Behavior of Reinforced Reactive Powder Concrete Two-Way Slabs with Openings

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Abstract. The principal of using the material regarding to its strength and durability within the service life of the structure while reducing the energy and resource consumption due to the construction and operation of a structure is called sustainable structural engineering, it is enlargement of sustainable construction in the future regarding to the standard concrete. Reinforced concrete slabs (solid and with openings) represents one of the common essential fundamental elements and are generally employed in many kinds of engineering constructions and applications. Reactive Powder Concrete (RPC) is a new ultra-high-performance concrete which tends to exhibit superior properties, high durability, and long-term stability, in form of superplasticizer, cement mixture with silica fume, steel fiber (of varying types, sizes, and geometries), and the fine glass of (<600 µm). Ten reinforced concrete slabs with different variables (opening shapes, opening locations, opening size and steel fiber content) were casted and tested to study the behavior of RPC material in flexure in term of deflection, concrete strains, and ultimate loads. RPC has better performance in term of flexural behavior, cracking control and deformation control. Preliminary investigation tests were conducted to study the fresh and hardened properties of concrete. The results show that increase in steel fiber content leads to an increase in the failure load and consequently increase in maximum deflection and the flexural toughness increases.

1. Introduction
In engineering application, openings are frequently encountered. The behavior of openings progresses the complexity of the analysis of constructing fundamental members. A manufactured hole is an identity that is produced by extracting material [1, 2], and heads to a crack that is produced by any kind of failure mechanism without transferring material. Openings are common in the building, construction, and structural engineering. Usually, it appears that constructions require to be rehabilitated due to various circumstances, or to specific situations. These situations are the demand for openings to be formed, in remarkable circumstances, the demand for openings in slabs represent an example of the most typical obstacles found in the structural engineering during employing reinforced concrete slabs [3, 4]. Post-construction establishment of elevators, installing different staircases, escalators, supplementary skylights pipes, fire shield pipelines, heat and air-conditioning channels, services (communications, power and wiring channels) and constructive characters are often expected within the current level slabs, openings ordinarily require to be performed, modifying the current floor arrangement. [4, 5]

2. Reactive powder concrete (RPC)
UHPC, further identified as (RPC), is ultra-high-strength, ductile and high-performance material expressed by merging Portland cement, silica fume, fine silica sand, high-range water minimizing, water, and steel fibers [6, 7]. Reducing concrete brittleness by inserting a specific volume of small steel fibers in the matrix which can enhance the toughness of mixture. It can be applied in various application domains, e.g. civil engineering, water-powered engineering, tunneling engineering, bridge installation and service work [8, 9]. The essential characteristics of RPC mixture composition involve extremely high Portland cement content, remarkably low w/cementitious proportions including essential dosages of the advanced generation of superplasticizers, the inclusion of high pozzolan material and the
association of exceptional steel fibers for reinforcement [9, 10]. In RPC, substances with special silica content are essential for excellent performance and greater strengths [11, 12]. These elements produce chemically effective silicate which assists to generate higher amounts of calcium silicate hydrate (C-S-H), where high quantities of C-H-S improve the strength of the adhesive and enhance the connection between cement and aggregate. superplasticizer (water reducing) (HRWRA) is applied to compose flowable concrete with high strength and durability [13, 14].

3. Details of two-way reinforced concrete slabs with openings
Ten two-way RC slabs with the dimension of (660x660x40mm) were cast in the laboratory and tested under four symmetrical concentrated point loads in order to engage the entire cross section and to simulate a distributed load around the opening. The slabs were supported along the four corners. The RPC proved to be effective in enhancing the load-carrying capacity of the slabs with openings. The slabs were designed to have flexure failure. All slabs were identical in size but different in openings shapes and location. Figure 1 shows the isometric view of the slabs and the geometry and reinforcement details. The slabs were internally reinforced isotropically with steel bars having reinforcement ratio of (ρx=0.0036) at the bottom in each direction, with bars of (4mm) diameter and spaced at (150mm) in each direction. The reinforcement was placed leaving (10mm) as concrete cover with an effective depth of (26mm average of the two directions). Table 1 show details of slabs specimens, overall dimensions, reinforcement details, opening sizes and locations. A study was carried out to determine the effect of opening shape, size and locations on the ultimate load capacity and stiffness and flexure capacity. Five values of steel fibers with volume fractions of (0, 0.5, 1.0, 1.5 and 2.0%), were used, in order to study the effect of steel fiber content on the flexural strength.

Table 1. Details of slabs specimens, overall dimensions, reinforcement, opening sizes and locations.

