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Full Length Research Paper

Performance of reactive powder concrete slabs with different curing conditions

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In this paper, the material performance of Reactive Powder Concrete (RPC) with two different curing conditions, water-curing of 25°C and heat-treatment of 90°C and 95% relative humidity was experimentally studied. An experimental investigation is carried out to study the influence of using steel fiber and heat-treatment on RPC slab specimens. All the slabs are simply supported along the four edges and loaded concentrically by a square plate of dimensions (70×70×25 mm). The test results showed adequate improvements by increasing adding steel fiber, using of heat-treatment on the compressive strength, indirect tensile strength and modulus of elasticity. It also showed a great positive effect on the flexural strength. The 28-day compressive strength varied between 163.4 and 194.6 MPa for the non-heat-treated and heat-treated specimens. Test results proved that the increase slab thickness leads to significant increase in ultimate load. The ultimate load of RPC slabs that have 20, 40 and 60 mm thickness are 17.5, 13.0 and 12.6% respectively compared to RPC slab specimens non-heat-treated when steel fibers are used at 2% by volume and the percentage increment when thickness decrement. It was found that the deflection at ultimate load, showed a significant decrease when the slab thickness was increased.

Key words: Reactive powder concrete; mechanical properties; curing conditions; steel fibers.

INTRODUCTION

Reactive Powder Concrete (RPC), a cement-based composite material well known for its ultra-high strength, high-durability and low-porosity made its international debut in 1994 (Richard and Cheyrezy, 1994). The advance mechanical and physical properties of RPC are obtained by optimizing packing density of concrete mixture with precise gradation of all mix particles, and by using highly refined silica fume to improve the microstructure of hydrated cement pastes through the pozzolanic reaction. To produce a very high compressive strength of RPC, applications of pressure before and during setting and heat-treating after setting are normally required. Compressive strengths of 200 to 800 MPa, modules of elasticity of 50 to 60 GPa and flexural strength of 6 to 13 MPa have been achieved with RPC (Richard and Cheyrezy, 1995).

On the other hand, maximum compressive strengths for the commonly used normal weight concrete in most concrete structures are in the range of 30 to 60 MPa with the corresponding modules of elasticity of 14 to 35 GPa

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Table 1. Chemical composition of the cement.

Chemical composition	Component	CaO	SiO_2	Al_2O_3	Fe_2O_3	MgO	SO_3	Na_2O
	Content [%]	63.2	20.2	4.1	3.4	2.8	2.6	0.3
Physical properties	Fineness using Blaine (m^2/kg)				3270			
	Soundness using autoclave method				0.19 %			

(Mindess et al., 2003). Due to advantage of the super material properties, RPC has been applied to many real constructions where the substantial weight savings of structure can be appreciated and where its distinguished features of material property can be fully utilized (Adeline and Cheyrezy, 1998; Etienne et al., 2001; Rebentrost and Cavill, 2006). In a typical RPC mix proportioning, in order to enhance the homogeneity and optimize the density of concrete granular mixture, the coarse aggregates of conventional concrete are totally eliminated such that the amounts of fine aggregate, Portland cement and silica fume need to be substantially increased.

Twelve square RPC slabs of dimensions (45×45) inch were tested to investigate the boundary between a flexural failure and a punching shear failure. The variables considered were the slab thickness (2, 2.5, and 3 in) and loading plate dimensions (from (1×1) inch to (3×3) inch. All the slabs are supported on the fully restrained end and loaded concentrically (Harris, 2004).

It was concluded that for small plate tests, a very small loading area was required to force a punching shear failure in the RPC slabs and based on this assessment, a (2 inch) slab thickness should provide sufficient punching shear capacity for bridge applications. The actual slab thickness selected for design should also consider factors such as flexural capacity and deflection criteria. Also, the RPC is more suited for precast operations due to the controlled environment and special formwork required. He also concluded that the casting method has a strong influence on the orientation of the steel fibers, which in turn influences the flexural strength in orthogonal directions in the slabs, The brittle punching shear failure mechanism exhibits limited warning prior to failure, but is still significantly less abrupt than for a reinforced concrete punching shear failure (Harris, 2004).

The effect of subjecting UHPC to a temperature of 90°C during its early ages (for 24 to 48 h) was studied. It was shown that such heat treatment accelerated the pozzolanic reaction of silica fume with $Ca(OH)_2$ and resulted in high strength development of UHPC. The compressive strength of a heat treated UHPC was observed to increase from 220 to 280 MPa over 8 years' storage in water. The chain length of the C-S-H phases increased from values between 5 and 6 to 9 during this period. A distinct increase in compressive strength of UHPC not subjected to heat treatment was also observed at high ages. The compressive strength was 250 MPa at an age of six years which was 58% more than the 28 day strength of 160MPa (Schachinger et al., 2008).

Cwirzen studied the influence of the curing regime on the mechanical properties and microstructure of ultra-high-strength mortar. Nine different curing procedures were applied in which the start and duration of the heat treatment were varied. The studied mortars had a water-binder ratio of (w/b) 0.17 and additions of amorphous silica fume and fine quartz filler. The microstructure and microchemistry were investigated by electron scanning microscopy and mercury intrusion porosimetry. The results revealed that longer heating times increased the degree of hydration, refined the microstructure and resulted in higher ultimate compressive strength. Very late and very early application of the heat treatment caused a lower degree of hydration and a smaller long-term increase of compressive strength (Cwirzen, 2007).

Up to now, all previous studies concise on the flexural behavior of the simply supported slab under normal water curing. While in this paper, the first object of project is focused on the behavior of square RPC reduced scale slab under heat treatment and the second object of this research was to determine the mechanical properties of the produced materials. Additionally, mode of failure of RPC slab specimens was evaluated.

EXPERIMENTAL PLAN

Materials

The RPC considered here is prepared by the following ingredients: ASTM Type I Portland cement produced in Iraq of (TASLUJA) and taken from local markets; natural sand (0-2.0 mm, with a specific gravity of 2.7); a polycarboxylate-based superplasticizer (SP) SikaViscocrete-5930 and brass-coated steel micro-fibers, with a density of 7850 kg/m³, a length of 13 mm, a diameter of 0.18 mm and an l/d ratio of 72. The cross section of the fiber was circular. The chemical composition and physical properties of the cement and silica fume used are presented in Tables 1 and 2 respectively. The composition of RPC with a water to cement ratio (W/C) of 0.18 used in this study is given in Table 3.

