J. Eng. Technol. Sci., Vol. 54, No. 3, 2022, 220302

Flexural Behavior of the Layered Beams Containing Reactive Powder Concrete and Self-Compacting Concrete

Aseel A. Abdulridha, Sura A. Abbas*, Lubna S. Danha & Zainab H. Shaker

Department of Civil Engineering, University of Technology-Iraq, Al-Sinaa St.,
Baghdad 10066, Iraq
*E-mail: 40348@uotechnology.edu.iq

Highlights:

- Study of the effect of partial use of RPC on the flexural behavior of reinforced concrete beams with the thickness of the RPC layer and its position as the main variables.
- Study of the effect of the partial use of RPC on the first crack load (Pcr), the ultimate flexural load (Pu), the maximum deflection (Δmax), the load-deflection response, and the crack pattern of beams.
- Study of the influence of RPC layer thickness and its location (in the tensile zone or the compressive zone) of the concrete beam.

Abstract. Reactive powder concrete (RPC) possesses superior structural and mechanical characteristics. Despite these excellent properties, the main drawback of RPC is that it is a very costly material. This study included an experimental program for studying the flexural behavior of hybrid beams containing RPC together with self-compacting concrete (SCC) in the same section. Five specimens with dimensions of 100 x 150 x 1000 mm were investigated. The first crack load, ultimate load, maximum deflection, load-deflection response, and crack pattern were investigated. The experimental program included testing five reinforced concrete beams with four-point loading. The specimens were cast as follows: full depth of self-compacting concrete; full depth of reactive powder concrete; half of the section depth of RPC (tension zone); quarter of the section depth of RPC (tension zone); and half of the section depth of RPC (compression zone). The experimental results of the hybrid beams showed that using RPC in the tension zone of the beam significantly improved the performance of the hybrid beams when compared with the SCC beam. The improvement rate increased with the RPC layer thickness in the tension zone. Using RPC in the compression zone together with SCC did not produce a significant improvement in the performance of the hybrid beams.

Keywords: *flexural strength; hybrid beams; mechanical properties; reactive powder concrete; self-compacting concrete.*

Received 5 April 2021, 1st Revision August 20th, 2021, 2nd Revision September 30th, 2021, Accepted for publication November 10th, 2021.
ISSN: 2337-5779,
DOI: 10.5614/j.eng.technol.sci.2022.54.3.2

1 Introduction

Concrete is the most broadly utilized building material in most parts of world. Very often it is used for flexural members such as beams and slabs, and compression members like structural columns [1]. The approaches utilized in reinforced concrete beam (RCB) analysis are different from those employed in designing beams completely consisting of steel, wood, or any other construction material, because RCB is heterogeneous, i.e., produced from two completely different materials. The parameters considered are basically the same: in a cross-sectional beam there are interior forces that are resolved into two components: normal and tangential to the beam section. Normal components represent the bending stresses (compression at one side of the neutral axis and tension at the other). Their function is to withstand the bending moment in this section. Tangential components are exposed to shear stresses and also withstand transverse or shear forces [2]. The design criteria for hybrid elements are based on the idea that when the structure is exposed to drastic environmental circumstances, the resistance or stiffness of the structural elements should be raised without raising the dead weight at the points of focused load application. Therefore, enhanced performance materials like ultra-high-performance concrete are used. However, the use of these materials must be minimized due to their high price. Therefore, HPC is used in some parts of the structure, whereas the other components are made of normal strength concrete (NSC) [3].

RPC is the latest and highly important development in the technology of concrete. In recent years, it has received great interest owing to its excellent mechanical properties, such as high durability and ductility, high strength, restricted shrinkage, and high corrosion resistance [4]. Also, RPC is recognized as an ultra-high performance concrete (UHPC) according to its excellent structural performance. RPC contains a large cement proportion, fine sand (particle size ≤600 mm), superplasticizer, steel fibers, silica fume, and a low water/cement ratio (<0.2) [5]. Despite its excellent properties, a major drawback of RPC is that it is a very expensive material. From an economical point of view, shortening the time of construction operations and cost reduction are crucial. Self-compacting concrete (SCC) is produced using mineral admixtures as well as superplasticizing chemical additives [6]. This type of concrete fills the framework in a normal way, passes obstructions, and consolidates under its own weight without requirement for vibration. Also, the action required to place and finish self-compacting concrete is minimized as is the noise linked to vibration [7-9].