| Slab No. | Vf % Steel fiber | SF % Silica fume | Cement Kg/m³ | Sand Kg/m³ | Superplastizise Kg/m³ | F w/ e | ρ % | Wdth h (b) mm | Lenght h (L) mm | Dept h (b) mm | Openings size | Opening shape |
|----------|------------------|-----------------|--------------|------------|----------------------|-------|-----|---------------|----------------|--------------|----------------|---------------|
| S1       | 0                | 25%             | 1000         | 1000       | 4.8                  | 0.2   | 0   | 0.3          | 6              | 660          | 660            | 40            | 150x150/Center | Square        |
| S2       | 0.5%             | 25%             | 1000         | 1000       | 4.8                  | 0.2   | 0.1 | 0.3          | 6              | 660          | 660            | 40            | 150x150/Center | Square        |
| S3       | 1.0%             | 25%             | 1000         | 1000       | 4.8                  | 0.2   | 0.2 | 0.3          | 6              | 660          | 660            | 40            | 150x150/Center | Square        |
| S4       | 1.5%             | 25%             | 1000         | 1000       | 4.8                  | 0.2   | 0.3 | 0.3          | 6              | 660          | 660            | 40            | 150x150/Center | Square        |
| S5       | 2.0%             | 25%             | 1000         | 1000       | 4.8                  | 0.2   | 0.5 | 0.3          | 6              | 660          | 660            | 40            | 150x150/Center | Square        |
| S6       | 2.0%             | 25%             | 1000         | 1000       | 4.8                  | 0.2   | 0.5 | 0.3          | 6              | 660          | 660            | 40            | Solid         | -----          |
| S7       | 2.0%             | 25%             | 1000         | 1000       | 4.8                  | 0.2   | 0.5 | 0.3          | 6              | 660          | 660            | 40            | 100x100/Center | Square        |
| S8       | 2.0%             | 25%             | 1000         | 1000       | 4.8                  | 0.2   | 0.5 | 0.3          | 6              | 660          | 660            | 40            | 200x200/Center | Square        |
| S9       | 2.0%             | 25%             | 1000         | 1000       | 4.8                  | 0.2   | 0.5 | 0.3          | 6              | 660          | 660            | 40            | 150x150/Edge   | Shifting Square |
| S10      | 2.0%             | 25%             | 1000         | 1000       | 4.8                  | 0.2   | 0.5 | 0.3          | 6              | 660          | 660            | 40            | 170 Center     | Circle        |
4. Materials and Methods

4.1. Cement
ASTM Type I ordinary Portland cement, from Iraq Northern cement factory, was used in casting all specimens throughout the research work according to the [Iraqi specification No.5/1984 and ASTM C150-89].

4.2. Fine aggregate
For RPC silica sand (glass sand) as fine aggregate used in casting the slabs. It is very fine sand with a maximum size of 600µm. It is a crushed Iraqi silica rock brought from Al-Ramadi Glass Factory. Its grading satisfies the fine grading in accordance with the [B.S. specification No.882/1992 and Iraqi Specification No.45/1984], as shown in figure 2 which conformed to the chemical and physical requirements of ASTM C 618 class N Pozzolan.

4.3. Mineral Admixture Silica Fume (SF)
Silica fume is an extremely densified fine powder as shown in figure 2 with a grey color, with particles <100 times an average cement grain from (Basif Materials Company) has been used as a mineral admixture, conforms to the chemical and physical requirements of [ASTM C1240-04], it is a highly active pozzolanic material and is a by-product from the manufacture of Silicon or Ferro-silicon metal. The used percentage is (25%) of the cement weight (as an addition).

4.4. Chemical admixture high range water reducing agent (Superplasticizer)
A modified polycarboxylates based polymer (Sika ViscoCrete-PC20) yellowish liquid superplasticizer manufactured and supplied by SIKA® which used in preparing all the specimens as a high range water-reducing admixture as shown in figure 2. It has three functions, i.e. superplasticizer, viscosity modifying agent, and retarder increases compressive, tensile and flexural strength. The workability of the reactive powder concrete mixes was determined by flow tables test before casting concrete in molds. Water reduction was determined by increasing the dosage of superplasticizer gradually, adjusting the w/c ratio while maintaining the same workability for a flow of 90 as shown in figure 3. At the optimum dosage of superplasticizer, the water reduction reached its maximum value beyond this; there is no further water reduction in water content [ASTM C109/C109M-05 and ASTM C1240-03].
4.5. Steel reinforcement

One steel reinforcement ratios (0.36%) of (bar-Ø4mm) were used as shown in figure 4. The bars were uniformly spaced and placed in two directions at (150mm c/c) spacing each way to obtain the desired steel ratios. A clear cover of (10mm) giving an effective depth of 26 mm (average of two directions) for all slabs was provided.

4.6. Steel fibers

The proposed employment of steel fiber inside RPC demands that the fibers should be with very high tensile strength. Steel fibers constructed by (Hebei Yusen Metal Wire Mesh Company Ltd, China), $(L=13$ mm, $D=0.25$ mm, Tensile strength=2600 MPa, Modulus of Elasticity=210 GPa, Density=7800 kg/m$^3$, Cross section=Round and Aspect ratio $L/D=52$), as shown in figure 4, suited to the conditions of [ASTM A820/A 820M-04] for Standard II (Cut Sheet Fibers). A light brass (gold painted) layer was implemented to the fibers through the production process. According to [12], fiber regularly extends from 0.25 to 2% by volume.

