

The Shrinkage Cracking Behavior in Reinforced Reactive Powder Concrete Walls

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Abstract

In this study, the reduced scale wall models were used (they are believed to resemble as much as possible the field conditions) to study the shrinkage behavior of reactive powder concrete (RPC) base restrained walls. Six base restrained RPC walls were casted in different length/height ratios of two ratios of steel fiber by volume in Summer. These walls were restrained by reinforced concrete bases to provide the continuous base restraint to the walls.

The mechanical properties of reactive powder concrete investigated were; compressive strength between (75.3 – 140.1) MPa, splitting tensile strength between (5.7 – 13.9) MPa, flexural tensile strength (7.7 – 24.5) MPa, and static modulus of elasticity (32.7 – 47.1)GPa.

Based on the observations of this work, it was found that the cracks did not develop in the reduced scale of the reactive powder concrete (RPC) walls restrained from movement at their bases for different L/H ratios (2, 5, and 10) and for two ratio of steel fiber (1% & 2%) during 90 days period of drying conditions. Moreover, the shrinkage values increase toward the edges. Based on the results of this work, the increase in the maximum shrinkage values of walls with 1% steel fiber were (29%, 28%, 28%) of the maximum shrinkage values of walls with 2% steel fiber of length/height ratios of (2, 5, and 10) respectively.

The experimental observation in beam specimens showed that the free shrinkage, tensile strain capacity and elastic tensile strain capacity (at date of cracking) of beams with 1% steel fiber were higher than the beams with 2% steel fiber by about (24%), (45%) and (42%) respectively.

Key words : Reactive Powder Concrete, Drying Shrinkage , Maximum Shrinkage Values and Location in the Wall Base Restraint.

الخلاصة

في هذا البحث تم استخدام نماذج بحث مصغرة يعتقد بأنها توفر ظروفًا مشابهة للظروف الطبيعية الموقعية لدراسة سلوك الانكماش للجدران المصنوعة من خرسانة المساحيق الناعمة. تم صب ستة جدران لنسب مختلفة من الطول/الارتفاع بوجود ألياف الحديد بنسبتين وقد تم تقييد تلك الجدران بواسطة أساس خرساني.

الخواص الميكانيكية للخرسانة التي تضمنها البحث، مقاومة الانضغاط، مقاومة الشد (الانشطار)، مقاومة الشد (الانحناء)، ومعامل المرونة. تراوحت القيم بالنسبة لخرسانة المساحيق الناعمة، مقاومة الانضغاط (140,1-75,3) ميكا باسكال، مقاومة الشد بالانشطار (24,5- 7,7) ميكا باسكال، مقاومة الشد بالكسر (13,9 – 5,7) ميكا باسكال، ومعامل المرونة الاستاتيكي (32,7 – 7,1) ميكا باسكال للأعمار من (3-60 يوم).

لقد تبين من خلال المراقبة إن جميع هذه الجدران ولهذه النسب من الطول/الارتفاع (10,5:2) لا تبدي تشققًا خلال فترة تعرض للجفاف قدرها (90) يوم. وكانت قيم الانكماش غالبًا ما تزداد كلما اتجهنا نحو نهايات الجدار. كانت نسب الزيادة في القيم العظمى للانكماش للجدران ذات 1% من ألياف الحديد بحوالي (29%، 28%، 28%) من القيمة العظمى للانكماش للجدران ذات 2% من ألياف الحديد لنسب الطول إلى الارتفاع (2، 5، 10) على التوالي.

وقد بينت النتائج المخبرية للعبوات الخرسانية المقيدة إن الانكماش الحر وانفعال الشد الأقصى وانفعال الشد المرن في وقت حدوث الشق للعبوات ذات 1% من ألياف الحديد أعلى مما هو عليه للعبوات ذات 2% من ألياف الحديد بحوالي (45%، 42%) على التوالي.

الكلمات مفتاحية : خرسانة المساحيق الفعالة، أعلى قيمة للانكماش وموقعها في الجدران المقيدة عند القاعدة.

Introduction

Reactive powder concrete (RPC) is a high strength ductile material formulated from a special combination of constituent materials. These materials include Portland cement, silica fume, quartz flour, fine silica sand, high-range water-reducer, water and steel fiber. RPC is considered as one of the most important products viewed by the construction industry world during the last decades in the field of producing new and improved types of concrete. This type of concrete has many distinctions properties like high strength, high ductility, high modulus of elasticity, very low permeability,

and high impact resistance as compared with the ordinary and the high performance concrete. Due to the higher cement content, the shrinkage deformation of RPC was large. The effect of the steel fibers in RPC mixtures is to reduce the shrinkage by restraining effect offered by the fibers. (Allena and Newton, 2013).

Garas *et.al.*, 2008 have reported a reduction in free shrinkage by about 50% and autogenous shrinkage by about 42% when 2% of steel fibers (by volume) is added to RPC mixture. The durability of RPC is comparable to that of the natural rocks with very low permeability and it is resistant to carbonation. After early age heat treatment, there is almost neither shrinkage nor creep.

Reactive powder concrete suffers an autogenous shrinkage strain of about 500×10^{-6} . The shrinkage is essentially the result of the chemical reactions within the RPC and is not the same as the drying shrinkage in conventional concretes. As a result, even for RPC cured at room temperatures, the great majority of the shrinkage occurs in the first 28 days after casting. (Michael, 2012).

Ian, 2000; György, 2009 found that the autogenous shrinkage of RPC is very pronounced and may reach values beyond 1200×10^{-6} . When such measurement starts e.g. at the concrete age of one day, most of the autogenous shrinkage, which develops mainly between an age of 8 to 24 hours, has already taken place and is consequently not recorded.

The microfiber reinforcement reduces the inherent brittleness of the concrete, especially RPC. Fibers spaced at the micron scale can interact with the microcracks, delay localization and increase the tensile strength of the matrix. In addition, microfiber reinforcement delays the age of the first visible crack and reduces the crack width in the restrained shrinkage tests. The performance of fiber-reinforced concrete (FRC) is governed by the ratio of the elastic modulus of the matrix, strength of fiber-matrix bond, aspect ratio (fiber length/fiber diameter) of the fiber, and the material properties of the fiber. Only relatively small amounts, usually less than 1% by volume, of fiber reinforcement can be added to the conventional concrete because the fibers significantly reduce the workability of the fresh concrete. At this dosage, the fibers can improve shrinkage cracking resistance and slightly enhance the ductility. To maximize these benefits and produce a strain-hardening response, larger doses must be added to the matrix. (Anson *et.al.*, 2002).