Many researchers have studied hybrid concrete beams. Wasan and Tayfur [10] studied the flexural behavior of ultra-high performance reinforced concrete beams comprising crimped and hooked steel fibers at various percentages (0.5%, 0.75%, and 1%) in complete and incomplete depths of the beam's cross sections.

The effect of steel fiber addition on the load-deflection relation, maximum load, ultimate moment capacity, and cracking pattern was investigated, and the maximum tensile strength of the beams was re-derived and used for calculating the capacity of moment.

Sarsam and Mohammed [11] studied the flexural conduct of hybrid reinforced concrete beams by using NSC and RPC. The results showed that the increase in maximum load was determined by the thickness increase of the reactive powder concrete layer, the ratio of longitudinal reinforcement, and the volumetric ratio of steel fibers in the hybrid beams with reactive powder concrete, in both tension and compression. Also, the ratio of longitudinal steel had a greater effect than the other factors.

Al-Hassani, *et al*. [12] investigated the flexural behavior of hybrid T-beams by using RPC with NSC in the same section. The outcomes showed that when compared with an NSC T-beam, using reactive powder concrete in the web significantly improved the performance of the hybrid T-beams. The increases in initial crack load (Pcr), ultimate loading capacity (Pu), and maximum deflection were 86.67, 60, and 29.19%, respectively, and the increases when using RPC in the flange were 20, 34.28, and 14.97%, respectively.

Pająk and Ponikiewski [13] studied the behavior of hybrid steel fiber reinforced self-compacting concrete under flexure test. The influence of the combined usage of corrugated and straight steel fibers was investigated with steel fiber type and length, cross-sectional shape, and percentage of steel fibers as the variables. The results indicated that the flexural parameters were obviously improved in the hybrid fiber reinforcement self-compacting concrete due to addition of hybrid fibers. Using a higher percentage of steel fibers (more than 2%) did not result in higher values of the flexural variables.

Deng, *et al.* [14] studied the flexural behavior of reinforced concrete beams that were strengthened via highly ductile fiber reinforced concrete as well as reactive powder concrete in the tension and compressive zones. The experimental results showed that the flexural capacity of the specimens strengthened by a HDC layer in the tension zone remarkably increased, and the specimens strengthened by an RPC or HDC layer in the compression zone revealed much higher ductility than the control specimen.

Yaarub and Hind [15] investigated the flexural behavior of hybrid reinforced concrete beams combining ultra-high strength concrete (UHSC) in the compression zone with proclinate aggregate lightweight concrete (LW) in the tension zone. The variables were RPC layer thickness (0, 50, 100 and 200 mm) and longitudinal reinforcement ratio ($\rho = 0.0033$ and $\rho = 0.0227$). The results showed that the initial and maximum loads increased when the RPC layer thickness was increased.

Danha, *et al.* [16] presented the flexural behavior of hybrid ultra-high performance concrete (UHPC). The variables included the steel fiber percentage and the depth of the content fraction of the steel fibers. The results showed that utilizing steel fibers in the tension zone significantly improved the UHPFRC's flexural efficiency, and the most effective depth of the content fraction of steel fibers was 75% of the cross-section of the specimen.

Insufficient experimental work has been done on hybrid reinforced concrete beams under flexure. Therefore, in the present study, SCC and RPC were used in reinforced beams to take the advantage of these two types of concrete in an optimum manner.

2 Methodology

2.1 Materials

RPC mix: Portland cement – type I; steel fibers with 0.2 mm diameter, 15 mm length, 70 aspect ratio, and 2000 MPa maximum tensile strength; silica fume with 650 kg/m^3 bulk density; quartz sand with 2.57 specific gravity; and a superplasticizer (Sika Viscocrete 2810) with 1.07 relative density were used to reduce the water/cementitious ratio. Figure 1 shows the steel fibers that were utilized in the present research.

