 100*400) mm and concrete strength f'c =60 MPa with longitudinal reinforcing steel 0.0113 of cross section area and lateral ties and spiral of 4 mm at 60 mm spacing . The second group consists of four specimens of dimensions (70*70*400) mm and concrete strength f'c =60 MPa with longitudinal reinforcing steel of

0.0103 of cross sectional area and lateral ties of 4 mm at 60 mm spacing as shown in Fig. (1). Table (1) illustrates all short column details. In this table the concrete types are identified as: (RPC) reactive powder concrete, (RRPC) reactive powder concrete with reinforcement and (HSC) high strength concrete while the cross sectional dimension of column are identified by a number of 70 and 100 . Also the type of lateral reinforcement are identified by T for tie lateral reinforcement and S for spiral lateral reinforcement (i.e., RRPC-70T stands for RPC column with reinforcement and cross section 70mm*70mm and tie lateral reinforcement, while HSC-100S stands for HSC column with cross section 100mm*100mm and reinforced by main reinforcement and lateral spiral reinforcement).

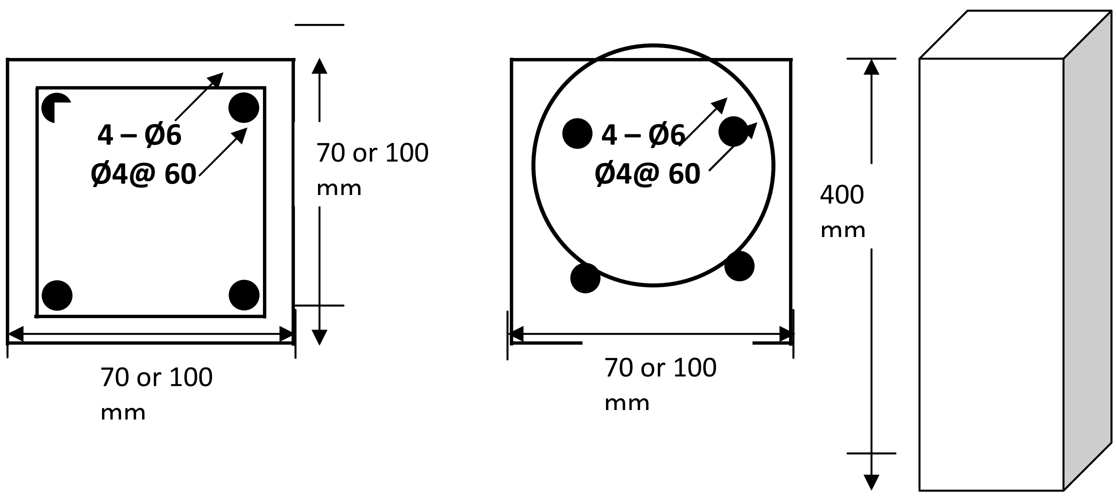

Fig.(1) Details and Dimensions of the Tested Columns.

Table (1): Details of the Tested Columns Specimens and Results.*

Specimens	Dimensions (mm)	f'c (MPa)	Longitudinal steel bars	Tie or spiral bars	Ultimate load (kN)
RPC-100	100*100*400	132	-----	-----	880
RRPC-100T	100*100*400	132	4 – Ø6	**Ø4@ 60mm**	**720**
RPC-70	70*70*400	132	-----	-----	440
RRPC-70T	70*70*400	132	4 – Ø4	**Ø4@ 60mm**	**360**
HSC-100S	100*100*400	60	4 – Ø6	**Ø4@ 60mm**	**200**
HSC-100T	100*100*400	60	4 – Ø6	**Ø4@ 60mm**	**180**
HSC-70S	70*70*400	60	4 – Ø4	**Ø4@ 60mm**	**110**
HSC-70T	100*100*400	60	4 – Ø4	**Ø4@ 60mm**	**100**

*The test program included 2 specimens for each type of column specimen used.