Concrete mixing and properties

All the dry constituents of the RPC were batched by an electronic balance. The dry constituents were first mixed for about 4 min at low and high speed in Pan Mixer. Water and superplasticizer were added gradually and re-mixed for about 5 min at high speed until the materials were uniformly mixed. Lastly the fibers were introduced, dispersed uniformly by using a sieve and additional mixing was applied for about 2 min.

The mixing procedures proved satisfactory in that the dispersion of fibers were found to be uniform and there was no evidence of fiber balling. Flow table tests, as per ASTM C230, were undertaken

Table 2. Chemical composition and physical properties of silica fume.

Chemical composition	
Component	**Content [%]**
SiO_2	90
Al_2O_3	1
Fe_2O_3	1
CaO	0.4
MgO	1
Cl	< 0.3
SO_3	< 2
Loss o n ignition, LOI	3
Physical properties	
Specific gravity	2.2
Percent passing 45 μm (%)	Approximately 90-100
Bulk density [kg/m^3]	640
Form	Amorphous

Table 3. Composition of RPC.

Mix ID	Slab thickness (mm)	Amount kg/m^3					
		Cement	Water	SF	SP	FS	Steel fiber (%)
RPC1-20	20	860	195	215	43	980	1
RPC2-20	20	860	195	215	43	980	2
RPC1-40	40	860	195	215	43	980	1
RPC2-40	40	860	195	215	43	980	2
RPC1-60	60	860	195	215	43	980	1
RPC2-60	60	860	195	215	43	980	2

SF, Silica fume; FS, Fine Sand; SP, Superplasticizers (quantity of SP represented in percentage by weight of cement material), Steel Fibers (quantity is represented in percentage by volume of the total mixture).

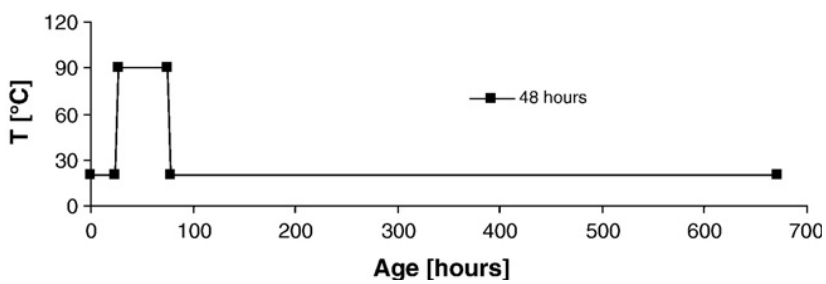


Figure 1. Curing regime adopted.

before casting of the specimens to assure that the fiber reinforced concrete mix had achieved a flow between 160 and 250 mm for the selected mix.

The hardened specimens were demolded after 24 h, and cured by two procedures were applied. The first procedure included demoulding of the specimens 24 h after casting and their subsequent storage at 95% RH and 25°C. The second procedure included a heat treatment at 90°C which was followed by storage at 95% RH. Based on an extensive study whose results are described by Cwirzen (2007), the heat treatment started after 24 h from casting and lasted 48 h. The curing protocol adopted in this study is indicated in Figure 1. Heating rate of treatment was 12°C /h. This extended (48 h) high temperature (90°C) heat treatment which is different from conventional curing process was preferred due to the high amount of reactive cementitious materials in RPC. Studies showed that high mechanical properties can be achieved under

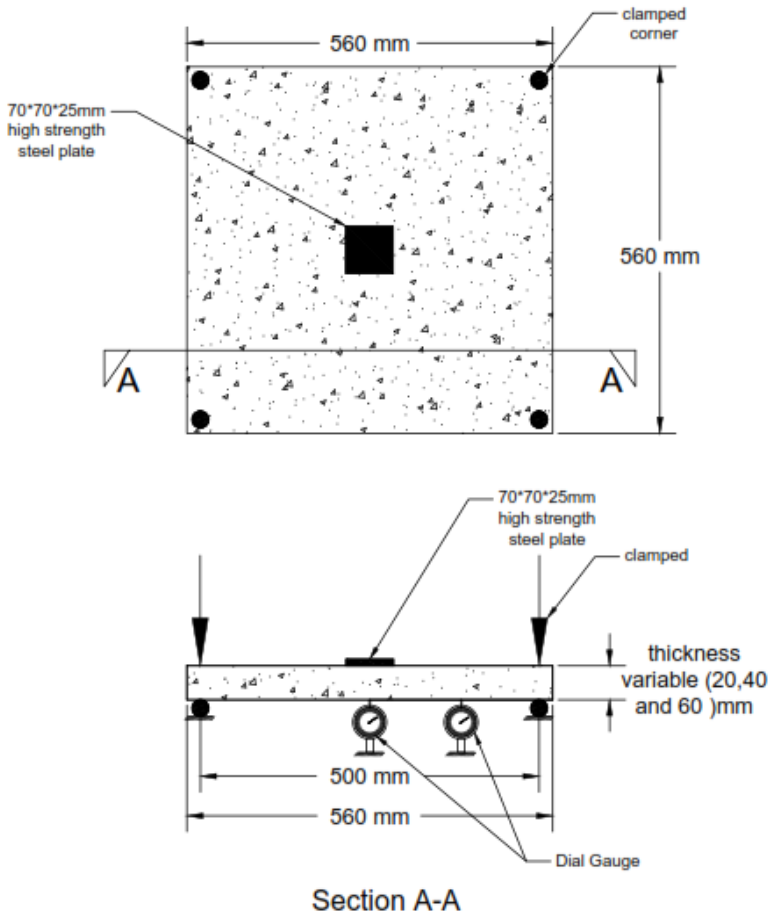


Figure 2. Slab test schematic.

these conditions at early ages. Heat treatment densified the microstructure of the RPC matrix. The specimens, which were subjected to heat treatment, were kept in laboratory conditions for cooling before testing in this study.