Figure 1 Steel fibers used in RPC.

SCC mix: Portland cement – type I; fine aggregate: natural sand was utilized as fine aggregate with 2.36 fineness modulus and maximum size 4.75 mm; 12 mm maximum size crushed gravel with 2.62 specific gravity was utilized as coarse aggregate; and the superplasticizer used was Sika Viscocrete 2810. Limestone powder was utilized as filler material for the self-compacting concrete, with fineness 315 m^2/kg and a white color. To achieve the specifications of self-compacting concrete, a theoretical mix design was conducted for the required compressive strength of concrete. Slump flow, V-funnel, L-box, and T50 tests were performed and compared with the limitations of EFNARC- 2002 [17] and ACI 237R-07 [18], as shown in the Table 1. Figure 2 shows the tests of the fresh self-compacting concrete. The mix proportions of the two types of concrete (RPC and SCC) are given in Table 2.

Table 1 Test results for fresh SCC.

Test method	Results	EFNARC-2002 [17]	ACI-237R-07 [18]
Slump flow (mm)	710	650-800	450-760
T500 (sec)	2	2-5	2-5
L-box (H2/H1)	0.8	0.8-1	0.8-1
V-funnel (sec)	9	6-12	-

Table 2 Mix proportions for RP and SC concrete.

Concrete type	SC	RPC
Cement (C) (kg/m^3)	420	1030
Gravel (G) (kg/m^3)	910	---
Sand (S) (kg/m^3)	810	---
Limestone powder (kg/m^3)	170	---
Silica fume (kg/m^3)	---	240
Super-plasticizer (kg/m^3)	5	46.4
Water (kg/m^3)	185	216
Water/cement	0.44	0.21
Steel fibers (%)	---	2

Figure 2 Fresh self-compacting concrete tests.

2.2 Mixing, Casting and Curing Procedures

All specimens were cast in horizontal wooden molds with dimensions of 100 mm × 150 mm × 1000 mm. The mixtures of SCC and RPC were prepared utilizing a rotary mixer; adequate blending is essential for achieving the required effectiveness and consistency of the concrete. In the RPC mixtures, prolonging the blending time is essential for completely dispersing the silica fume and breaking up any agglomerated particles, and to permit the complete prospective evolution of the superplasticizer agent. For specimens with two layers, the casting was conducted in two stages, the initial stage being the pouring of RPC inside the molds until the portion of depth needed. The second stage begins with pouring of SCC up to the top of the mold. After 24 hours, all specimens were stripped, marked and located in curing tanks for 28 days. The cast specimens are shown in Figure 3.

Figure 3 The cast specimens.

2.3 Tested Specimens

Five RC beams with a length of 1000 mm long and a rectangular cross-section with 150 mm depth and 100 mm width were tested. The simply supported specimens were loaded with two equivalent concentrated loads located at the middle third of the beam span, as shown in Figure 4. Longitudinal reinforcement ratio ρ = 1.88% and fy = 560 MPa was used in the tension zone of the beams. To ensure that all the beam specimens would fail in flexure, the shear reinforcement was kept constant with the appropriate quantity (8 mm stirrups at 50 mm spacing) in all beams.

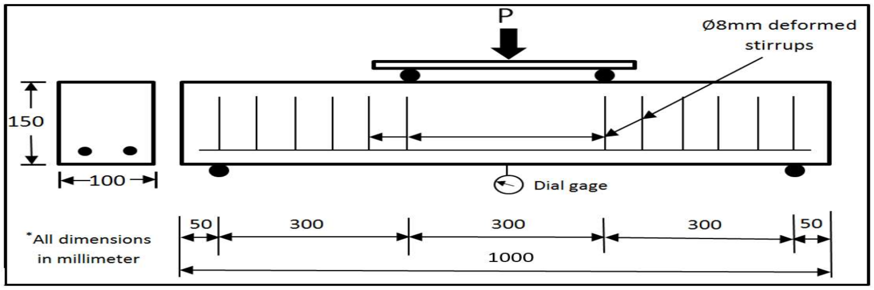

Figure 4 Details of the tested beams.