Experimental Work

Materials

Aljisir locally available ordinary Portland cement Type V (OPC) was used in all concrete mixtures. The chemical composition shown in Table (1). The local natural sand obtained from Najef sources in Iraq, all particles of RPC separated sand were greater than $600 \mu\text{m}$ and smaller than $150 \mu\text{m}$; and they were removed by sieving, as presented in Table (2). Micro silica made in U.A.E commix LTD; P.O. Box 5936. Sharjah was used throughout this research. A superplasticizer (high range water reducing) called Glenium 54 was used. Micro steel fibers used throughout the experimental program were manufactured by Changzhou Luqiao Building Materials Company, China.

Table (1): Chemical Composition and Main Compounds of Aljisir Cement.

Chemical Composition	Percentage by Weight	Limit of IQS No.5/1984
Lime (CaO)	63.19	----
Silica (SiO ₂)	21.19	----
Alumina (Al ₂ O ₃)	4.32	----
Iron oxide (Fe ₂ O ₃)	5.51	----
Magnesia (MgO)	1.57	5.0 (max)
Sulfate (SO ₃)	1.89	2.8 (max)
Loss on ignition (L.O.I.)	1.42	4.0 (max)
Insoluble residue (I.R.)	0.21	1.5 (max)
Lime saturation factor (L.S.F.)	0.94	(0.66-1.02)%
Main compounds (Bogue's equation)		
Tricalcium Silicate (C ₃ S)	53.84	---
Dicalcium Silicate (C ₂ S)	20.22	---
Tricalcium Aluminate (C ₃ A)	2.14	≤ 3.5
Tetracalcium Aluminoferrite (C ₄ AF)	16.75	---

Table (2): Fine Aggregate Test Result

Sieve size (mm)	RPC Separated Sand	
	Cumulative passing	Limits of IQS No.45/1984, zone 4
10	100	100
4.75	100	95-100
2.36	100	95-100
1.18	100	90-100
0.60	100	80-100
0.30	41	15-50
0.15	11	0-15
Specific gravity =	2.60	---
Absorption % =	0.72	---
Sulfate content as SO ₃ % =	0.09	≤0.5

Mix Proportions

Eight RPC trial mixes were used in this research as it is presented in Table (3) to evaluate the performance of the RPC mix in fresh and hardened state

Table (3): Mix Proportions

Trial Mix No.	Cement Kg/m ³	Sand Kg/m ³	Silica fume Kg/m ³	Micro Steel fiber Vf%	W/ b	Super plasticizer by wt. of cementious (%)	Compressive strength at 28 days(MPa)
1	950 Alasad	950	200	2	0.217	5 G54	124.51
2	950 Alasad	950	200	2	0.217	5 G51	114.23
3	950 Alasad	950	200	2	0.217	5 Sp 711	120.26
4	950 Aljisir	950	200	2	0.217	5 G54	127.84
5	950 Aljisir	950	200	2	0.217	5 G51	115.45
6	950 Aljisir	1000	200	2	0.217	5 Sp 711	126.86
7	950 Aljisir	1050	200	2	0.217	5 G54	133.43
8	950 Aljisir	1050	200	2	0.217	6 G54	128.74

Molds :

The molds in this research were as follows:

- 1- (50×50×50) mm cubes to obtain concrete specimens for compressive strength test.
- 2- (100×200) mm cylinders to obtain concrete specimens for splitting tensile strength and modulus of elasticity test.
- 3- (100×100×300) mm prisms to obtain concrete specimens for flexural tensile strength test.
- 4- End restraint molds which have a channel section with a necking at the mid- span with the dimension shown in Figure (1). This mould was used to determine free shrinkage, creep, tensile strain capacity and elastic tensile strain capacity.

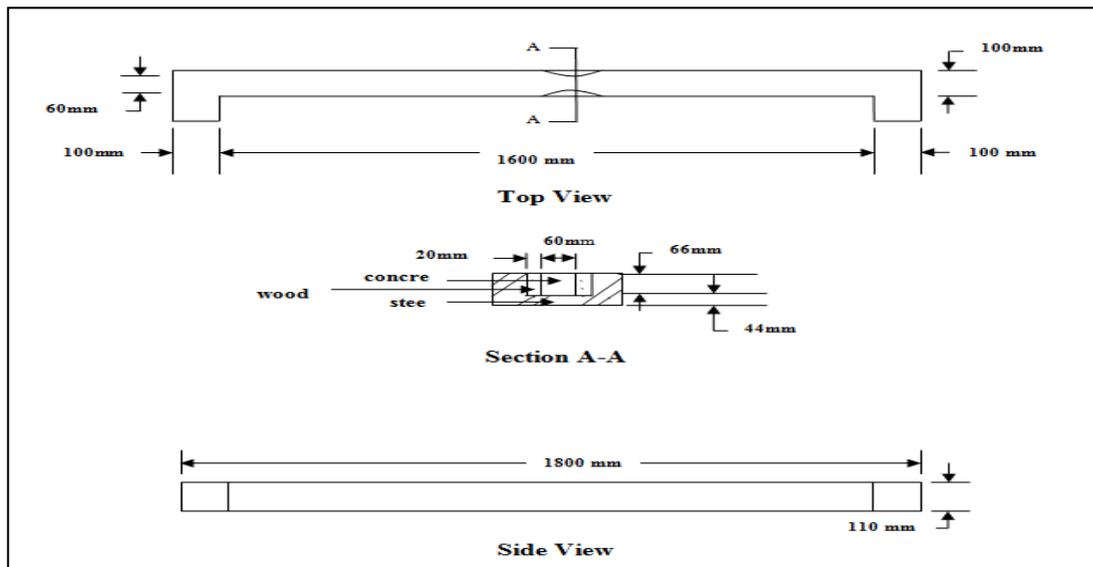


Fig. (1): Schematic Diagram of the End Restrained Beam.

Concrete Base

Three identical reinforced concrete bases were cast, to provide the continuous base restraint to the walls. The first base dimensions were (2.5 x 0.75 x 0.25)m (length x width x height respectively), and the other two bases dimensions were (5.5 x 0.75 x 0.25)m (length x width x height respectively). Figure (2) shows the cross section of concrete base and steel dowels.