Test specimens

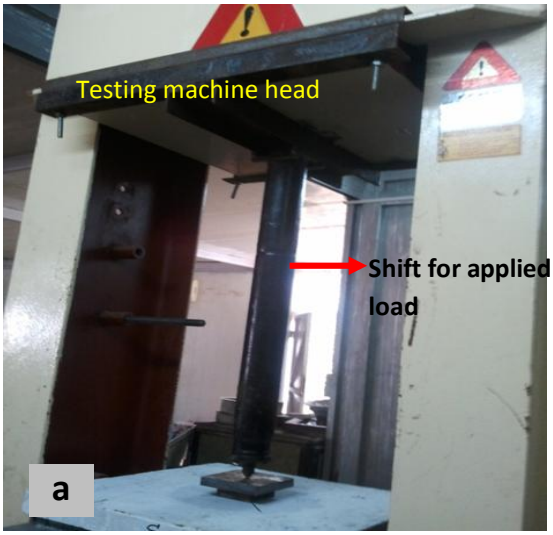
In the present work, twelve RPC square slabs with full side length of 560 mm, and center to center span between supports of 500 mm with a different thickness of 20, 40 and 60 mm. The slab was simply supported along its four edges and loaded by a central steel plate of dimension 70×70×25 mm. Three experimental variables are investigated in this study to show their effects on the behavior of the reinforced reactive powder concrete slab specimens. These variables are percentage of steel fibers, types of curing and thickness of the RPC slab.

Concrete tests

The compressive strength test was carried out according to B.S: 1881: part 116 (B.S. 1881:1983) using a digital testing machine with a capacity of (2000 kN). For each measurement, a set of three specimens 5×5×5 cm^3 was used. The tests were performed at the following ages: 1, 7 and 28 days. The loading was applied at a rate of 0.9 kN s^{-1}. Splitting tensile strength has been determined by testing six standard cylinders of 100×200 mm for every mix depending on ASTM C496-04 specification (ASTM C 496/C 496M, 2005). The cylinders were cast, demoulded and cured in a similar way as for slab specimens. Prismatic specimens (50×50×300 mm) were used to determine the flexural behaviors in conformity with ASTM C78-02 (ASTM C78-02, 2002). Each prism was simply supported and subjected to a two point loading using an electrical testing machine with a capacity of (2000 kN). The tests were performed at the age of 28 days. Elastic modulus test was carried out on 100×200 mm cylindrical specimens. The 40% of ultimate compressive strength of concrete specimen was applied on the concrete cylinders to perform the elastic modulus test as specified by ASTM C469 (ASTM C469-02, 2002). In each taken slab, each data presented here are the average of test results of the three specimens.

Testing procedure

Before the testing day, the slab was taken out from the curing container, cleaned and painted with white paint on both surfaces, to achieve clear visibility of cracks during testing. The slab was labeled and carefully placed along the edges on simple supports. The point load was applied at the center of the slab and the dial gauges were positioned in their places, so that a precise setup of the testing equipment was achieved. Figure 2 shows the testing of slab specimens mentioned above. The slab specimens were tested



Photograph showing the testing machine.

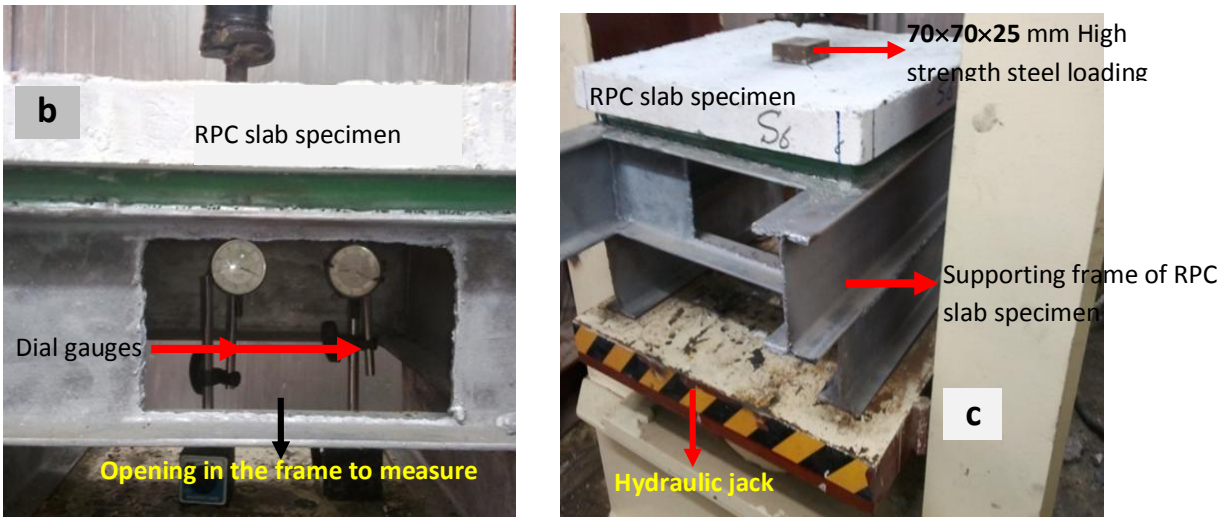


Figure 3. Photograph showing the details of slabs testing setup.

used a hydraulic testing machine with a capacity of (20000 kN) available in the structural Laboratory in Civil Engineering Department; College of Engineering is illustrated in Figure 3a.

The load was applied gradually in increments of 4 kN until failure occurs. This amount of incremental loading allows sufficient number of loads and corresponding value of deflections to be taken during the test which gave a good picture for the structural behavior of the slab specimens. Tow dial gauges having accuracy of 0.001 mm per deviation and capacity of 10 mm and a maximum sensor length of 50 mm were used to measure the mid-span deflection and 125 mm from mid-span of slab specimen see Figure 3b and c).

It is worth pointing out here that the 560 mm length of the square slabs of the present investigation was larger than the maximum space of 450 mm offered by the MFL system testing machine. Therefore a special supporting frame was manufactured and used inside the testing machine, as shown in Figure 4, to provide the required span of the slab. This supporting frame was made using four steel beams of the type W-shape (W4×13) welded and arranged to form a square shape. Each of which had a 25 mm steel bar welded on its top face to provide a simple support for the slab edge.