3 Experimental Program

The five reinforced concrete beams were built and examined in the lab of the University of Technology at Baghdad-Iraq. These five specimens were utilized for investigating the effect of the partial use of RPC on the behavior of a rectangular beam in comparison with a fully SCC beam as well as a fully RPC beam. Figure 5 shows the cross-sections of the tested beams.

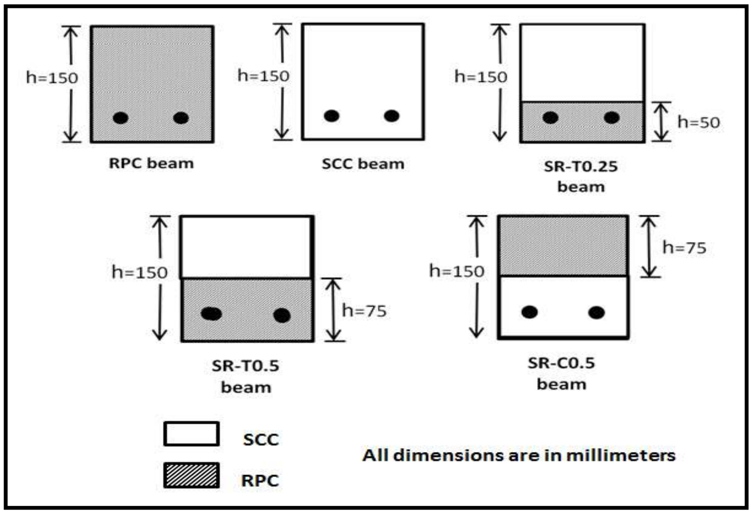

Figure 5 The cross-sections of the tested beams.

4 Test Setup and Instrumentation

A hydraulic machine with 2500 kN capacity was used to test the beams with a rate of loading of 10 kN/min until failure. The crack propagation was drawn at each loading stage. A dial gauge was utilized for measuring the deflection at the beams' mid-span. Figure 6 presents the beam under testing utilizing the testing machine.

Figure 6 Beam testing setup.

5 Concrete Mechanical Properties

Compressive strength (*fc'*), modulus of rupture (*fr*) and splitting tensile strength (*ƒsp*) of SCC as well as RPC are listed in Table 3. For each test, the required ACI 318M-11 code [19] was used to obtain the mean strength of the three specimens for each test.

Table 3 Mechanical properties of the concrete.

Type of Concrete Mix	fc' (MPa)	ƒsp (MPa)	fr (MPa)
SCC	33.8	3.1	3.5
RPC	110.6	12.14	17.31

6 Results and Discussion

Comparisons of the experimental outcomes of the reference specimens (SC) with the specimens of RP, SR-T0.5, SR-T0.25, and SR-C0.5 are indicated in Table 4. The following can be observed from the results:

First crack load: Figure 7 shows the first crack load for each specimen. For the fully RPC beam, the first crack load increased by 278.26% in comparison with the fully SCC beam, whereas the increase percentages for beams SR-T0.5, SR-T0.25 and SR-C0.5 were 82.6%, 34.78% and 17.39%, respectively. It is obvious that beams SC and SR-C0.5 had an approximate magnitude of the first crack load; this is due to the tension zone of these beams containing the same self-compacting concrete. For beams SR-T0.25 and SR-T0.5, containing RPC in the lower part, the cracking load increased with increasing RPC layer thickness.

Table 4 The results for the tested beams.