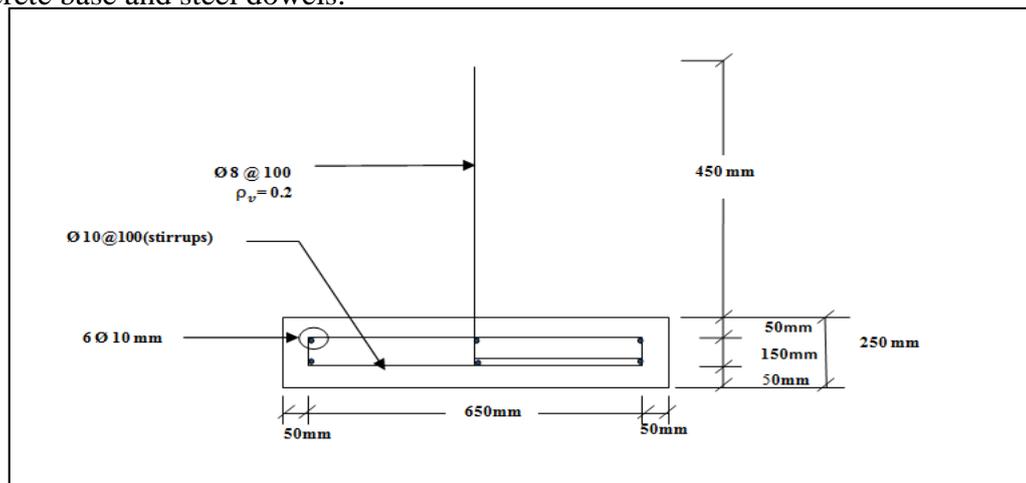


Fig. (2): The Schematic Diagram of the Restraining Base with the Welded Dowels and Roughness of the Base.

Wall Notation

The RPC walls which contain a six 50 mm thickness concrete walls reinforced with a steel fiber ratio (1% and 2%) were casted in Summer season, as shown in Table(4).

Table (4): Walls Characteristics.

Wall Notation	Length mm	Height mm	L/H Ratio	Steel fiber content $V_f\%$
RPC2-1*	1000	500	2	1
RPC2-2	1000	500	2	2
RPC5-1	2500	500	5	1
RPC5-2	2500	500	5	2
RPC10-1	2500	250	10	1
RPC10-2	2500	250	10	2

*RPC2-1 RPC: Reactive powder concrete wall 2: L/H ratio 1: Steel fiber content $V_f\%$

Mixing and Casting of Walls

The mixing method was important to obtain the required necessary homogeneity and workability of the concrete mix. RPC was mixed by putting cementitious materials (the required quantity of cement was mixed in dry state with the micro silica fume) into a container and dry mixed using a spiral hand mixer. Then, fine sand was added into the container and they were mixed. The required amount of water and super plasticizers were added and the mixing process continued, and then when the consistency is achieved, the fibers were added slowly and mixing process continued until the dispersion was evident.

Curing and Exposure to Drying

To prevent plastic shrinkage cracking due to rapid evaporation from the upper surface of the walls, the wetted hessian sheets and the polythene sheets were used to cover the walls after the final lift was cast. The formwork was removed after 24 hours from the casting and then the walls were covered with the wetted hessian sheets and the polythene sheets for 7 days. The same curing procedure was applied to cubes, cylinders, prisms and beams.

Results and Discussions

Restrained Shrinkage of the Walls

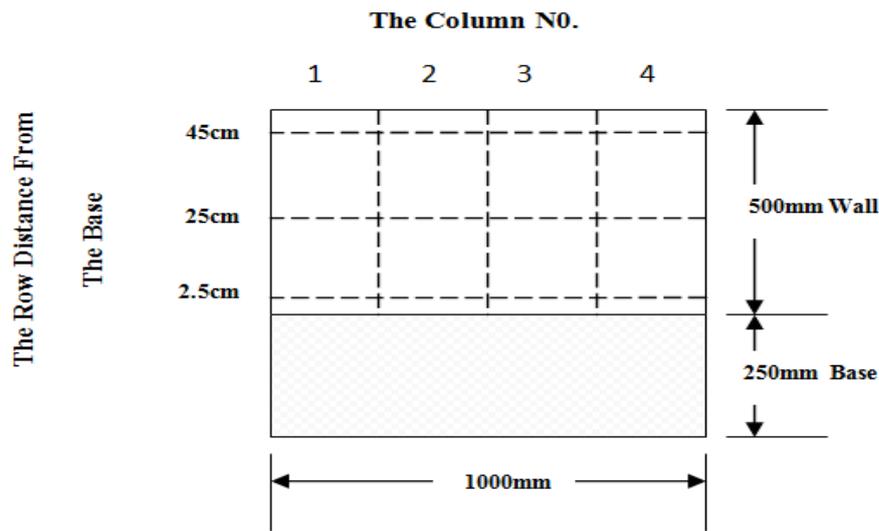
The measurement of longitudinal movement of the walls was carried out to investigate the effect of base restraint of the walls on the shrinkage behavior. These measurements were conducted for a drying period of 90 days in Summer. Table (5) and Figures (3 to 8) show the restrained shrinkage strain development with age at 3 rows (25, 250 and 450 mm distance from the base) for the walls of 500mm height and 1000mm length, 3 rows (25, 150 and 450 distance from the base) for the walls of 500mm height and 2500mm length and 1 row (200mm distance from the base) for the walls of 250mm height and 2500mm length.

Table(5) The maximum restrained shrinkage strains at top row and loss of restraint of the walls.