2.2.Materials and Mix Design

The cement used in this research was Tasloja ordinary Portland cement (ASTM Type I) manufactured in Iraq**.** Densified silica fume from Sika Materials Company in Baghdad has been used as a mineral admixture added to the mixtures. The used percentage is 25% and 10% of cement weight (as an addition, not as replacement of cement) for RPC and HSC mixes, respectively.

Fine silica sand known as glass sand is used for the the RPC mix. This type of sand is by-produced in Al- Ramadi Glass factory. The fineness modulus is 2.32. Al-Ukhaidher fine sand grading and limits of ASTM C33[(7)] and well-graded coarse aggregate with a maximum size of 12 mm are used for the HSC mix. The end-hooked steel fibers manufactured by Bekaert Corporation were used in RPC mix with volume fraction (V_f) of 2%. The fibers have the properties described in **Table (2).**

A new generation of modified superplasticizer, Sika® Viscocrete® PC20[8], is used in this research. The mix design of RPC using local constituent is 1:1: 0.25 (cement :sand :silica fume) with water cement ratio 0.2 plus 2.0% by weight of binder (Cement + Silica Fume)of Sika® Viscocrete® PC20 admixture. While the mix design of HSC using local constituent is 1:1.3:2.0 (cement :sand :gravel) [9] with water cement ratio 0.3 plus 2.0% by weight of binder (Cement + Silica Fume) of Sika® Viscocrete® PC20 admixture.

In this study, minimum steel reinforcement ratios were used (0.0113 for short columns with cross section 100*100 mm and 0.0103 for short columns with cross section 70*70 mm) as longitudinal reinforcement. Yield strengths of the 4 and 6 mm plain steel bars were 638 and 520, respectively.

2.3.Mixing, Curing and Fabrication

All the constituents were batched by an electronic balance and mixed in a horizontal pan mixer for about 10 minutes. Water and superplasticizer is added to the rotary mixer and the whole mix ingredients were mixed for a sufficient time. For the RPC mix the fibers were uniformly distributed into the mix slowly in 3 minute during mixing process, and then the mixing process continued for an additional 1 minutes. Three 200mm height by 100 mm diameter cylinders were prepared from each batch and used for determining the compressive strength (f'_c) of RPC and HSC at the age of 28 days.

The columns are prepared for vertical casting using wooden molds. Each mold consists of a bed and four movable sides. The sides were fixed to the bed by screws.

The hardened specimens were demolded after 24 hours. The RPC specimens were heat cured at about 70°C for 48 hours in a water bath. After that the samples were left to be cooled at room temperature, then placed in water and left until the end of water curing at 28 days.

Table (2): Properties of the Steel Fibers*

Description	End-Hooked
Length	13
Diameter	0.4
Density	7800 kg/m^3
Tensile Strength	1100 MPa
Aspect Ratio	32.5

*Supplied by the manufacturer

2.4.Loading Setup and Measurements

All of the specimens were tested under increasing concentric load up to failure by using a calibrated electrohydraulic testing machine (Avery) with a maximum range capacity of 2500 kN.

The vertical displacements along the columns were measured using dial gage. Demec points were used to measure the surface strains of concrete. Two demec gage points were mounted at spacing of 100mm at the column mid-height along the column vertical axis to measure longitudinal compressive strains at two perpendicular faces of the column. Also additional two demecs were mounted horizontally at spacing of 50mm to measure lateral strains at two perpendicular faces of the column.

Details of demec strain device distribution are shown in **Fig. (2).** The strain measuring extensometer was calibrated before the testing procedure.