Beams	SC	RP	SR-T0.5	SR-T0.25	SR-C0.5
Pcr* (kN)	6.8	26.1	17.6	11.3	7.5
(Pcr – Pcr SC) / Pcr SC × 100	0	278.26	82.6	34.78	17.39
Pult** (kN)	69	111.6	87.7	81.2	76.6
(Pult – Pult SC) / Pult SC × 100	0	61.74	27.1	17.68	9.57
(Pcr / Pult) × 100	9.86	25.69	20.07	13.92	9.79
Δmax (mm)	6.8	12	9.5	8.7	8.1
(Δmax – Δmax SC) / Δmax SC ×100	0	76.47	39.71	27.94	19.12

Pcr*: First crack load
Pult**: Ultimate load (failure load)

A significant increase of the first crack load of the fully RPC beam was observed as compared with the fully SCC beam. The increases in first crack load for beams SR-T0.25, SR-T0.5 and the fully RPC beam as compared with the SCC beam were because of the presence of steel fibers in the tension zone delaying the formulation and propagation of cracks due to the enhanced bond strength. There was no improvement in first crack load when using RPC in the compression zone for beams as compared with the fully SCC beam.

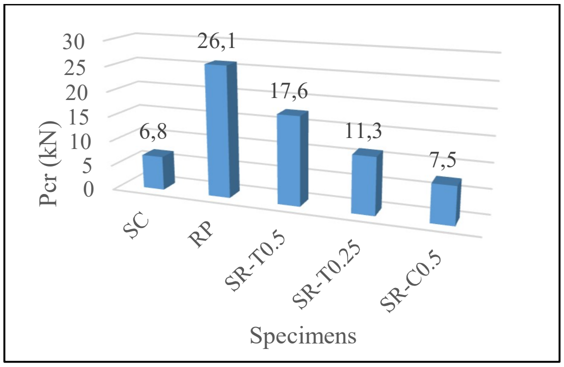

Figure 7 The first crack load of the beams.

Ultimate load: Figure 8 shows the ultimate load for all beams. For the fully RPC beam, the ultimate flexural strength increased by 61.74% in comparison with the fully SCC beam, whereas the increase percentages for beams SR-T0.25, SR-T0.5 and SR-C0.5 were 17.68%, 27.1% and 9.57%, respectively, as compared with the fully SCC beam. Obviously, the usage of RPC in the tension zone of the beam improved the maximum flexural strength, and this improvement was proportional to the thickness of the layer of RPC. This improvement may be due to enhancing the stiffness and the mechanical properties of the beams that contain RPC, such as the elasticity modulus, tensile strength, and compressive strength of the concrete.

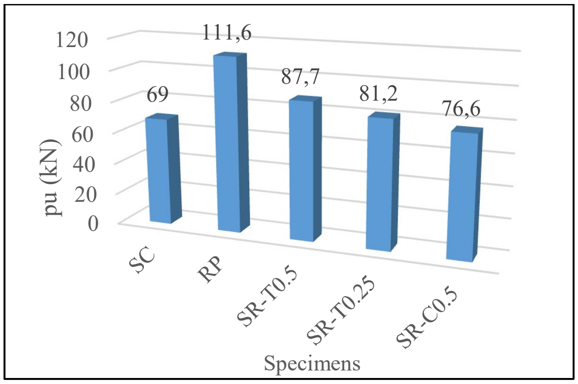

Figure 8 The ultimate load of the beams.

Deflection: Figure 9 shows the deflection values of the beams. It is obvious that the presence of reactive powder concrete in the section led to an increase of the ultimate deflection (Δmax). The increase percentages of ultimate deflection were 76.47, 39.71, 27.94, 19.12% for the fully RPC beam, SR-T0.5, SR-T0.25 and SR-C0.5, respectively, as compared with the fully SCC beam. This behavior may be due to the presence of steel fibers in the RPC section.