RESULTS AND DISCUSSION

Engineering properties of RPC

The engineering properties of RPC under two different curing conditions are shown in Table 4. The highest measured 28-day compressive strength values for the mixes of the heat-treated and non-heat-treated specimens are shown in Figure 5. The highest compressive strength value of 194.6 MPa was obtained in case of the heat-treatment incorporating a volume fraction of 2% steel fibers. On the other hand, the 28-day

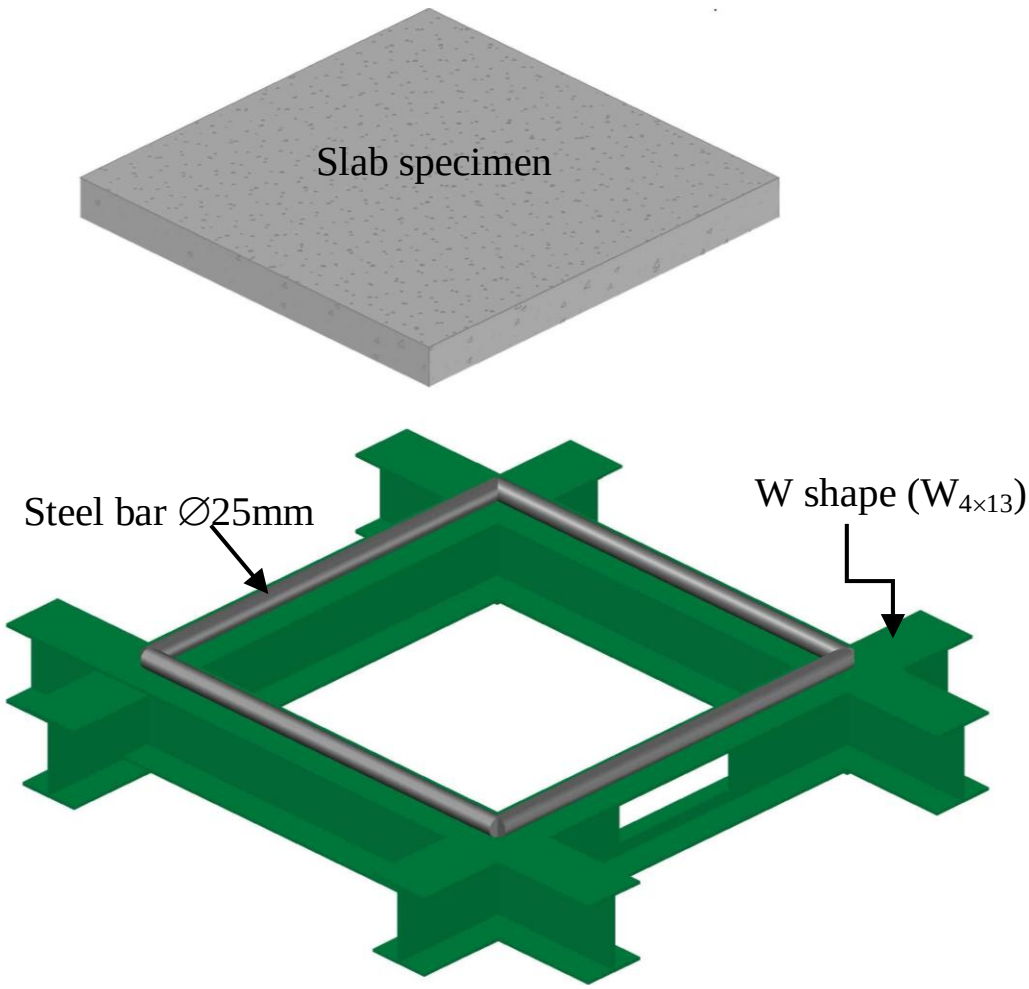


Figure 4. Supporting frame of slab specimens.

Table 4. Engineering properties of RPC under water curing of 25ºC and heat treated.

Mix	Compressive strength [MPa]			Flexural 28 day [MPa]	Splitting tensile 28 day [MPa]	Modulus of elasticity 28 day [GPa]
	1 day	7 day	28 day			
RPC1/N	119.2	139.0	163.4	24.0	13.2	42.01
RPC2/N	128.6	152.3	173.0	28.7	17.0	45.15
RPC1/H	143.0	166.8	181.5	30.8	15.4	44.56
RPC2/H	154.5	178.0	194.6	36.0	19.7	48.30

compressive strength value of the non-heat-specimens reached 173 MPa and was measured in mix RPC2/N. Because the pozzolanic reaction resulting from the ingredients of silica fume, in the RPC mixture will be activated energetically by the high temperature and moisture of curing. This pozzolanic reaction causes adenser microstructure of C-S-H cement hydrate and results in a faster development of strength gain.

The splliting tensile strength of RPC for all mixes is much lower than the compressive strength, because of the ease with cracks which propagate under tensile loading, and is usually not considered in design. However, it is an important property, since cracking in concrete is most generally due to the tensile stresses that occur under load, or due to environmental changes. Referring to Table 4, the splitting tensile strength of RPC cylinders can be increased up to (27.9 and 28.8%) as the micro fine steel fibers volume ratio increases from 1 to

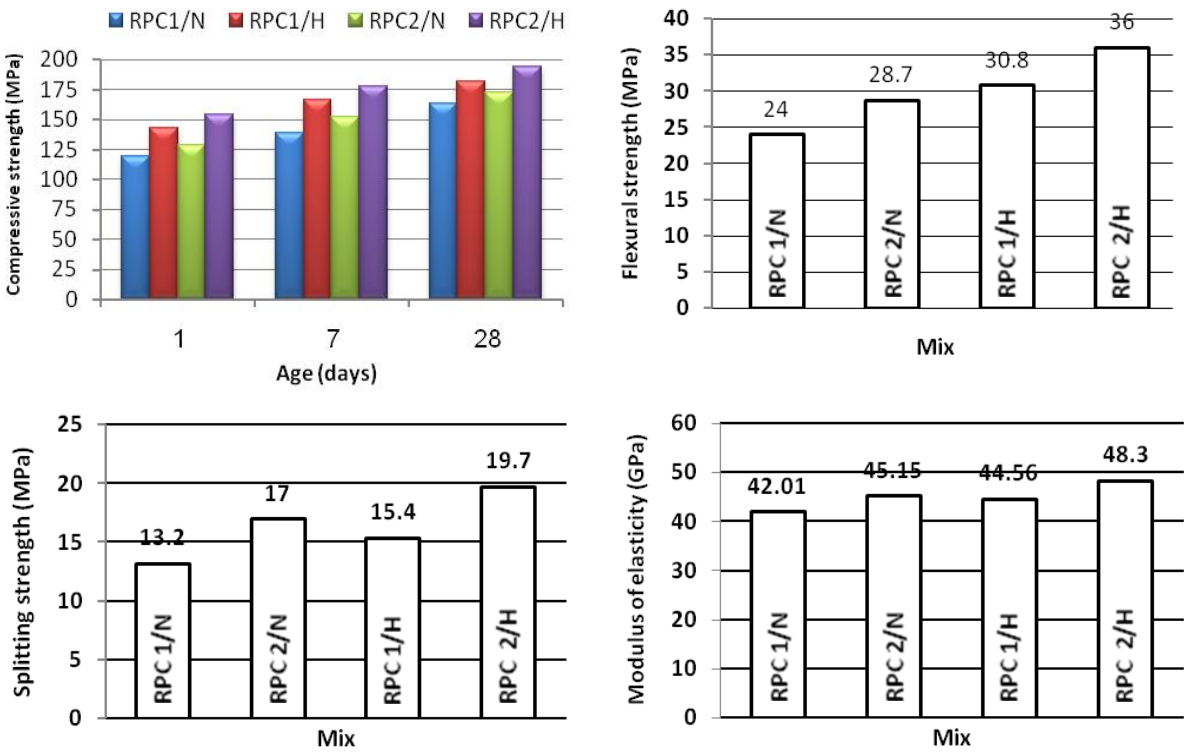


Figure 5. Engineering properties results of the studied RPC.