5. RPC mix design (mixing procedure) and curing

The test program was divided into two stages. Preliminary investigation stage, tests were conducted to study the influence of using a different ratio of steel fiber on the properties of concrete. The second stage was conducted to study the flexural behavior of RPC reinforced slabs. The slabs, designed to have an appropriate dimension that can be manufactured, handled and tested easily as possible. Five types of RPC mixes were used with a volume ratio of (five volume ratios were considered 0, 0.5, 1, 1.5 and 2%) with 25% Silica fume. The best final mix which gave the highest values is 1: cement, 1: sand, 0.25: silica fume with water cement ratio 0.2 whose w/b ratio is 0.18 plus 4.8% by weight of the binder of SikaViscoCrete-PC20 admixture and max concrete compressive strength was 114 MPa at 28 days. Cement and silica fume were first mixed. This operation was sustained for 3 minutes to guarantee that
silicofume particles were completely separated consistently within the cement. Later, fine sand was placed inside the blender and combined for 5 moments; the substances were blended till a regular appearance was achieved. Next, the expected quantity of superplasticizer was suspended in water and agitated, and the solvent was joined continuously to the rotating machine and the entire mix components were joined for a satisfactory period. The blender was closed and mixing is maintained manually by hand to move the mix particularly for the parts not touched by the edges of the mixer. The mixer next is performed for 5 minutes to achieve consistent fluidity. This level was returned in three rounds to guarantee the uniformity of the mixture. Introduced the steel fibers and dispersed uniformly to the mixture by hand sprinkling and then the mixing system extended for a further 5 minutes figure 5. For slabs, the reinforcement mesh was carefully placed in its proper position. The opening was made by wood with different sizes and shape and fixed in their correct positions using bolts. The opening mold was covered with wide tape and oiled before casting, to prevent bonding between the mold and the concrete. Before casting, all specimen molds were well cleaned thoroughly, tightened well and their internal surfaces were lightly oiled to avoid and prevent the adhesion of hardened concrete to the internal surface of the molds. Then all specimens were filled with concrete mix and compacted by using external electrical vibrating table to remove the entrapped air voids as much as possible and to get well-compacted concrete and consolidate the mix into the mold, the process of vibration was continued until no further air bubbles appeared on the surface and the slab surface then leveled as shown in figure 5. After casting stage, all specimens were covered with plastic nylon sheets to prevent evaporation and loss of moisture from fresh concrete until final set had occurred and avoided cracks correlated with water-loss shrinkage. One day later, the units (slabs and cubes, cylinders and prisms) removed out of the molds, identified and later cured in the water tank for 27 days at the completion of the curing stage; all units were transferred from the containers and stored in the workroom continuously to the appointment of examination.

6. Concrete tests strength and mechanical properties of hardened concrete

6.1. Compressive strength:
Different types of tests for hardened concrete properties were made which are cylinders and cubes tested in compression and cylinders tested in indirect tension, prisms for flexure at the age of 28 days as shown in figure 6. Table 2 shows the average test results. The dimensions of the molds are shown in table 3. The compressive strength test was determined typically to [B.S-1881; part 116 and ASTM C39-2005]. (100x200 mm cylindrical specimens and 100x100 cube were employed to manage the compressive strength of RPC utilizing a digital compression examination device (ELE-Digital Elect2000) with load rate (15MPa per minute), According to [ASTMC109/C109M-05].

![Image](image_url)
Table 2. Details of reactive powder concrete (RPC) mixes and Properties of hardened concrete.

| Specimens Designation | SF by volume % | SF by weight of cement kg/m³ | Cement kg/m³ | Sand kg/m³ | SP % by binder cement-silica fume | Compressive Strength f'c (MPa) | Splitting Tensile Strength f'S (MPa) | Modulus of Rupture f'R (MPa) | Modulus of Elasticity E (GPa) | Density (kg/m³) |
|-----------------------|----------------|-----------------------------|--------------|------------|---------------------------------|-------------------------------|-------------------------------|---------------------|---------------------|----------------|
| Mix 1                 | 0.0            | 25%                         | 1000         | 1000       | 4.8%                            | 72                            | 6                             | 5                   | 36.1                | 2240.6         |
| Mix 2                 | 0.5            | 25%                         | 1000         | 1000       | 4.8%                            | 85                            | 8                             | 8                   | 40.7                | 2334.0          |
| Mix 3                 | 1.0            | 25%                         | 1000         | 1000       | 4.8%                            | 93                            | 11                            | 11                  | 43.1                | 2352.3          |
| Mix 4                 | 1.5            | 25%                         | 1000         | 1000       | 4.8%                            | 105                           | 13.5                          | 14                  | 46.8                | 2396.0          |
| Mix 5                 | 2.0            | 25%                         | 1000         | 1000       | 4.8%                            | 114                           | 15.8                          | 18                  | 50.1                | 2502.3          |

Table 3. Specifications of the control specimens.

| Type of test                  | Number and type of specimen | Specimen dimension (mm) |
|-------------------------------|-----------------------------|-------------------------|
| Compression                   | 3 cylinders for each mix    | 100diamx200 long        |
| Elastic modulus of elasticity| From compression test       | 50x50x50 cube           |
| Splitting tensile strength    | 3 cylinders for each mix    | 100diamx200 long        |
| Modulus of rupture            | 3 prisms for each mix       | 70x70x280               |

Figure 6. Concrete properties test.

When steel fiber increases from (0 to 0.5, 1.0, 1.5 and 2.0%) an increase in average compressive strength (0, 18.05556, 29.16667, 45.83333 and 58.33333%) as shown in table 4 and figure 7.

Table 4. Percentage increase in concrete properties, due to steel fiber content.

| Mix | Steel fiber content | Compressive Strength (MPa) | Compressive Strength (%) | Average Split (MPa) | Split (%) | Average Modulus of Elasticity (GPa) | Modulus of Elasticity (%) | Average Modulus of Rupture (MPa) | Modulus of Rupture (%) |
|-----|---------------------|-----------------------------|--------------------------|---------------------|----------|-------------------------------------|---------------------------|---------------------------------|------------------------|
| 1   | 0                   | 72                          | 0                        | 0                   | 0        | 36.1                                | 0                         | 5                               | 0                      |
| 2   | 0.5                 | 85                          | 18.05556                 | 8.5                 | 41.667   | 40.7                                | 12.74238                  | 8                               | 60                     |
| 3   | 1.0                 | 93                          | 29.16667                 | 11                  | 83.33    | 43.1                                | 19.39058                  | 11                              | 120                    |
| 4   | 1.5                 | 105                         | 45.83333                 | 13.5                | 125      | 46.8                                | 29.63989                  | 14                              | 180                    |
| 5   | 2.0                 | 114                         | 58.33333                 | 15.8                | 163.33   | 50.1                                | 38.78116                  | 18                              | 260                    |
Figure 7. Effect of steel fiber content on compressive strength results of RPC concrete mixes at 28-day age.