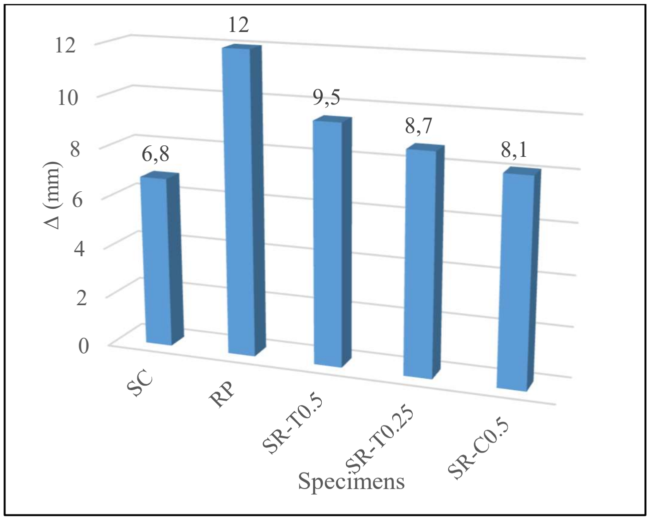

Figure 9 The deflection values of the beams.

Compared to SCC, the loading capacity (Pult) enhanced the loading capacity, and the deflection increased due to the presence of steel fibers, which act as a mechanical interlock with the concrete matrix. This means that the hybrid beams that contained RPC, especially in the tension zone, were more ductile as compared with the SCC beam. For concrete structural members, this property is very important to give a warning prior to failure and to avoid abrupt breakdown.

Load-Deflection curves: Figure 10 shows the load-deflection curves as documented from the investigational testing data. In general, the curves have three parts: the elastic stage part represents the linear behavior under a low applied load until the first crack load (Pcr); the second part represents the yielding of the tensile reinforcement steel, which shows a steady increase in both concrete compression and tensile stresses of the reinforcing bars after cracking of the tension zone of the beam; and the third part represents the yielding of the tensile steel, the extension and growth of the cracks until failure of the beams. The load-deflection curves of the fully SCC beam and SR-C0.5 have an approximate slope linearly in step with the first crack load. After the first crack load, the curve takes a different path due to the weakness of SCC in comparison with RPC. It is obvious that the energy absorption capacity of the beams (which is represented by the area under the load-deflection curve) increased with the presence of RPC in the section of the beam.

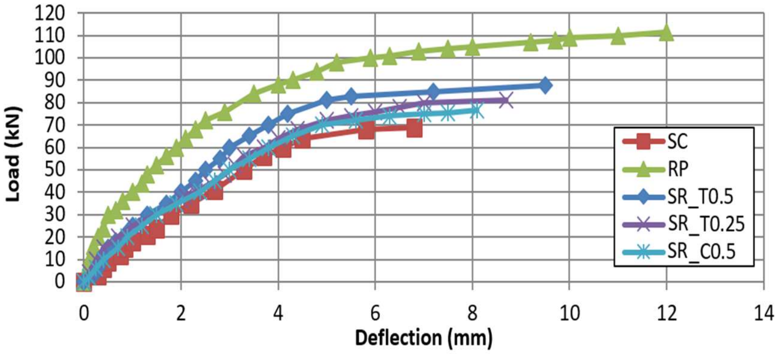

Figure 10 The load-deflection curves of the beams.

Generally, in an RPC beam, in the pre-cracking stage, under an external force, the load is transferred by the reactive powder concrete matrix to the steel fibers through interfacial adhesion. Both the RPC matrix and the steel fibers sustain the load together. The loading capacity is enhanced, and the cracking is delayed compared to NSC. After cracking, the load is sustained by the steel fibers only through mechanical interlock and friction at the matrix-fiber interface. After the fibers are pulled out, the crack energy is absorbed, and the ultimate deflection and load are increased.

7 Crack Patterns

The crack patterns of the SCC, RPC and hybrid beams are shown in Figure 11. It can be seen that the fully SCC beam and the hybrid beam with SCC in the tension zone (SR-C0.5) had fewer wide cracks as compared with the fully RPC specimen. Meanwhile, beams SR-T0.25 and SR-T0.5, with RPC in the tension zone, had thin cracks in this zone.