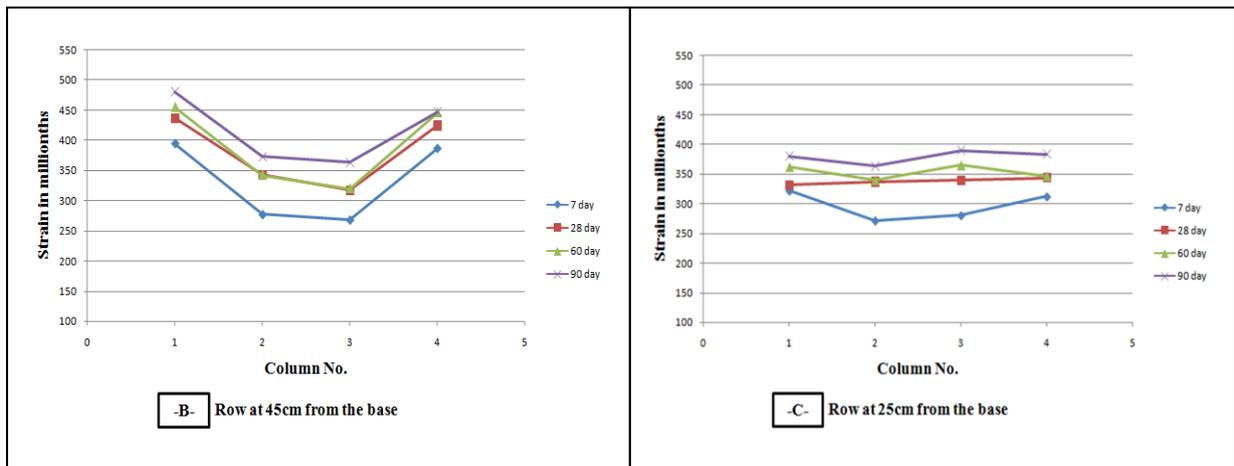
Wall Notation	L/H Ratio	Max. Shrinkage Strain (Microstrain)	Loss of Restraint L.O.R (Microstrain)
RPC2-1	2	481	64
RPC2-2	2	373	60
RPC5-1	5	462	70
RPC5-2	5	361	61
RPC10-1	10	332	72
RPC10-2	10	260	65

From Table (5), it can be noticed the followings:

- 1- The maximum shrinkage strains were found to be decreasing with increasing in L/H ratios for two ratio(1% & 2%) of steel fiber walls. This may be attributed to the fact that the action of restraint is increasing with the increasing of L/H ratio, this agrees with (AL-Ta'ee, 2008) study of high strength concrete.
- 2- There is an increase in the maximum shrinkage values of walls with 1% steel fiber by about (29%, 28%, 27.6%) of the maximum shrinkage values of walls with 2% steel fiber for walls with length/height ratio (2, 5, and 10) respectively. This due to the addition of further fibers which improve the tensile cracking resistance, post cracking strength, ductility and energy absorption capacity.
- 3- The maximum shrinkage strains found in all the casted walls at the upper row were (45cm from base for 50cm wall height and 20cm from base for 25cm wall height). This is because the base restraint decreases toward the upper row, this agrees with AL-Ta'ee's (2008)study.



-A- Longitudinal Cross Section



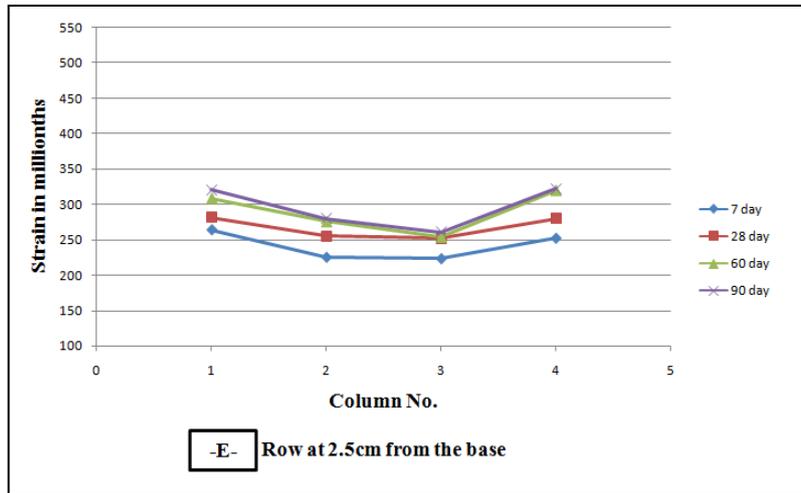
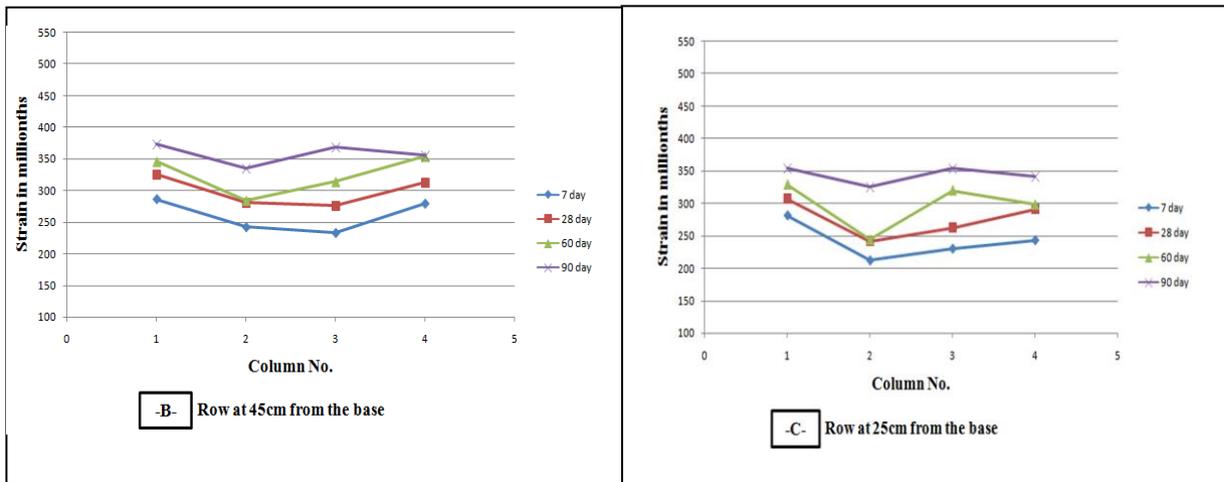
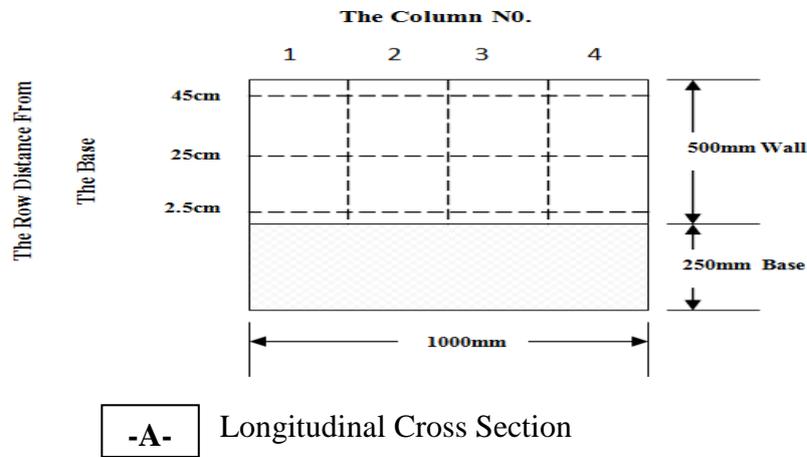


Fig. (3): Strain Development History for RPC Base Restrained Wall (RPC2-1).