6.2. Modulus of Rupture

The regular examination for flexural strength [ASTM C1018], which implies experimenting simply supported third point loading beams, was utilized. Prisms of (70x70x280 mm) were provided typically to the [ASTM C348-02] terms. Modulus of rupture of RPC was prepared utilizing (ELE-Digital device) flexural testing device. The addition of steel fibers to concrete will give better characteristics and improve strength. This behavior is due to pore size and grain size refinement processes which strengthen the transition zone and reduce micro cracking in the interface. Table 4 and figure 8 shows the percentage increase in modulus of rupture due to steel fiber content.

Figure 8. Effect of steel fiber content on modulus of rupture results of RPC concrete mixes at 28-day age.

6.3 Splitting Tensile Strength

Splitting tensile strength test was conducted on cylinders of (100mm diameter×200mm height). The test was carried out in accordance with [ASTM specification C496-04] and tests were performed using a digital testing (ELE-Digital Elect 2000). The loading was applied at a rate of 1.5 MPa per minute. Table 4 and figure 9 shows percentage increase in average splitting tensile strength due to steel fiber content of RPC concrete mixes at 28-day age. When steel fiber increases from (0 to 0.5, 1.0, 1.5 and 2.0%) an increase in average splitting tensile strength (0, 41.66, 83.33, 125 and 163.33%). Fibers improve the characteristics of cement-based matrices during the hardening and in the hardened state; they are able to bridge cracks, to transmit stress across a crack and to counteract crack growth.

Figure 9. Effect of steel fiber content on Splitting tensile strength results of RPC concrete mixes at 28-day age.
6.4 Modulus of Elasticity

The Elastic modulus is completely affected by the concrete substances and proportions adopted. An improvement in the elastic modulus is presumed with an advance in compressive strength considering the ascending branch slope of the stress-strain diagram displays steeper for higher-strength concretes, although at a lower rate than the compressive strength. Table 4 and figure 10 shows the percentage increase in average modulus of elasticity results of RPC concrete mixes at 28-day age due to steel fiber content.

![Figure 10. Effect of steel fiber content on Modulus of Elasticity results of RPC concrete mixes at 28-day age.](image)

6.5 Flexural Toughness tests

Toughness determined in terms of areas beneath the curve of load-deflection relationship is evidence of the capability of the energy absorption of the selective examination specimen. ASTM [ASTM C1018-97] technique will be used to evaluate the flexural toughness. Toughness is affected in several processes by the quantity and type of fiber in the concrete matrix. To determine the area under the curve for different deflection intervals we need the program so, AutoCAD program and trapezoidal rule are used.

7. Concrete strain, deflection and crack width measurement (Installation of Demec Disc)

After proper curing, a smooth surface of the concrete slab is prepared by cleaning. Then, white paint was applied to the surface so that the cracks developed will be easily detected during the flexural test. Demec disc was installed on the concrete surface to obtain the strain reading during an experiment at different locations. The strain readings were obtained using 100mm gage length by the extensometer of 0.01 mm accuracy. 3 readings were taken for the two-way slab at the top face. The deflections were measured by using a dial gauge of 0.01mm/div accuracy was attached firmly to the bottom face of slabs in proper positions to record deflections at every load stage, Figure 11 shows demec point, extensometer, and dial gage, locations of demec point and dial gage position and crack meter used in test.

![Figure 11. Demec Point, Extensometer, Dial Gage, locations of Demec point and Dial Gage position used in test.](image)

8. Experimental test results analysis and discussion

The results presented include first cracking and ultimate load, crack patterns, strain in concrete, failure mode, load-deflection relations for each slab specimen. Before the day of testing, the slabs were taken out from the curing water tank and dried for one day in fresh air. The slab specimen was cleaned and painted with white color in order to clarify the crack propagation so that cracks can be easily detected and to give a more precise picture of the crack. Slabs were labeled and the locations of support points,
loading points, and the dial gage positions and demec point positions were marked on the surface. The dial gages were mounted in their marked positions to touch the bottom of slabs. The load magnitude for each load stage was chosen according to the expected strength of the slab. The experiment began with the employment of the load to position and monitor dial gauge, later unloading to zero. At zero loading, the original register of dial gages and mechanical strain gages were obtained. The load was implemented in steps. At any load increment, measurements were performed of crack improvement on the concrete slabs. Additionally, at various examinations, the first cracking load was registered and crack width is estimated and the mechanically measured demec strains reading were registered. Once this method was performed, loading was continued to the following load level and the corresponding system was developed. The positions and extents of the first and the other consequent cracks were marked on the surface of the slab. The loading was continued until ultimate load that recorded. All slabs supported at the corner were tested under four points loading which applied on the slab by external frame in sequence to distribute the entirety implemented point load into four-point loads utilized on the slabs. The single load was then equally divided into four point loads which were transferred to the concrete slab through the four plates supporting the bridge. (50x50mm) four steel rigid plates are connected at the edge of the rigid steel carrying support to obtain a four-point frame position on four solid steel support. The clear dimensions within certain steel posts are (560mm). Three dial gages were usually used for each slab; one was placed at the slab center or at the opening while the second under the point load and the third one at the center of the edge. Three pairs of demec discs were used to monitor the strain in concrete at selected levels of loading at several positions on the compression side of the slabs figure 12.

Figure 12. Testing procedures for two-way slabs.