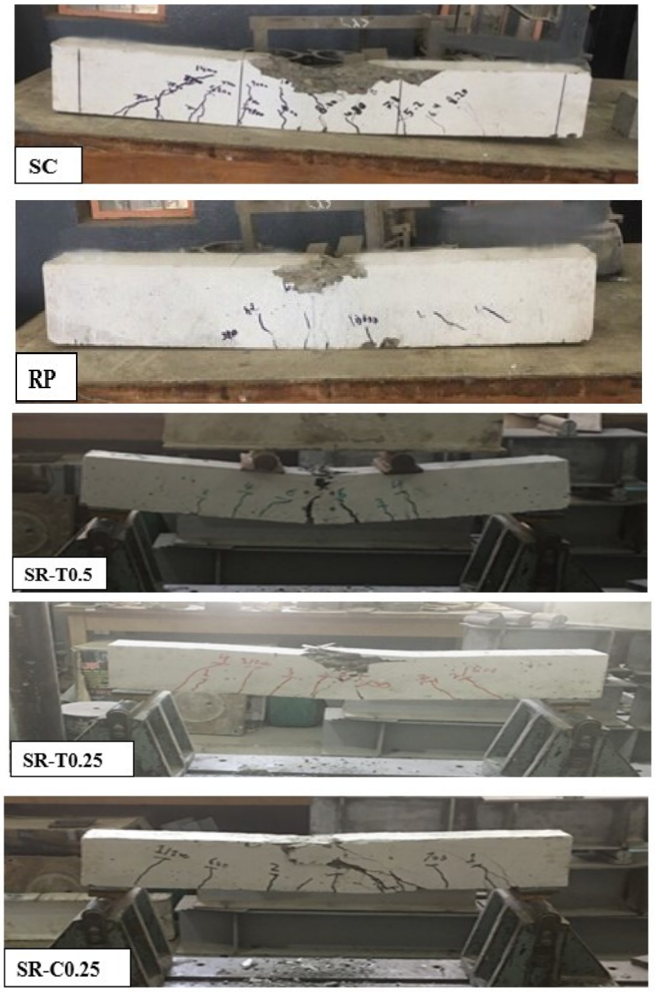

Figure 11 Crack patterns in the tested specimens.

8 Conclusions

Usage of RPC in the tension zone together with self-compacting concrete in hybrid beams showed an increment in the (Pcr), the ultimate flexural load (Pu), the maximum deflection (Δmax), and the energy absorption capacity of the beams as compared with a fully SCC beam. This increase was directly proportional to the RPC layer thickness. The fully RPC beam showed a significant increase in initial crack load (Pcr) by 278.26%, in ultimate flexural strength by 61.74%, and in ultimate midspan deflection by 76.47% as compared with the fully SCC beam. The presence of RPC in the tension zone (at 50%) of the hybrid beam manifested an increase in first crack load (Pcr) by 82.6%, in ultimate flexural load (Pu) by 27.1%, and in ultimate midspan deflection (Δmax) by 39.71% as compared with the fully SCC beam. Meanwhile, the presence of RPC in the tension zone (with a percentage of 25%) of the hybrid beam exhibited an increase in first crack load (Pcr) by 34.78%, in ultimate flexural load (Pu) by 17.68%, and in ultimate deflection (Δmax) by 27.94% as compared with the fully SCC beam. The presence of RPC in the compression zone (with a percentage of 50%) of the hybrid beam showed an insignificant rise in first crack load (Pcr) by 17.39%, in ultimate flexural load (Pu) by 9.57%, and in ultimate deflection (Δmax) by 19.12% as compared with the fully SCC beam.

References

[1] Prakash, R., Thenmozhi, R. & Raman, S.N., *Mechanical Characterisation and Flexural Performance of Eco-friendly Concrete Produced with Fly Ash as Cement Replacement and Coconut Shell Coarse Aggregate*, International Journal of Environment and Sustainable Development (IJESD), **18**(2), pp.131-148, 2019.

[2] Arthur, H.N., *Design of Concrete Structures*, 14th Edition, David Darwin and Charles W. Dolan, pp. 67, 2010.