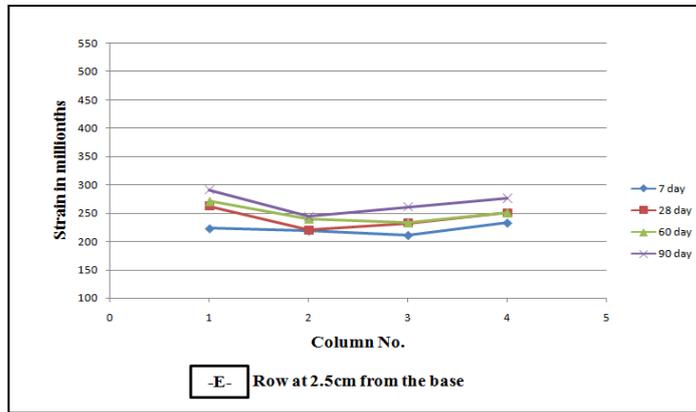


Fig. (4): Strain Development History for RPC Base Restrained Wall (RPC2-2).

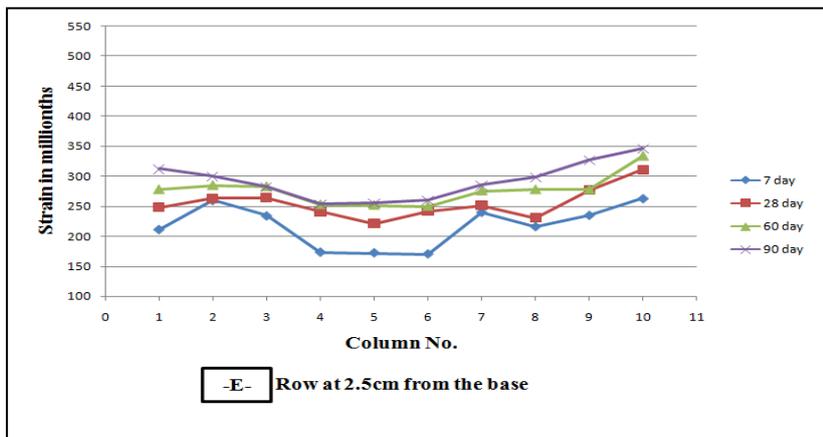
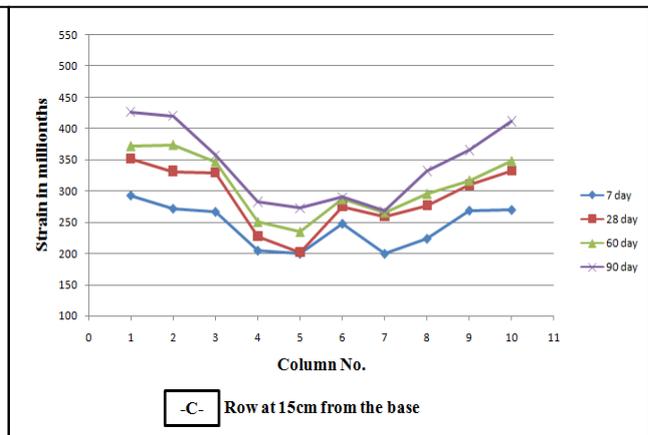
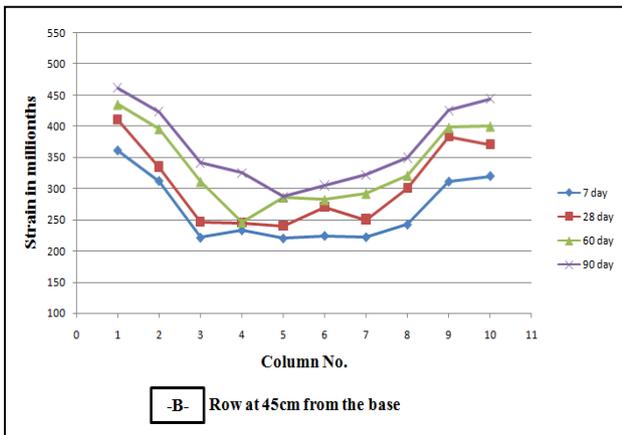
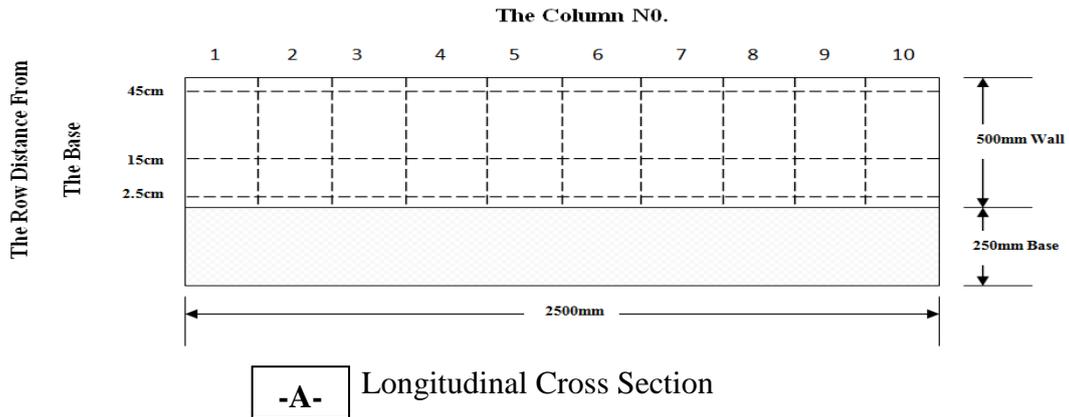


Fig. (5): Strain Development History for RPC Base Restrained Wall (RPC5-1).