Based on experimental load-deflection curves, as presented, the slabs have been seen to have the following three stages of behavior under applied load:

1. Elastic Stage (Untracked): Initial straight portion of the load-deflection curve, few hair cracks were spotted initiating at bottom of the slab. Fine flexural cracks were formed first, usually at the bottom face of the slabs close to mid-span. The width of these initial cracks was very small. After that, these cracks continued to propagate.

2. Elastic-Plastic Stage: flexural cracks were found to initiate at the bottom face of the slab central region and started to spread out towards the slab edges as load increased.

3. Plastic Stage (Post Yielding) a slight increase in the load as applied to test slabs was seen to cause a larger deflection. The rising portion of the load-deflection curve could mainly be attributed to strain hardening of reinforcement, biaxial bending in concrete.

9. Mode of failure crack pattern and general behavior
When the load was applied to the slabs, minor cracking at the central region took place early in the test and first cracking of the tension surface occurred when the load reached various percentages of the ultimate load depending on the load level. Four major cracks radiate from the center, extending well towards the edges of the slab. As load increased, cracks became wider. At failure, yield-line mechanisms were fully developed. As the load increased, the failure became faster and the yield-line becomes wider. Cracks in concrete slabs are formed generally at regions where the tensile stresses exist and exceed the specified tensile strength of concrete. The faces shown in these plates are the tensile faces of the specimens. The crack was initiated at the extreme fiber of tensile zone of slab cross-section in the region of pure bending. The crack did not open widely during the post-cracking behavior of the slab since the extension of the crack had been arrested by the fibers. In fact, the mode of an orientation of fibers has a
significant effect on an extension of the crack. If the fibers are oriented away from the direction of the principal tensile stress, then the load carried by the fiber will not be aligned with its longitudinal axis. And hence the load carried by the fiber can be decomposed into two orthogonal components. One of them aligned with fiber longitudinal axis and act as a pull cut force, while the other will act as a normal force on the fiber axis. The latter component will initiate a friction force between the fiber and the matrix along the fiber axis. The friction force act toward the opposite direction of the first component. Thus, the crack extension will be hindered and the crack itself propagate toward the internal fibers of the tensile zone of slab cross section leaving the intensity of tensile bending stress at the cracked fibers to be more or less constant as shown in figure 13.

Figure 13. two-way slabs crack pattern.

10. Cracking load, ultimate load and Load-Deflection Behavior
Cracking is one of the important data needed in this study. The first cracking load is known as the point where the load-deflection curve changes its curvature; it was recorded experimentally as the first cracking load observed in the tension zone of the slab. First cracking loads are recorded for all investigated reinforced concrete slabs and crack patterns are marked at different loading stages. For all tested specimens no crushing of mortar was observed on the compression face of the cross section. Main cracks generally commenced at the middle zone bounded by the lines of load application and all specimens exhibited ductile flexural failure. The experimental cracking and ultimate loads of all specimens are summarized in table 5. The load-deflection curves for all test slabs determined from loading tests of reinforced concrete slabs failing in flexure. The increase in the first crack load is due to the retardation of crack propagation because of the counter stress induced at the tip of the plausible crack due to the interaction force between the fibers and the matrix. This additional compressive stress will relieve the tips of the cracks from the high stresses concentration caused by the flexural stresses. Therefore, the elastic stress required for crack propagation will be elevated leading to a higher proportional limit. The second stage is the nonlinear behavior of the load-deflection diagram. This stage covers the region beyond the proportional limit. During this stage, the material behaves inelastically in tension and still elastic in compression and the cracks are initiated at the extreme fiber of the cross section and propagated toward the internal fibers. The increase in the load carrying capacity beyond the proportional limit is due to a continuous lift in the position of the neutral axis toward the compression zone, while the intensity of tensile bending stress at the cracked fibers of the cross section remains more or less constant and equal to the maximum post cracking stress of the material. Figures from 14 to 24 shows the load-deflection curves.
Table 5. Details of cracking and ultimate load for two way slabs.

| Slab No. | Slabs parameters | Fiber ratio (%) | Silica fume ratio (%) | Reinforcement ratio (ρ %) | First crack load test (kN) | First crack load deflection (mm) | Ultimate load test (kN) | Ultimate load deflection (mm) | Crack load/ultimate load (P_cr/Pult) % |
|----------|------------------|-----------------|-----------------------|--------------------------|---------------------------|-------------------------------|--------------------------|-------------------------------|-----------------------------------|
| 1        | 150 Openings @ Center | 0.36            | 3                     | 1                         | 0.48                      | 8.25                          | 10.95                    | 36.36                         | 36.36                             |
| 2        | 150 Openings @ Center | 0.36            | 3.25                  | 1                         | 0.47                      | 9                            | 11.67                    | 36.11                         | 35.89                             |
| 3        | 150 Openings @ Center | 0.36            | 3.5                   | 1                         | 0.46                      | 9.75                         | 12.76                    | 38.89                         | 38.89                             |
| 4        | 150 Openings @ Center | 0.36            | 3.75                  | 1                         | 0.44                      | 10.75                        | 13.22                    | 34.88                         | 34.88                             |
| 5        | 150 Openings @ Center | 0.36            | 4                     | 1                         | 0.46                      | 11.75                        | 14                       | 34.04                         | 34.04                             |
| 6        | Solid             | 0.36            | 7                     | 1                         | 0.65                      | 19.25                        | 20.4                     | 36.36                         | 36.36                             |
| 7        | 100 Openings @ Center | 0.36            | 5                     | 1                         | 0.52                      | 14                           | 15.5                     | 35.71                         | 35.71                             |
| 8        | 200 Openings @ Center | 0.36            | 2.75                  | 1                         | 0.52                      | 8.25                         | 16.66                    | 33.33                         | 33.33                             |
| 9        | 150 Openings @ Edge | 0.36            | 3.5                   | 2                         | 0.7                       | 9.75                         | 15.25                    | 35.89                         | 35.89                             |
| 10       | 170 Circle opening @ center | 0.36 | 4.25                 | 2                         | 0.69                      | 12                           | 20.01                    | 35.41                         | 35.41                             |