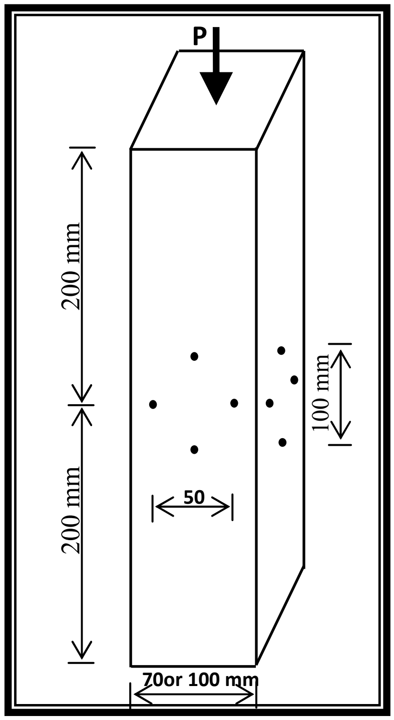

Fig. (2) Distribution of Demec Points on Column Specimens

3.1.Observed Failure Mode of Column Specimens

During testing of column specimens up to failure, it was observed that failure of RPC columns without reinforcement is by the formation of the longitudinal cracks at certain location followed by cracks which propagated to upper ends of columns. It was also noticed that for RPC specimens without reinforcement a sudden explosive type of failure occurs. In contrast, RPC columns cast with reinforcement (minimum longitudinal and lateral reinforcement) failed in a ductile manner, small crack width and much less cover spalling were observed for the RPC columns with reinforcement when compared to the RPC columns without reinforcement.

It could be noticed that the presence of steel fibers resulted in bulging of some parts of the RPC columns relative to HSC columns without steel fibers, then failure occurred by rupture of one or more ties and outward buckling of the longitudinal bars as shown in **Fig.(3).**

For RPC reinforced columns, it can be seen that the steel fibers played a significant role in preventing concrete cover from early spalling. This is because steel fibers cross the cracks preventing them from further widening and allowing other cracks to form at other locations. It seems that the presence of steel fibers is highly effective at load stages after peak where it is observed that the RPC column bulging continues to increase without loss of column integrity which resulted in increasing tensile stresses in the ties leading to rupture of some of these ties, as shown in **Fig.(3).**

Fig.(3) Failure Mode of Column Specimens

3.2.Stress-Strain Relationship of Columns

Typical stress-strain (axial and lateral) curves of concentrically loaded square short RPC columns with and without reinforcement measured using axial and lateral demec devices are shown in **Fig.(4).**

The strains in the axial and lateral directions of RRPC (reinforced RPC) columns are greater than the strains in the axial and lateral direction of RPC columns, which means greater stiffness of RPC compared with the RRPC. However, some columns (e.g. RPC-10T) showed a stiffer response in axial stress-strain beyond the initiation of cracks, compared with the same columns but with reinforcement.

Fig.(4) also illustrates the effect of the columns cross section dimensions on the stress-strain curves (axial and lateral). It can be noted that the variation of the columns aspect ratio significantly affects the pre and post-cracking stages.