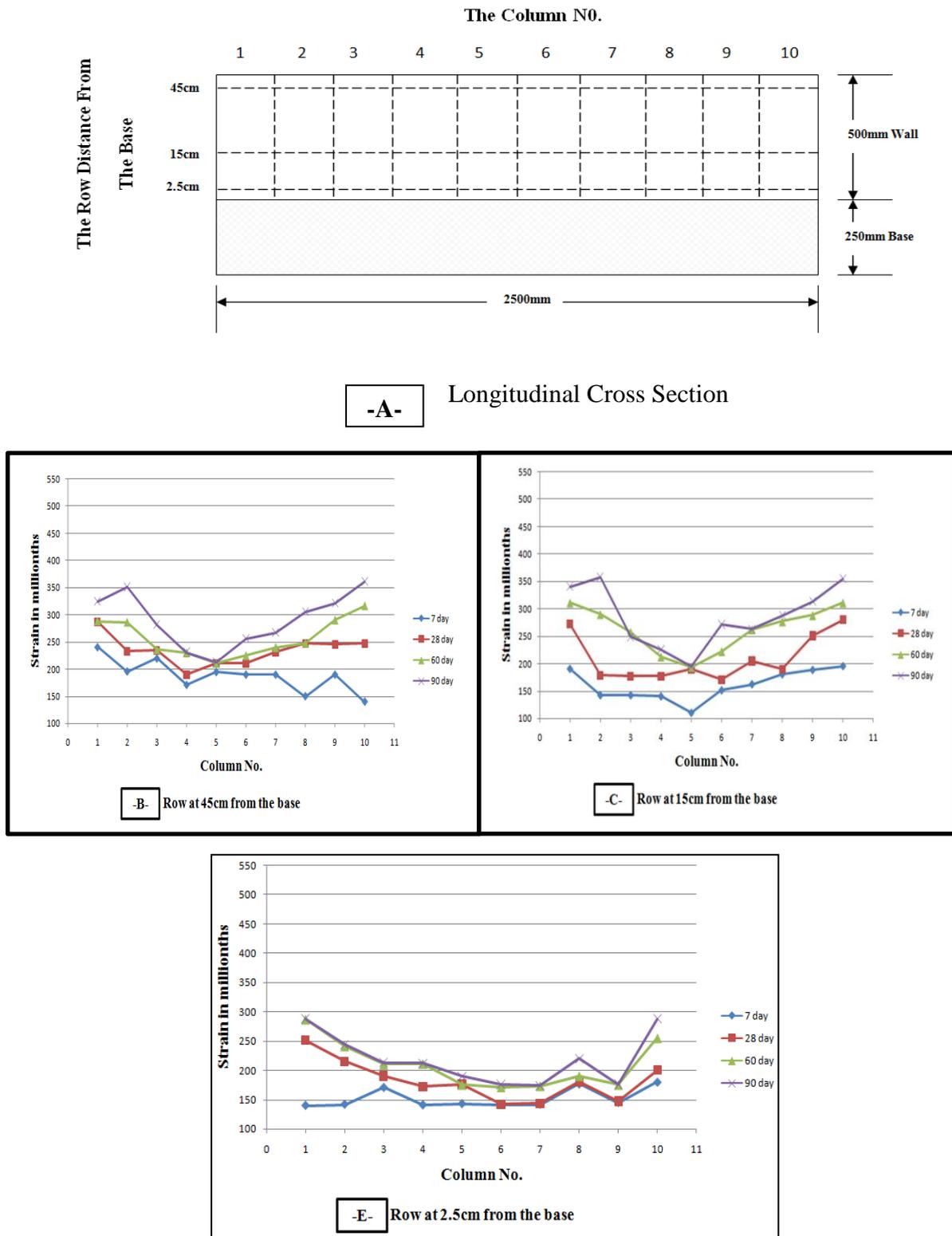


Fig. (6): Strain Development History for RPC Base Restrained Wall (RPC5-2).

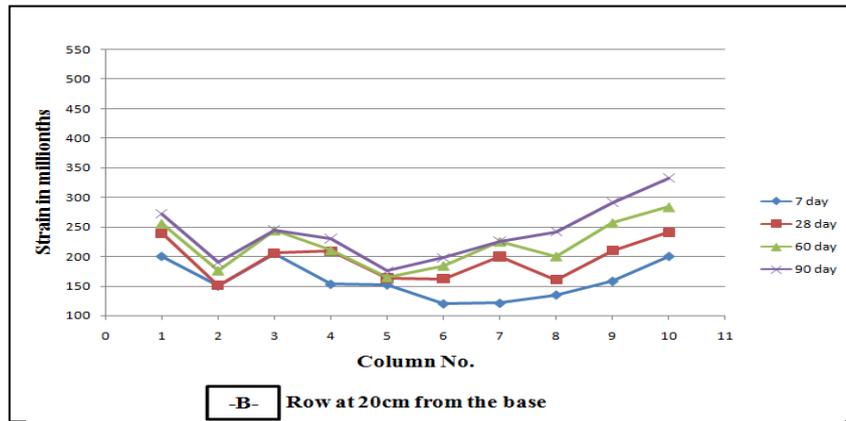
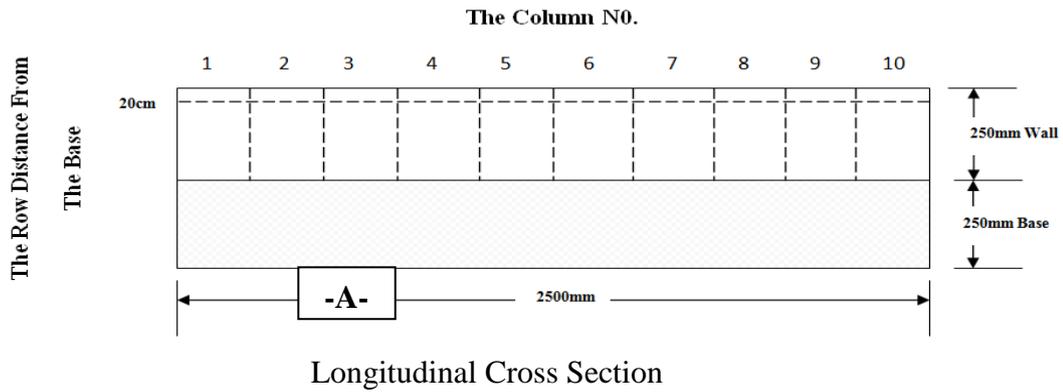


Fig. (7): Strain Development History for RPC Base Restrained Wall(RPC10-1).