2% for heat-treated and non-heat-treated RPC mixes respectively. This is due to the fact that fibers bridge tensile cracks and retard their propagation (Graybeal and Hartman, 2002). The steel fibers improve the characteristics of cement-based matrices in the hardened state; they are able to bridge cracks, transmit stress across a crack and counteract crack growth (Mahdi, 2009). As shown in Figure 5, the presence of micro steel fibers influenced the flexural strength of the studied mixes. The results showed an increase of the flexural strength from 24 to 28 MPa after the addition of 2% of steel fibers and up to 36 MPa in the case of the heat-treated mixes.

The splitting tensile strength is related to the failure mechanism in tension due to the concentration of stresses at the tip of an elliptical crack. According to this theory the tensile strength will increase with shorter cracks, higher total modulus of elasticity and lower porosity (Penttala et al., 1995). The modulus itself is influenced by three concrete phases; binder matrix, aggregates and ITZ. Consequently, the wide and porous ITZ or weak and cracked aggregates will lower the tensile strength. Furthermore, the larger maximum aggregate size the greater their ultimate influence on the mechanical properties. Thus, it can be concluded that the main function of the short steel fibers is to stop the opening and the propagation of the microcracks. A negligible increase of the flexural strength of the RPC after the addition of steel fibers can be explained by the unfavorable combination of at least two effects. The first effect is due to de-bonding of the binder matrix from the aggregate surface in tension. The second is due to described possible increase of the internal stresses caused by the presence of micro cracked aggregates. In order to overcome these effects significantly, higher amount of the steel fibers would have to be incorporated into the binder matrix.

With respect to these curves, it can be noticed that the highest value of the modulus of elasticity of 48.3 GPa was measured in the RPC2/H mix. The lowest value of the modulus of elasticity which equaled 42.01 GPa was measured in case of the RPC1/N mix. The heat treatment did not have significant effect on the measured values.

Typical failure modes of RPC specimens from the compressive and splitting tensile tests are shown in Figure 6a and b respectively. It is noted that, unlike the normal weight concrete specimens with the failure modes of either in crushed state or two separated pieces, these failed RPC specimens are still kept together by the steel fibers.

First crack load, ultimate load and load versus deflection for slab specimens

In this study, twelve slabs were tested. The test results of these slabs included the first crack load, peak load, load-deflection curves and crack pattern as well as modes of

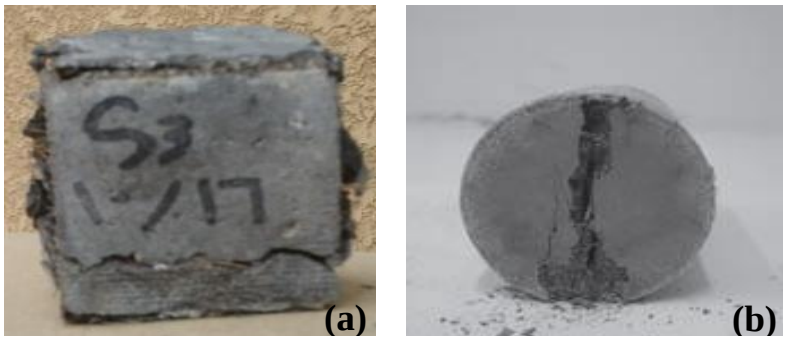


Figure 6. Typical failure modes of RPC specimen after testing: (a) Compressive test; (b) Splitting tensile test.

Table 5. Test results of the first crack load, ultimate load and mid-span deflection for RPC slab specimens.

Slab Identification	First crack load (kN)	Peak load (kN)	Mid-span deflection at first crack (mm)	Mid-span deflection at peak load (mm)	Mode of failure
RPC1-20/N	42.2	79.0	2.6	9.1	Flexural
RPC1-40/N	45.8	94.6	2.1	6.9	Flexural
RPC1-60/N	47.7	109.2	1.5	4.2	Flexural
RPC2-20/N	43.0	89.6	4.4	13.6	Flexural
RPC2-40/N	76.2	103.5	3.8	11.4	Flexural
RPC2-60/N	85.3	114.0	2.5	8.9	Flexural
RPC1-20/H	49.8	93.2	3.0	10.2	Flexural
RPC1-40/H	53.0	101.0	2.5	7.8	Flexural
RPC1-60/H	54.8	117.3	1.8	5.3	Flexural
RPC2-20/H	50.1	105.3	5.1	14.6	Flexural
RPC2-40/H	86.0	117.0	4.6	12.1	Flexural
RPC2-60/H	97.2	128.4	2.9	10.3	Flexural

failure data are presented in Table 5. In all slabs, flexure failure occurred and the cracks initially formed near the center of the slab on the tension face and radiated to the edges. As loading continued, the cracks along the diagonals on the tension face widened and extended with additional cracks forming at the central region of the tension face. At higher loads, further flexural cracks were formed progressively and widened as the loading increases. As the flexural cracks widened, the fiber pullout reached its final stages and the slab failed. The test revealed that the increasing micro steel fibers content usually leads to an increase in the peak load and ultimate deflection with delays the propagation of cracks and controls their growth in the slab as shown in Figure 7. This can be attributed to the fact that the efficiency of steel fibers in arresting the propagation and controlling the growth of cracks within the slab, and hence, steel fibers maintain the slab integrity throughout the post cracking stages of behavior. The slab, hence could withstand greater loads and deflection before failure. It is evident from Table 5 that the deflection at ultimate load is considerably increased by the presence of steel fibers and using heat treated.