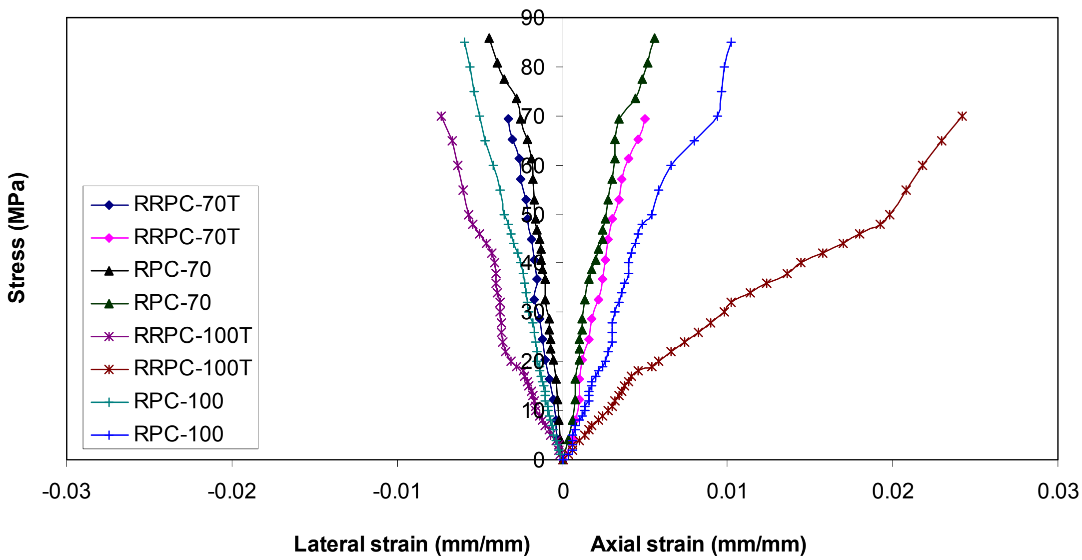

Fig.(4) Stress-Strain (Axial and Lateral) Curves of Concentrically Loaded Short RPC Columns With and Without Reinforcement.

3.3Columns Ductility

Ductility is the ability of columns to deform without significant loss of strength. The ductility of the tested columns were computed using the procedure developed by Pessiki and Pieroni [10] in **1997** which defined column "displacement ductility" as the ratio of the axial displacement of the column at an axial load corresponding to 85 percent of the maximum axial load on the descending branch of the axial load-deflection curve, Δ85 to the displacement at the limit of elastic behavior, Δy. **Fig.(5)** illustrates how the limit of elastic behavior, Δy is determined. Typical load-displacement curves of concentrically loaded square short RPC and HSC columns with and without reinforcement measured using dial gage device are shown in **Figs.(6)** and **(7).**

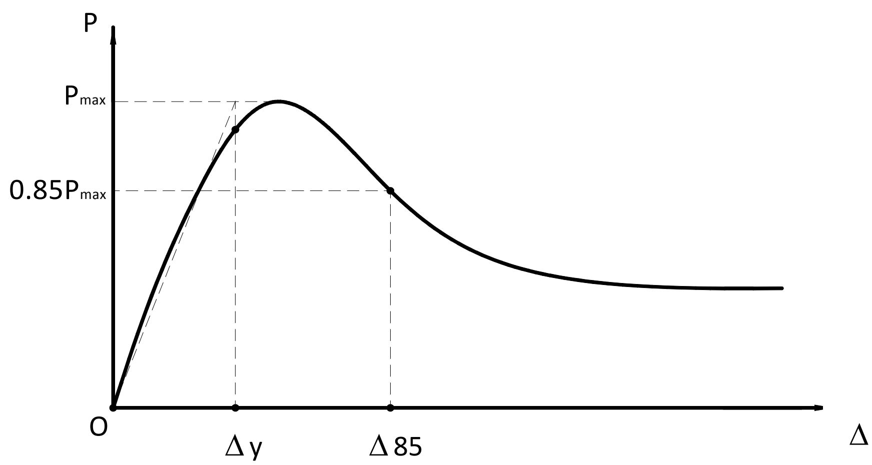

Fig.(5) Determination of Column Displacement Ductility [10].

In **Table (3)** the computed ductility of the tested RPC and HSC columns with and without reinforcement is shown. The comparisons indicate that the ductility for both RPC and RRPC columns is greater than HSC columns by about (100-130)% . This is due to the inclusion of steel fibers in RPC which enhances the ductility of columns with and without reinforcement.

Table (3): Columns Displacement Ductility

Specimens	Displacement Ductility
RPC-100	3
RRPC-100T	2.6
RPC-70	2.8
RRPC-70T	2.5
HSC-100S	1.3
HSC-100T	1.2
HSC-70S	1.2
HSC-70T	1.1