**Figure 14.** Load-deflection curve for slab (1).

**Figure 15.** Load-deflection curve for slab (2).

**Figure 16.** Load-deflection curve for slab (3).

**Figure 17.** Load-deflection curve for slab (4).

**Figure 18.** Load-deflection curve for slab (5).

**Figure 19.** Load-deflection curve for slab (6).

**Figure 20.** Load-deflection curve for slab (7).

**Figure 21.** Load-deflection curve for slab (8).

**Figure 22.** Load-deflection curve for slab (9).
Figure 23. Load-deflection curve for slab (10).

Figure 24. Non-dimensional plot of ultimate load to the cracking load with ultimate deflection/cracking deflection for slab location (1).

10.1 Effect of steel fiber content on cracking load and ultimate load

Figure 25 show effect of steel fiber content ratio (%) on load deflection curve of slabs (1,2,3,4 and 5) at location (1 and 2). When steel fiber increase from (0 to 0.5, 1, 1.5 and 2%) an increases in the cracking and ultimate load recorded are about (0, 8.333, 16.667, 25 and 33.33%) and (0, 9.09, 18.18, 30.30 and 42.42%) as shown in table 6. That means when the steel fiber content is increased the ultimate loads and deflection increase. The presence of steel fibers results in a more ductile type of failure. The larger the fiber contents the greater deflection at failure. Slabs with fibers exhibited considerably less damage at failure than slabs without fibers. The steel fibers become effective after first cracking load and continue to resist the principal tensile stresses until the complete pullout of all fibers occurs at one critical crack. Combined effect of fibers and steel reinforcement is very clear on an ultimate load of reinforced concrete slabs. Both the cracking and ultimate failure loads improve by including and interest of steel fiber. Though, the improvement in the final load appears more consistent and notable than the one in the cracking load.

Table 6. Increasing percentage in load for slabs (1,2,3,4 and 5) with different steel fiber content.

| Slabs | Fiber ratio (%) | Silica fume ratio (%) | Reinforcement ratio (\( \rho \)) | First crack load test (kN) | Increasing percentage (%) | Ultimate load test (kN) | Increasing percentage (%) |
|-------|----------------|-----------------------|-------------------------------|--------------------------|--------------------------|--------------------------|--------------------------|
| 1     | 0              | 25                    | 0.0036                        | 3                        | 0                        | 8.25                     | 0                        |
| 2     | 0.5            | 25                    | 0.0036                        | 3.25                     | 8.333333                 | 9                        | 9.0909                  |
| 3     | 1              | 25                    | 0.0036                        | 3.5                      | 16.6667                  | 9.75                     | 18.1818                 |
| 4     | 1.5            | 25                    | 0.0036                        | 3.75                     | 25                       | 10.75                    | 30.3030                  |
| 5     | 2              | 25                    | 0.0036                        | 4                        | 33.3333                  | 11.75                    | 42.4242                 |

Figure 25. Effect of SF content on load deflection curve of slabs (1,2,3,4,5) with reinforcement location (1, 2).

10.2 Effect of opening size on cracking load and ultimate load

Three types of square openings (100, 150 and 200mm) were chosen. The ultimate load is significantly decreased in slabs with the presence of openings for slabs (5, 7 and 8) when compared to the corresponding solid slabs (6) as listed in tables 7. The decrease in the ultimate load recorded was about (0, 38.9610, 27.2727 and 57.1428%) and (0, 28.57, 42.81 and 60.7143%) for cracking load. Figure 26 shows the effect of opening size on load deflection curve of slabs (5,6,7 and 8) location (1). It is indicated that the ultimate load capacity decreases with the increase in the size of the opening which in agreement with many research.
### Table 7. Decreasing percentage in cracking and ultimate load for slabs (5, 6, 7 and 8) with different opening size.

| Slabs | Fiber Ratio (%) | Opening Size | Silica Fume Ratio (%) | Reinforcement Ratio (ρ %) | First Crack Load Test (kN) | Decreasing percentage (%) | Ultimate Load Test (kN) | Decreasing percentage (%) |
|-------|----------------|--------------|-----------------------|--------------------------|---------------------------|---------------------------|---------------------------|---------------------------|
| 6     | 2.0            | Solid        | 25                    | 0.36                     | 7                         | 0                         | 19.25                     | 0                         |
| 5     | 2.0            | 150x150      | 25                    | 0.48                     | 4                         | -28.5714                  | 11.75                     | -38.9610                  |
| 7     | 2.0            | 100x100      | 25                    | 0.24                     | 5                         | -42.8571                  | 14                        | -27.2727                  |
| 8     | 2.0            | 200x200      | 25                    | 0.36                     | 2.75                      | -60.7143                  | 8.25                      | -57.1428                  |

### Figure 26. Effect of opening size on load deflection curve of slabs (5,6,7 and 8) location (1).

### 10.3 Effect of opening location on cracking and ultimate load

One square opening (150mm) is chosen to study the opening location effect on two-way slabs. Opening at the center and openings at the edge (at the center of one-quarter) are chosen in the recent study. Reduction in ultimate load between solid and edge opening slab is (49.35%) as shown in table 8 and reduction in ultimate load between the opening at center and edge opening slab is (17.02%) as shown in table 9. Figure 27 show effect of opening location on load-deflection of solid slab and opening at edge of slab location (1, 2). Figure 28 show effect of opening location on load-deflection of slab with opening at center and edge location (1).