Figure 8 shows clearly that the fiber volume fraction has a significant effect on the ultimate load carrying capacity of slab specimens. Heat-treatment curing seems very effective ways to increase the peak load of RPC slab specimens. This can be attributed to the improvement of hydration process under these curing regimes. The RPC slabs under heat-treatment at volume fraction (1 and 2%) results in an increase in the mid-span deflection at peak load of 26.2 and 15.7%, respectively in compared to that of non-heat slabs.

The load versus deflection relationship of slab specimens is presented in Figures 9 to 11. Deflections of these slab specimens were measured by using two dial gages, one located at the center of the slab and the other at 125 mm away from slab center. In all RPC slab specimens, the deflections were recorded immediately after the application of the load. At peak load, the rate of increase in deflection was so fast that no reliable deflection value could be measured. Accordingly, all load-

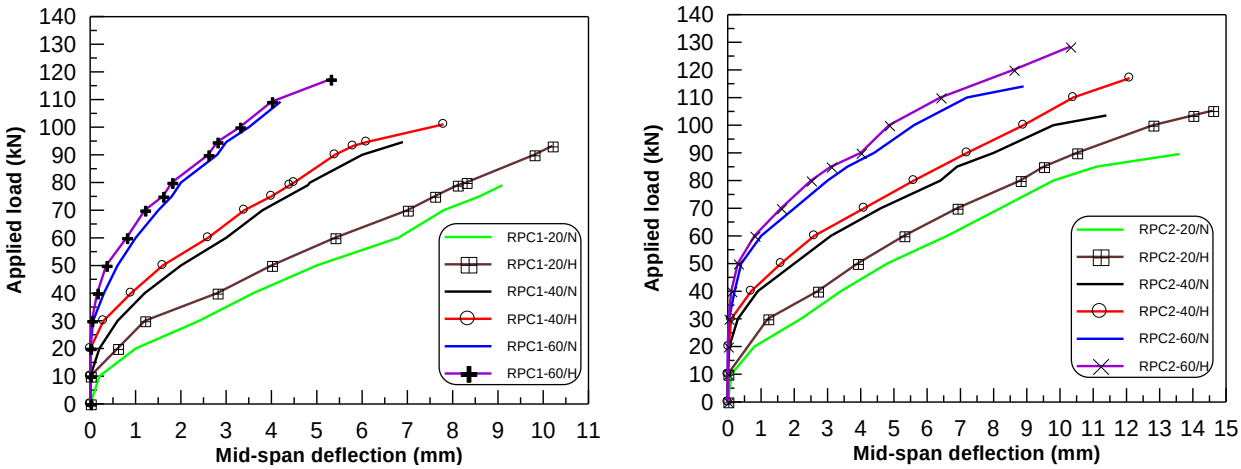


Figure 7. Load - mid-span deflection curves of RPC slab specimens.

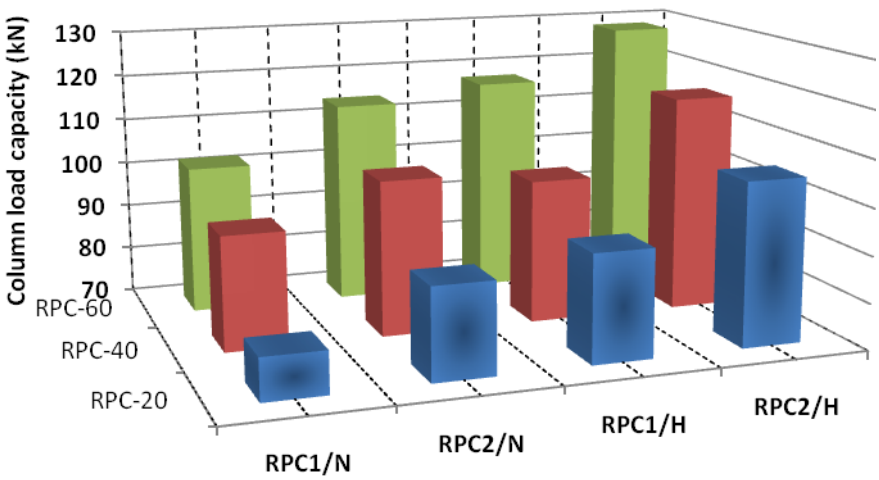


Figure 8. Effect of steel fiber percentage and curing conditions on the ultimate load for slab specimens.

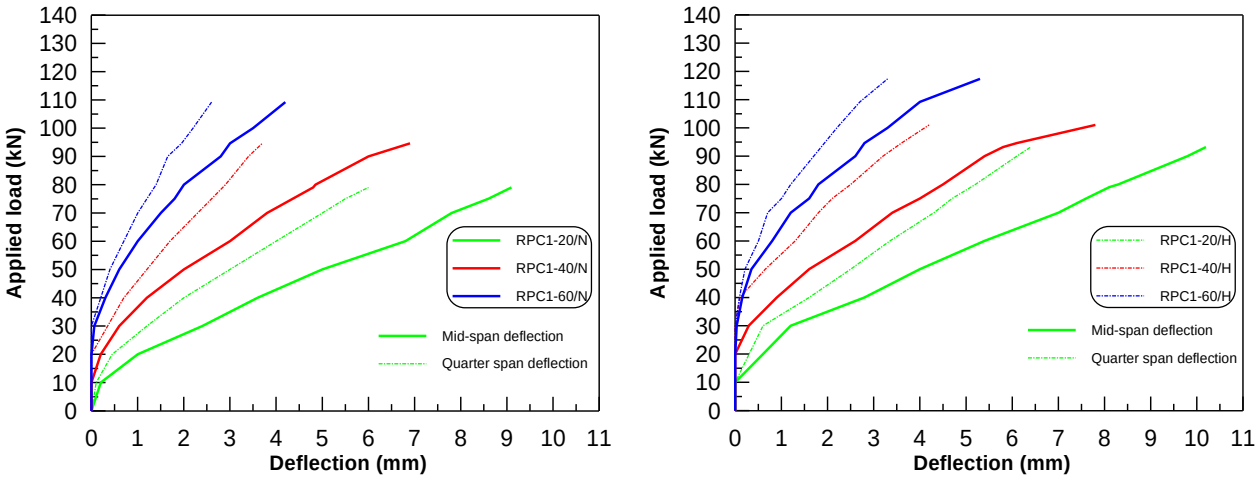


Figure 9. Load - deflection curves of RPC slab specimens with 1% steel fibers.