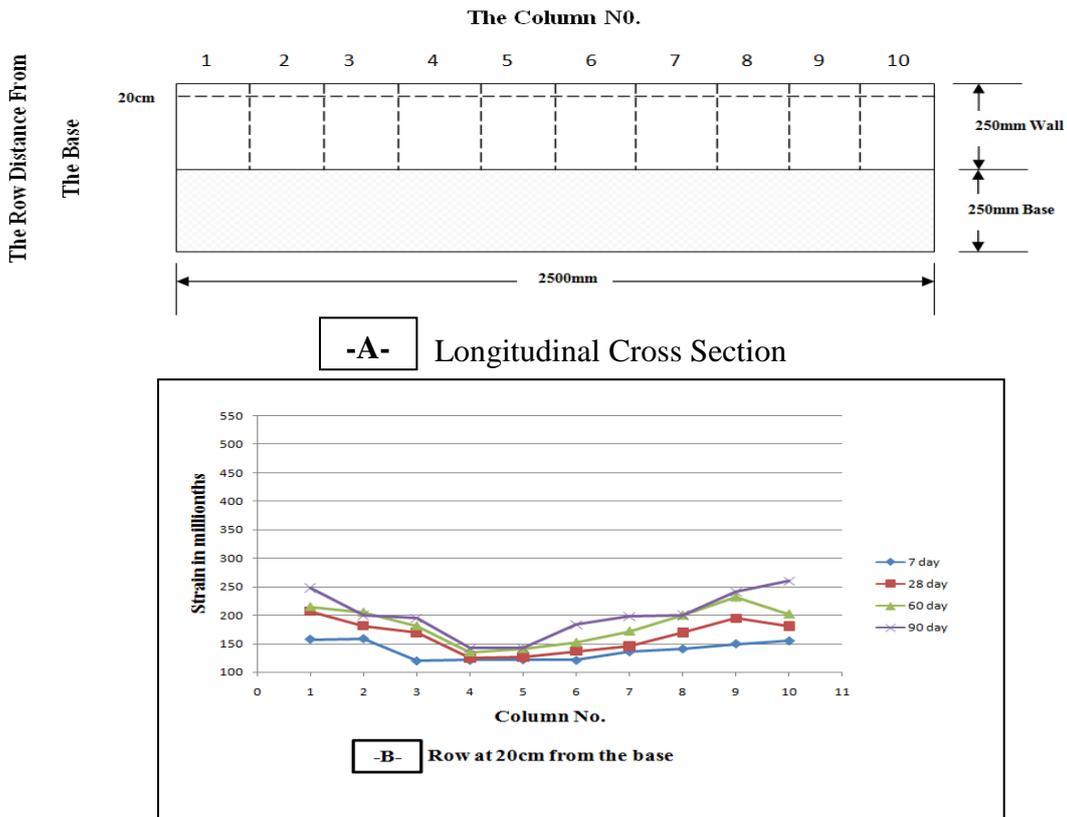


Fig. (8): Strain Development History for RPC Base Restrained Wall (RPC10-2).

From Figures (3 to 8), it can be noticed that:

- 1- The shrinkage strains in the exterior columns were more than the shrinkage strains in the interior columns of most walls. This may be attributed to the large surface area which is subjected to the drying conditions
- 2- There is a continuous increasing in the shrinkage strains with age. This indicates that no crack occurrence. This may be due to the dense microstructure and presence of steel fibers in RPC mixtures which provide superior mechanical properties (high strength, ductility, and toughness)
- 3- There are certain values in the row 2.5cm from the base in all walls although its position is very close to the base. This is may be due to some slippage which occurs between base and wall and due to the loss of restraint which comes from contraction of the base.

Cracking of The Walls

Theoretically, the first crack must occur at the centre of the wall and it starting from base, this can be attributed to the highest values of the degrees of restraint at this position (ACI 207, 1973). In spite of the long observation period (90 days) of all RPC walls, no crack occurrence at any place was observed.

Free Shrinkage of RPC End- Restrained Beams

The free shrinkage strain of RPC was measured under the same exposure conditions of the two ratios of steel fiber (1% & 2%) of the restrained walls. Table (6) and Figure (9) show the free shrinkage strain development of RPC of the two ratios and drying period. It can be seen from the results that the free shrinkage increases with the age progress of the two ratio of steel fiber (1% & 2%), when the free shrinkage of 1% steel fiber is higher than the free shrinkage of 2% steel fiber the rates were (39%, 34%, 31% and 28% at ages 7, 28, 60 and 90 days respectively).

Table (6): Shrinkage properties of RPC end restrained beams.

steel fiber ratio	Date of Crack in Beam (day)	Free Shrinkage at cracking date ($\times 10^{-6}$)	Width of crack (mm)	Tensile strain capacity ($\times 10^{-6}$)	Elastic tensile strain capacity ($\times 10^{-6}$)	Creep ($\times 10^{-6}$)	Loss of restraint ($\times 10^{-6}$)
1%	32	200	0.085	125	47	78	75
2%	38	161	0.06	86	33	53	75

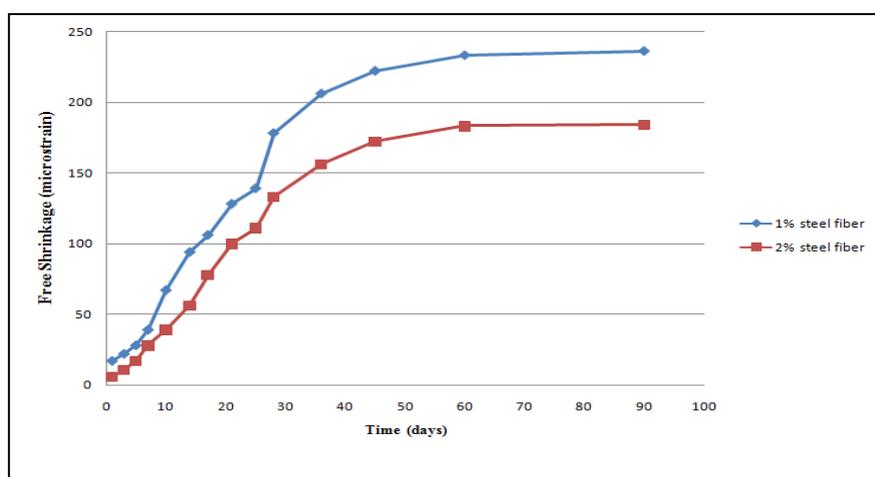


Figure (9): Free Shrinkage Development of the RPC Beam Models for two Ratio of Steel Fiber (1% & 2%).