### Table 8. Ultimate load for two-way slabs (6 and 9) solid and opening at edge.

| Slabs | Fiber Ratio (%) | Opening Location | Silica Fume Ratio (%) | Reinforcement Ratio (ρ %) | First Crack Load Test (kN) | Ultimate Load Test (kN) | Percentage (%) |
|-------|----------------|-------------------|-----------------------|--------------------------|---------------------------|---------------------------|----------------|
| 6     | 2.0            | Center            | 25                    | 0.36                     | 7                         | 19.25                     | 0              |
| 9     | 2.0            | Edge              | 25                    | 0.36                     | 9.75                      | 0                         | -49.35         |

### Figure 27. Effect of opening location on load-deflection of solid slab and opening at edge of slab location (1, 2).

### 10.4 Effect of opening shape on cracking and ultimate load

Two slabs with (circular and square) openings with dimensions (circular=170mm and square=1500mm) were chosen. When openings change from square to circle an increase in ultimate load is achieved about
and (6.25%) in cracking load. Table 10 shows the effect of opening shape in cracking and ultimate load for slabs (5 and 10). Effect of opening shape on load-deflection of a slab of two-way slab location (1) is shown in Figure 29.

### Table 10. Effect of Opening Shape in cracking and ultimate load for Slabs (5 and 10).

| Slabs | Fiber Ratio (%) | Opening Shape | Silica Fume Ratio (%) | Reinforcement Ratio (ρ %) | First Crack Load Test (kN) | Percentage (%) | Ultimate Load Test (kN) | Percentage (%) |
|-------|-----------------|---------------|-----------------------|---------------------------|----------------------------|-----------------|------------------------|---------------|
| 5     | 2.0             | Square        | 25                    | 0.36                      | 4                          | 0               | 11.75                  | 0             |
| 10    | 2.0             | Circle        | 25                    | 0.36                      | 4.25                       | 6.25            | 12                     | 2.1276        |

![Figure 29](image-url) Effect of opening shape on load-deflection of slab of slab location (1).

11. Flexural toughness evaluation techniques, energy ductility, ductility index, energy absorption and resilience

RPC presents linear performance up to the first cracking (which happens as a consequence of the cementitious matrix cracking). Although secondary cracks originate at the primary cracking, they are undetectable to the clear eye considering the matrix is reinforced with well-distributed steel fibers. The load progress continuously following which, the deflection is developed at a maintained load. Following that, the load causes breaking the units and the steel fibers held the two cracked parts of specimen together, this indicated that RPC is a highly tough material, which does not break but deforms as the steel fiber pulls off. This is because toughness of fiber reinforced concrete is influenced by strength, geometry, aspect ratio and volume fraction of steel fibers. It has been shown that the increase in steel fiber content increases the flexural toughness of the concrete. The increase in fiber content results in the consistent increase in ductility and energy-absorption capacity (toughness). To give a better quantification for the energy absorption capacity or toughness of (RPC), toughness indices are used table 11 and figures 30-33.

### Table 11. First crack, ultimate load, first crack, ultimate deflection, ductility, resilience and energy absorption.

| Slab | P<sub>cr</sub> Location | Δ<sub>cr</sub> Location | P<sub>ult</sub> Location | Δ<sub>ult</sub> Location | (P<sub>cr</sub>/P<sub>ult</sub>)% | Ductility Δ<sub>ult</sub>/Δ<sub>cr</sub> | Resilience | Energy Absorption (joules) (kN.mm) |
|------|--------------------------|------------------------|------------------------|-----------------------------|-----------------------------|---------------------------|------------|----------------------------------|
| 1/F=0% | 3 | 0.48 | 0.68 | 8.25 | 10.95 | 15.47 | 36.3636 | 22.81 | 0.7772 | 0.9900 | 1.1982 | 70.7713 | 99.9786 |
| 2/F=0.5% | 3.25 | 0.47 | 0.66 | 9 | 11.67 | 16.49 | 36.1111 | 24.83 | 0.9363 | 1.1314 | 81.8313 | 115.6434 |
| 3/F=1.0% | 3.5 | 0.47 | 0.65 | 9.75 | 12.76 | 18.03 | 35.8944 | 27.74 | 1.2755 | 1.8100 | 99.485 | 140.5838 |
| 4/F=1.5% | 3.75 | 0.44 | 0.62 | 10.75 | 13.22 | 18.68 | 34.8837 | 30.05 | 0.9736 | 1.3837 | 109.905 | 155.3 |
| 5/F=2.0% | 3.75 | 0.44 | 0.62 | 10.75 | 13.22 | 18.68 | 34.8837 | 30.05 | 0.9736 | 1.3837 | 109.905 | 155.3 |
| 6/Solid opening | 7 | 0.65 | 0.86 | 19.25 | 20.4 | 27.13 | 36.3636 | 31.38 | 2.6570 | 3.4900 | 286.707 | 381.27 |
| 7/100 opening | 5 | 0.52 | 0.73 | 14 | 15.5 | 21.70 | 35.7142 | 29.81 | 1.6300 | 2.2857 | 169.5976 | 237.4368 |
The areas under the load-deflection curves have been calculated with the aid of Auto-CAD computer program. Equation by DataFit Program to Calculate Toughness and Toughness Indices of two-way at max location solved by using Trapezoidal rule.