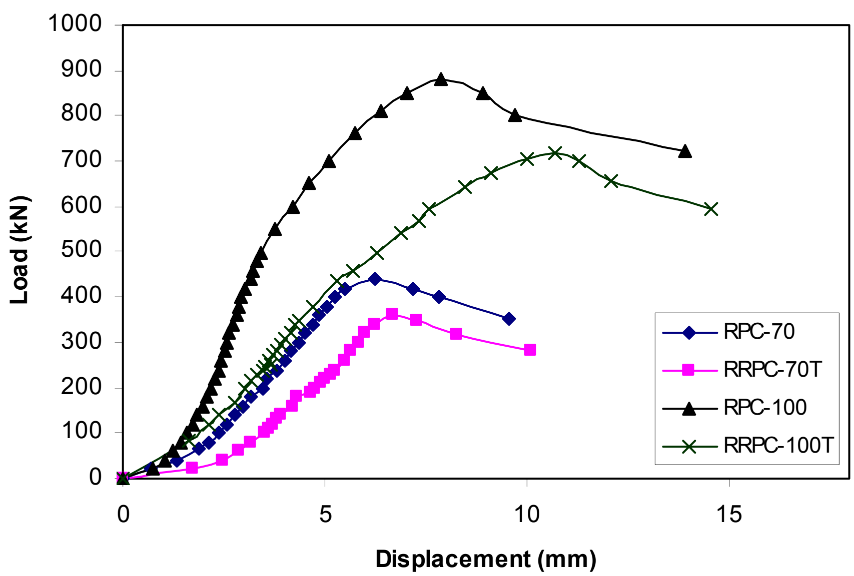

Fig.(6) Load-Displacement Curves of Concentrically Loaded Short RPC Columns With and Without Reinforcement.

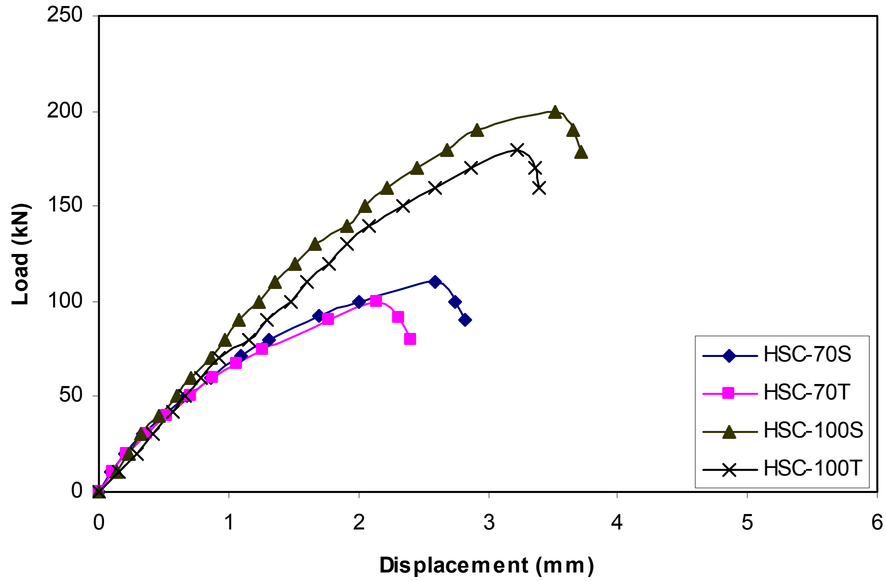

Fig.(7) Load-Displacement Curves of Concentrically Loaded Short HSC Columns.

4.Conclusions

1. The failure load of RPC short columns without reinforcing steel is more than the failure load of RPC short columns with reinforcing steel (minimum) by about 1.222 time. It was also noticed that for RPC specimens without reinforcement a sudden explosive type of failure occurs. Therefore it is possible to use RPC column specimens that containing no conventional steel reinforcement by using an appropriate safety factor. Thus saving time, effort and wages of the steel workers.

2. The carrying capacity of RPC columns without reinforcing steel and with reinforcing steel (minimum) is more than the carrying capacity of high strength reinforced concrete columns by about 4.4 and 3.6 times, respectively.

3. The failure mode of RPC short columns without reinforcing steel is shear failure, while the mode of failure of RPC short columns with reinforcing steel (minimum) is rupture of some of the ties.

4. The strains in the axial and lateral directions of RRPC (reinforced RPC) columns are greater than the strains in the axial and lateral directions of RPC columns, which means that RPC columns have greater stiffness than RRPC.

5. The comparisons indicate that the ductility for both RPC and RRPC columns is greater than HSC columns by about (100-130)%.

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