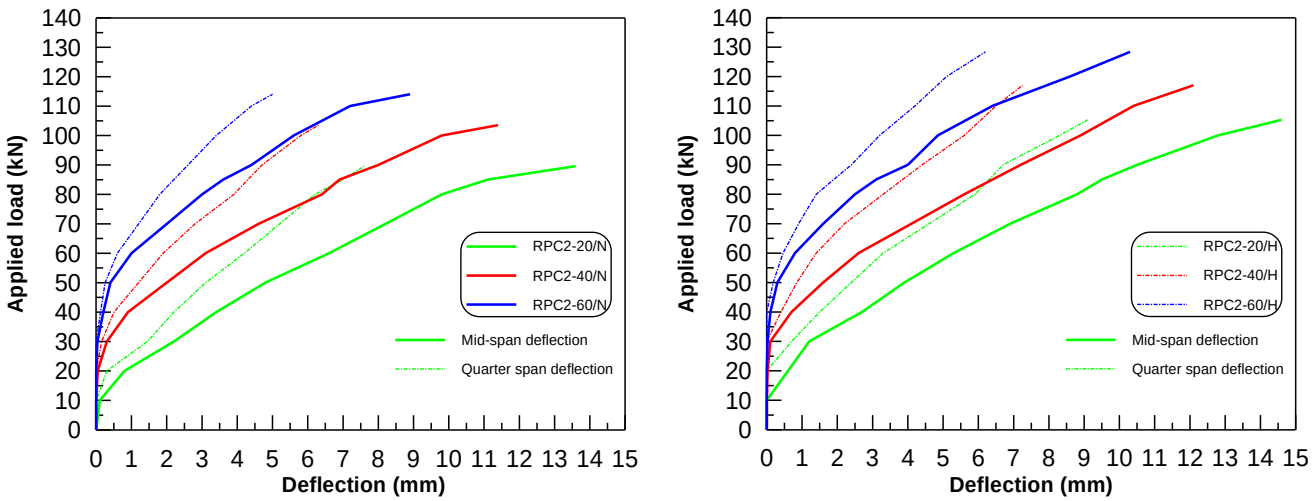


Figure 10. Load - deflection curves of RPC slab specimens with 2% steel fibers.

deflection curves were terminated at their peak load value. In addition, it can be concluded that the increase in the percentage of fibers with using heat-treatment increases the load carrying capacity and increases the deflection in slab specimens. This can be attributed to the fact that the efficiency of steel fibers in arresting the propagation and controlling the growth of cracks within the slab, and hence, the steel fibers maintain the slab integrity throughout the post cracking stages of behavior. The slab, hence could withstand greater loads and deflection before failure. For all slabs that fibers tend to align in the direction of the flow of the material and also with the formwork. For RPC mixes containing 1% micro steel fibers, it is obvious from the results that the percentage of peak load increases when the thickness of slab specimens increases from 20 to 60 mm, the peak load increased to 38.2 and 25.9% for non-heat specimens and heat-treated respectively and mixes containing 1% micro steel fibers. This result ensures that the slab thickness has a significant effect on shear strength of RPC slabs under heat or non-heat-treated. Also for the same mixes, it can be noticed that in increasing the slab thickness, the deflection at peak load shows significant decreases from 9.1 mm (RPC1-20/N) to 4.2 mm (RPC1-60/N) and 10.2 mm (RPC1-20/H) to 5.3 mm (RPC1-60/H) for non-heat treated and heat-treated respectively.

It is clear from the above Table that the thin slab with 20 mm thickness seems clearer in ductility behavior in comparison to the slab specimens. From the test results, it is clear that the role of slab thickness on the behavior of slab specimens, the values of mid-span deflection of slabs increases with decreasing of slab thickness. This indicates that the use of RPC allows for smaller, thinner, lighter sections to be designed while strength is still maintained or even improved and taking advantage by minimizing material usage and cost in addition to reducing the weight of slabs. The appearance of the RPC slab specimens after failure is shown in Figure 12.

Conclusions

The following observations and conclusions can be made on the basis of the current experimental results.

1. Test results showed that RPC has very high mechanical performance. Heat-treatment method seems very effective way to increase the compressive strength of RPC. This can be attributed to the improvement of hydration process under these curing regimes. Compressive strength of RPC with water-cementitious material ratio of 0.18 exceeded 190 MPa after heat-treatment curing in this study.
2. The inclusion of steel fibers leads to a considerable increase in splitting tensile strength and flexural tensile strength while the increase in compressive strength and modulus of elasticity is relatively lower. Therefore, it is recommended to use steel fibers as an enhancing material to RPC.
3. It was observed that fibers tend to align in the direction of the flow of the material and also with the formwork.
4. In this study, it was observed that the amount of ultra fine steel fibers in RPC slabs has an influence on the value of the peak load and deflection.
5. The experimental results clearly indicate that the presence of ultra fine steel fibers in RPC slabs resulted in an enhanced stiffness, reduced crack width, reduced rate of crack propagation.
6. In thin RPC slabs, the presence of steel fibers provides sufficient tensile strength and ductility even if conventional reinforcement is avoided. This allows the designer to reduce the amount of reinforcement needed to resist tension for many structural applications with