[3] Habel, K., *Structural Behavior of Elements Combining Ultra-High Performance Fiber Reinforced Concretes (UHPFRC) and Reinforced Concrete*, Ph.D. Thesis, Ecole Polytechnique Federal De Lausanne, Switzerland, 2004.

[4] Richard, P. & Cheyrezy, M., *Reactive Powder Concrete with High Ductility and 200-800 MPa Compressive Strength*, American concrete institute, ACI SP144-24, **144**, pp. 507-518, 1994.

[5] Richard, P. & Cheyrezy, M., *Composition of Reactive Powder Concrete*, Cement and Concrete Research, **25**(7), pp. 1501-1511, 1995.

[6] Prakash, R., Raman, S.N., Divyah, N., Subramanian, C., Vijayaprabha, C. & Praveenkumar, S., *Fresh and Mechanical Characteristics of Roselle Fibre Reinforced Self-compacting Concrete Incorporating Fly Ash and*

Metakaolin, Construction and Building Materials, **290**(1), 123209, pp.1-14, 2021.

[7] Pająk, M., *Investigation on Flexural Properties of Hybrid Fiber Reinforced Self-Compacting Concrete*, Procedia Engineering, **161**, pp. 121-126, 2016.

[8] Rambo, D.A.S., Silva, F.A. & Filho, R.D.T., *Mechanical Behavior of Hybrid Steel-Fiber Self-Consolidating Concrete: Materials and Structural Aspects*, Materials and Design, **54**, pp. 32-42, 2014.

[9] Pająk, M. & Ponikiewski, T., *The Laboratory Investigation on the Influence of the Polypropylene Fibers on Selected Mechanical Properties of Hardened Self-Compacting Concrete*, Architecture Civil Engineering Environment, **3**(3), pp. 69-78, 2015.

[10] Wasan, I.K. & Tayfur, Y.R., *Flexural Strength of Fibrous Ultra High Performance Reinforced Concrete Beams*, ARPN Journal of Engineering and Applied Sciences, **8**(3), PP. 200-214, 2013.

[11] Sarsam, K.F. & Mohammed, M.H., *Flexural Strength of Hybrid Beams Containing Reactive Powder Concrete and Conventional Concrete*, Journal of Engineering and Development, **18**(5), pp. 61-91, 2014.

[12] Al-Hassani, H.M., Al-Kafaji, J.M. & Ismael, M.A., *Flexural Behavior of Hybrid Tee Beams (Containing Reactive Powder Concrete and Normal Strength Concrete)*, Journal of Engineering and Development, **19**(2), pp. 123-140, 2015.

[13] Pająk, M. & Ponikiewski, T., *Experimental Investigation on Hybrid Steel Fibers Reinforced Self-Compacting Concrete under Flexure*, Procedia Engineering, **193**, pp. 218-225, 2017.

[14] Deng, M., Ma, F., Ye, W. & Li, F., *Flexural Behavior of Reinforced Concrete Beam Strengthened by HDC and RPC*, Construction and Building Materials, **188**, PP. 995-1006, 2018.

[15] Yaarub, G.A. & Hind T., *Flexural Behavior of Hybrid Reinforced Concrete Beams Combining Ultra High Strength Concrete and Porecilenite Aggregate Lightweight Concrete*, Journal of Engineering and Sustainable Development, **23**(6), pp. 178-193, 2019.

[16] Danha, L.S., Abdul-hussien, Z.A., Abduljabbar, M.S. & Yassin, L.A.G., *Flexural Behavior of Hybrid Ultra-High-Performance Concrete*, IOP Conf. Series: Materials Science and Engineering, **737**, 012008, 2020.

[17] European Federation for Specialist Construction Chemicals and Concrete Systems (EFNARC), *Specification and Guidelines for Self-Compacting Concrete*, 2002.

[18] American Concrete Institute (ACI 237R-07), *Self-Consolidating Concrete*, 2007.

[19] American Concrete Institute (ACI 318M-11), *Building Code Requirements for Concrete and Commentary*, Farmington Hills, MI 48331, 503, USA, 2014.