The production of the first crack was controlled during the examination to register the expanse of this crack with developing load continuously near collapse of the slabs. When the concrete tensile stress in a specimen approaches the ultimate tensile strength, the cracking occurs. The expected deviation is remarked in width of cracks between the slabs for each series. Crack width is useful when evaluating a structure for serviceability and durability. Measuring maximum crack width was done approximately and plotted against load level. Effects of each of steel fiber content, opening size on maximum crack width are very clear in Figure 34-36. Also silica fume content has a definite influence on crack expanse. It can be recognized that due to inhibition of the crack propagation by the behavior of the steel fibers, the maximum crack expanse adjacent to the start of failure loading and beside all the steps of loading for RPC slabs including fibers display a significant decrease in crack expanse with an increasing portion of the fiber. This decline is due to an improvement in bond strength within fibers and RPC matrix which occurs due to the development in the percentage of fiber. Also silica fume content has a positive effect on crack width. It can be recognized from this pattern that due to interference of the crack generation by the existing of the steel fibers, the values of the maximum crack width close to the onset of failure loading and beside all the level of loading for RPC slabs including fibers expose notable modification in crack width with improving percentage of fiber. This decrease is expected to an improvement in bond strength between fibers and RPC matrix which occurs due to the increase in the portion of the fiber.
Figure 34 Effect of steel fiber content (%) on crack width of slabs (1, 2, 3, 4 and 5).

Figure 35 Effect of opening (size, location and shape) on crack width of slabs (5, 6, 7, 8, 9 and 10).

Figure 36 Relationship between deflection and x-axis distance slab (1).

13. Concrete Strain Load-Concrete Strain Relationships

By taking the advantage of the symmetry of geometry and loadings for Two-way slabs. In general increasing steel fiber, the volumetric ratio increases the ultimate concrete strain at both tension and compression zones but the effect is more pronounced with regard to tensile strain. This can be connected to the greater works of steel fibers in the tension preferably than in compression. The impact of steel fibers was apparent following the development of the first crack. The decay in concrete compressive strain could be associated with the transforming in the neutral axis measurement near the tension face with the development in the fiber content. This is because of the tension behavior of steel fibers performs the measurement of the tension zone smaller. Figures 37-52 display the combination of compressive and tensile strains of concrete along the RPC slabs. It is obvious from these figures that the compressive and tensile strains of concrete improve with rising opening size. The purpose for this improvement could be associated with the development in the implemented moment on the slabs with increasing in opening size. At early stages of loading, all specimens behave linearly and the developed strains are small. Further increase in loading leads to a sudden change in the strain path.

Figure 37 Compression strain in top face slab (1) (location 1, 2, 3).
Figure 38 Compression strain in top face slab (2) (location 1, 2, 3).
Figure 39 Compression strain in top face slab (3) (location 1, 2, 3).
Figure 40 Compression strain in top face slab (4) (location 1, 2, 3).
Figure 41 Compression strain in top face slab (5) (location 1, 2, 3).
Figure 42 Compression strain in top face slab (6) (location 1, 2, 3).
14. Conclusions

1. 10 models of reinforced concrete slabs have been experimentally tested up to failure under loading. The utilization of steel fibers and silica fume improved ductility and toughness of the tested specimens as the fiber content increased. It was found that the deflection of specimens with steel fibers at
failure is higher than the deflection of similar specimens without steel fibers due to the fact that the fibers are able to transfer emerging loads by bridging the cracks.

2. Reactive powder concrete increase the concrete strength, this behavior is due to pore size and grain size refinement processes which strengthen the transition zone and reduce micro cracking in the interface.

3. Increasing of about (0, 8.33, 16.66, 25 and 33.33%) in cracking load and (0, 9.0909, 18.1818, 30.30 and 42.42%) in ultimate load due to fiber content (0.5, 1.0, 1.5 and 2.0%) were observed. That mean when the steel fiber content is increased the cracking loads and deflection increased.

4. For slab with steel fiber 2% and 25% silica fume and reinforcement ratio (0.0036), with square openings with size (100, 150 and 200mm) the decrease in cracking load according to solid slab the decrease in cracking load of (0, 28.57, 42.85 and 60.71%) and ultimate load of (0, 38.9610, 27.2727 and 57.1428%).

5. One square opening of size (150mm) is chosen to study the opening location effect on slabs with steel fiber 2% and 25% silica fume and reinforcement ratio (0.0036). The opening is at the center of one-quarter of the slab. When opening location change decrease in the cracking load is achieved. Reduction in ultimate load between solid and edge opening slab is (49.35%) and reduction in ultimate load between the opening at center and edge opening slab is (17.0212%).

6. Slab with steel fiber content 2% and 25% silica fume content and reinforcement ratio (0.0036). circle shape of opening with the equivalent area to (150x150mm opening) is chosen. When opening change from square to circle an increase in cracking load (6.25%) and ultimate load (2.1276%) is achieved.

7. For RPC slabs containing fibers show a significant reduction in crack width with increasing percentage of steel fiber. This reduction is due to an increase in bond strength between fibers and RPC matrix.

8. Increasing steel fiber ratio increases the ultimate concrete strain at both tension and compression zones but the effect is more pronounced with regard to tensile strain. This can be attributed to the better activity of steel fibers in the tension rather than in compression. Also, strain can be affected by the amount of longitudinal reinforcement, and this can be attributed to the increasing tensile force. The compressive and tensile strains of concrete increase with increasing opening size. The reason for this increase could be attributed to the increase in the applied moment on the slabs with increasing in opening size.

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