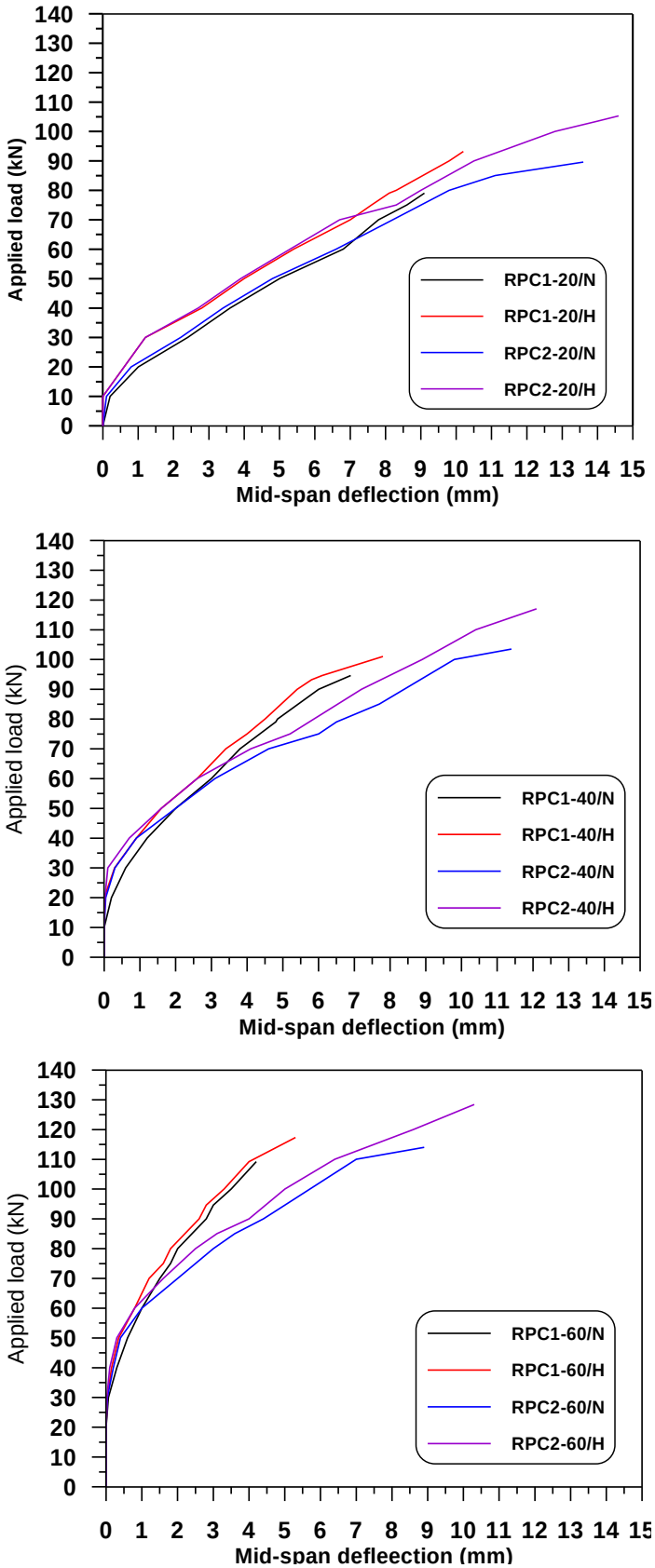


Figure 11. Effect of curing condition on load - mid-span deflection curves of RPC slab.

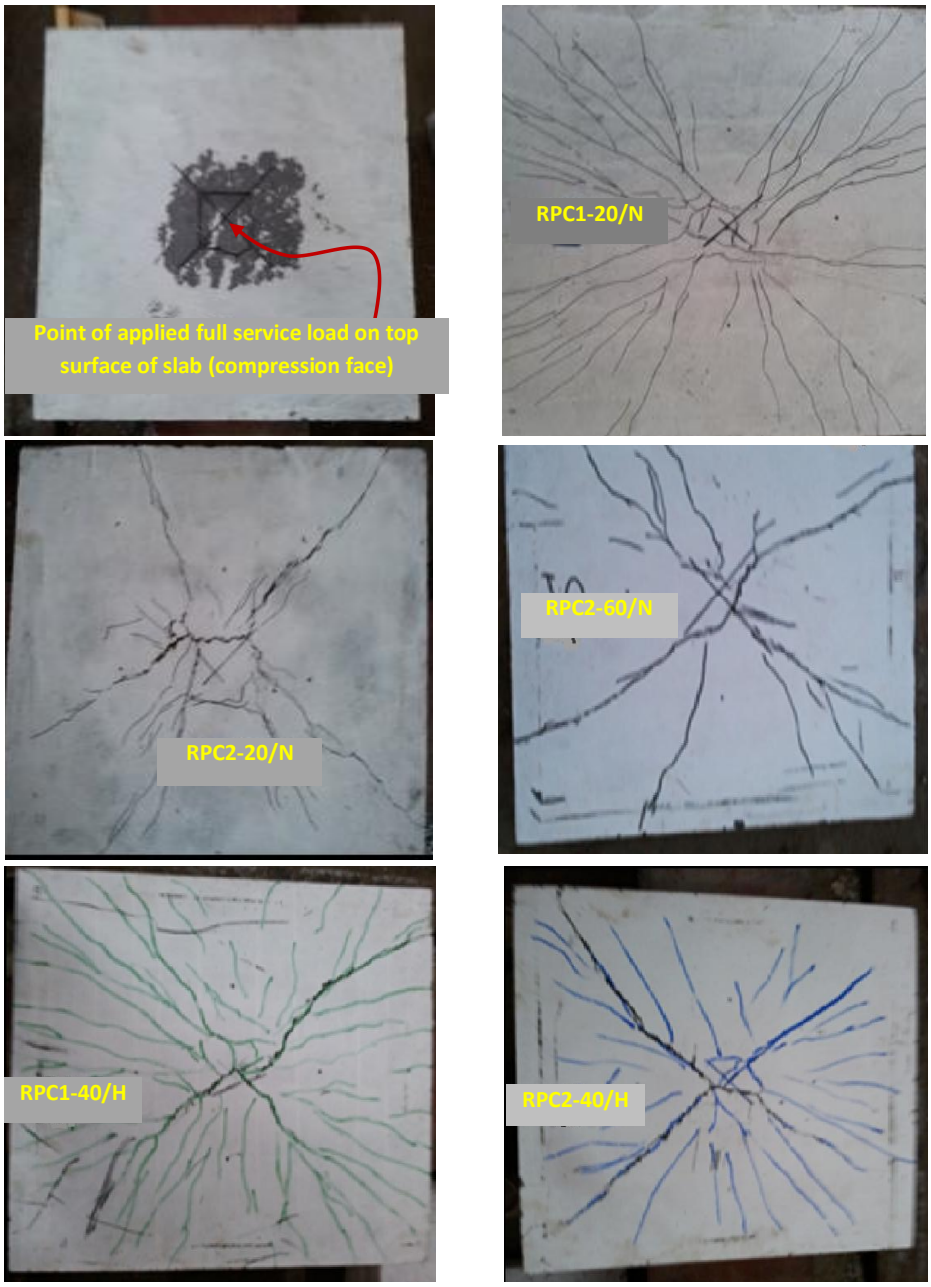


Figure 12. Typical crack patterns of slab specimens after failure at bottom view of failure (tension face).

beneficial effects on the cost and self weight and make it possible to create thinner sections, longer spans, and taller structures.

7. All the slabs behave similar in the aspect of failure patterns under load regardless of the variables. The using of heat-treatment method increases the first crack and ultimate loads of slab specimens.

8. Due to presence of fibres ductile failure is observed. In fact crack get arrested by fibres does not get fractured but pulling out of fibres from matrix is observed.

Conflict of Interest

The author have not declared any conflict of interest.

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