Elastic Tensile Strain Capacity of RPC Beam Models

Elastic tensile strain capacity of the RPC beam models was obtained directly by measuring the immediate movement after the cracking of the concrete in the end restrained beams in two ratios of steel fiber (1% & 2%), the results are summarized in Table(6). The elastic tensile strain capacity was also calculated indirectly by determination of flexural tensile strength divided by the modulus of elasticity. The results are illustrated in Table (7) and plotted in Figure(10).

Table (7): Results of the Calculated Elastic Tensile Strain Capacity of the RPC Beam Models for two Ratio of Steel Fiber (1% & 2%)(Indirect Method).

	Elastic tensile strain capacity $\times 10^{-6}$			
	3 days	7 days	28 days	60 days
1%	311.3	346.2	407.2	476.8
2%	414.8	475.6	475.3	520.2

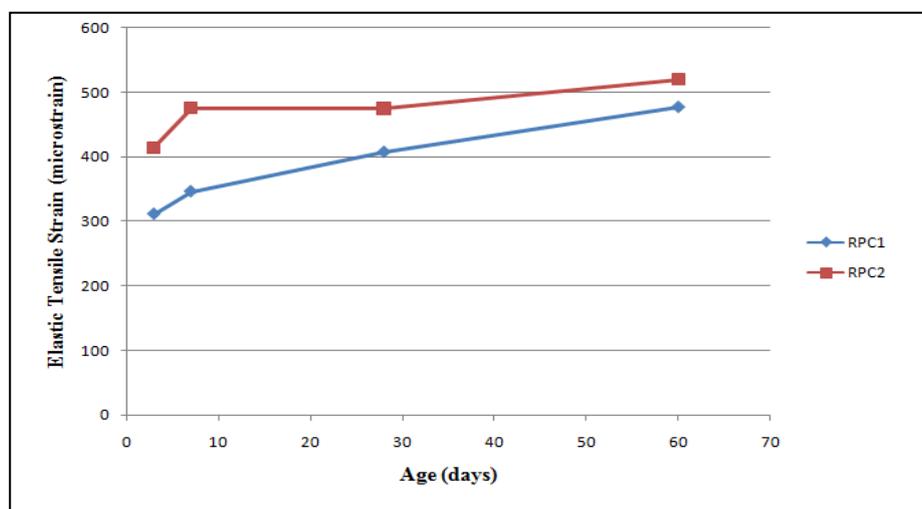


Figure (10):Development of Elastic Tensile Strain of the RPC Beam Models for Two Ratios of Steel Fiber (1% & 2%) (Indirect Method).

Tensile Strain Capacity of RPC Beam Models

The determination of tensile strain capacity of RPC was based on the end restrained shrinkage beam model. Table (6) shows the values of tensile strain capacity at the date of cracking obtained in the present work. It can be observed from the results that the tensile strain capacity of the beam with 1% steel fiber (125microstrain) is more than the tensile strain capacity of the beam with 2% steel fiber (86microstrain) although the crack date of beam with 1% steel fiber (32 day) is less than the crack date of beam with 2% steel fiber (38 day).

Creep of RPC Beam Models

Creep strain of RPC subjected to the end restrained shrinkage was calculated as the difference between the tensile strain capacity and the elastic tensile strain capacity. Table (6) shows that the creep strain of RPC ends the restrained beam specimen at cracking of two ratios of steel fiber (1% & 2%) is $(78 \text{ and } 53 \times 10^{-6})$ respectively.

Cracking Time of RPC Beam Models

The cracking time is the time required for first crack to occur. From Table (6), it can be observed that the cracking time in RPC with 2% steel fiber is 38 days, while it decreases in RPC with 1% steel fiber to 32 days.

Conclusions

Based on the test results and the theoretical analysis of the present work, the following conclusions can be drawn:

Mixture Preparation and Mechanical Properties of RPC

Using and increasing steel fiber volumetric content from 0% to 1% and 2% leads to an increase in the mechanical properties of RPC as follows:

1. The compressive strength increases by 15.9% and 23.6% respectively.
2. The splitting tensile strength increases by 60.6% and 84.5% respectively.
3. The flexural strength increases by 46.8% and 78.2% respectively.
4. The modulus of elasticity increases by 4.4% and 8.6% respectively.

Experimental Results of RPC Walls

- 1- The experimental observations clearly indicate that the cracking did not develop in RPC base restrained walls with L/H (2 , 5 and 10) for two ratio of steel fiber (1% & 2%) during 90 day period of drying.
- 2- The shrinkage strain in all the RPC walls occurred at high rates at early ages of 7, 14, and 28 days. when the shrinkage results are compared with shrinkage results of the high strength concrete & the normal concrete of the previous studies, the shrinkage of the reactive powder concrete at early age is more than the shrinkage of the high strength concrete & normal concrete, but at later ages it is less than the shrinkage of the high strength concrete & the normal concrete.
- 3- The maximum shrinkage values increased toward the edges and top of the most walls.
- 4- The maximum shrinkage strains for 1% steel fiber walls was more than of 2% steel fiber walls by about (29%, 28%, 28%) of L/H (2, 5 and 10) respectively.
- 5- It was found from the end-restrained beam specimens results that the drying shrinkage is less for reactive powder concrete than for the high strength concrete & normal concrete.
- 6- The free shrinkage of the beam with 1% steel fiber (at the date of cracking) was higher than of the beam with 2% steel fiber by about (24%) in end restrained beams, the free shrinkage is less for reactive powder concrete than for the high strength concrete & normal concrete.
- 7- The tensile strain capacity of the beam with 1% steel fiber at the date of cracking is higher than that of the beam with 2% steel fiber about (45%) . On the other hand, the elastic tensile strain capacity of the beam with 1% steel fiber at date of cracking is higher than that of the beam with 2% steel fiber by about (42%), the tensile strain capacity and the elastic tensile strain capacity at date of cracking are less for reactive powder concrete than for the high strength concrete & normal concrete.
- 8- The creep strain of the beam with 1% steel fiber, the beam with 2% steel fiber (78 and 53 microstrain), and the creep coefficient (0.15) in reactive powder concrete are less than for high strength concrete & normal concrete.
- 9- The creep strain of beam with 2% steel fiber at date of cracking is higher than that of the beam with 1% steel fiber by about (47 %).
- 10- The date of cracking in end restrained beam increases with the increases of steel fiber ratio, the cracking time was of the beam with 1% steel fiber and the beam with 2% steel fiber were (32 and 38 day).

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