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Residual strength capacity of reinforced reactive powder concrete two-way slabs subjected to drop weight

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ABSTRACT

This paper presents an experimental investigation of the effect of impact force on the residual strength capacity of simply supported reactive powder slabs. Eight specimens of reinforced reactive powder concrete slabs were examined in the research. These slabs had dimensions of 500 x 500 mm and 70 mm in four categories. The influence of slab compressive strength (conventional concrete and reactive powder concrete), steel fiber proportion (1, 1.5, and 2%), percentage of reinforcement in the tension zone ($\rho1=0.007$, $\rho2=0.011$, $\rho3=0.0179$), and the number of impacts (two impacts, four impacts, and six impacts) were investigated in this research. Investigations were carried out to ascertain each slab's residual response, including the first cracking load, residual failure load, residual steel reinforcement strain, maximum central deflection, and crack pattern. The results showed that using reactive powder concrete instead of normal concrete increased the mechanical properties of the concrete and resulted in a significant increase in the failure load. This also led to an increase in deflection and strain. Furthermore, increasing the reinforcement ratio increased the failure load while simultaneously decreasing the deflection due to the improvement in slab moment resistance. Furthermore, it was discovered through the experiments that the addition of steel fiber to the mixture enhanced the slab's post-cracking reactivity. The presence of steel fiber raised the slab's strength resistance by 21.63% as the steel fiber ratio increased from 1% to 2%, which is due to the addition of steel fiber increasing the slab's tension resistance.

1. Introduction

Reactive powder concrete (RPC) is a super concrete with excellent mechanical qualities and durability due to its homogeneity. The expression "reactive powder concrete" refers to a superplasticizer, silica fume, cement, and very fine sand (0.6 mm) combination with extremely low water-cement proportion [3]. RPC was developed in the 1990s by the French Bouygues Company [1] and has attracted wide acceptance because of its remarkable endurance, high tensile strength, and durability [2]. Because of its remarkable structural benefits that are not available in ordinary concrete, RPC is often used in building constructions such as roads, stadiums, industrial facilities, and maritime platforms.

Impact forces come in a variety of shapes and for a variety of purposes. Numerous structural elements are expected to be subjected to impact loads a long time. Car crashes, falling rock hits, and criminal assaults are all examples of impact loadings that can jeopardize RC elements, which are frequently used in the creation of structures and industrial infrastructure. Concrete buildings have been widely used as protective structures to ensure strong loads. During the last 20 years, several investigations on the dynamic response of RC elements under impact loads were performed to explain the impact process. Because of the large amount of energy produced in such a short period of time, the dynamic behavior and collapse process of RC strictures under collision and nonlinear loads change. The system's time-

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history response is also less important than the peak reaction due to the complexity of the impact process.

In 2001, Kishi *et al*. [1] performed falling-weight impact tests to assess the strength properties of flexural-failure-type reinforced concrete (RC) beams under impact loading. Eight simply supported rectangular RC beams, each with a clear-span length of 2 m, were used. A falling mass of 200 kg was subjected to the center of the beams. The tests showed that the higher reaction force at failure can be used to evaluate the ultimate strength of flexural failure and that this type of RC structure can be prudently intended to be associated with a specific parameter using the relationship between maximum reaction force and static bending capacity. In 2010, Tachibana *et al*. [2] developed a methodology for designing reinforced concrete beams exposed to vertical shock load. A series of low-intensity studies were conducted on RC beams with variable parameters such as beam dimensions and reinforcement ratio. Depending on the collision energy and the static maximum bending capacity, a formula is developed to calculate the ultimate deflection of the beam. The suggested equation's accuracy is proven by comparison with experimental data acquired by other researchers as well as numerical results obtained through FEM simulations. In 2017, Zhao *et al*. [3] analyzed the shear failure mechanisms of RC beams exposed to impact loads. Projectile mass, impact velocity, and beam span were all variables in the test. The shock and reacting forces, as well as the deformation and maximum acceleration at different places along the beam, were measured, Fracture progression was documented with high-speed recording equipment. Finite element models were also used to determine whether modern software could replicate the observed behavior. The study's findings showed that when impact velocity increases, samples tend to break in shear with diagonal cracks, generating shearing plugs near the loading site. In 2019, Zhao *et al*. [4] suggested a methodology for determining the optimum capacity of impact-loaded RC beams. The principal interaction of the peak impact force, can be calculated theoretically using the rule of energy efficiency, the impulse theory, and the wave principle. A comparison with 143 impact tests indicated that the proposed approach accurately forecasts the maximum midspan displacement of RC beams under shock loads. In 2022, P´erez *et al*. [5] evaluated RC beams with varied amounts of steel fibers. Falling mass with various projectile impact velocities were used under impact loads. In addition, the Karagozian and Case concrete constitutive model was used for numerical simulation. Impact velocities that do not produce cracking were found to be the same, regardless of the fiber content in all materials. Force and impulse peak magnitudes grew virtually linearly with the speed of impact, and repeating the strikes with the same velocity did not change this trend. A concrete dynamic tension strength test showed that fiber content had no effect on impact velocity that caused the first cracks.

As a result of the above review, it was determined that various significant investigations have been conducted into the structural aspects of ordinary concrete elements subjected to impact loads. However, because Reactive Powder Concrete (RPC) is a relatively new material in the industry, it is clear that none of the previous local studies of RPC considered the structural behavior of reactive powder concrete structural elements exposed to impact load.

The present study investigated the residual strength of RPC slabs and the effects of several factors on slabs subjected to impact loads, including the percentage of steel fiber, slab steel reinforcement, and the number of blows.

2. Experimental work

2.1. Test specimens

Eight reinforced reactive powder concrete slabs with dimensions of 500mm x 500mm x 70mm were exposed to impact force represented by the free - falling mass of a 125mm steel ball linked to a cylindrical tube of 200 mm height and 150mm diameter, with a total weight of 26kg falling freely from a height of 2.1m. The effect of the dynamic load on the slab's residual resistance was discussed in this research. The main variables of the experiment were the effects of compressive strength, reinforcement, steel fiber, and repeated impact load. Three reinforcement ratios, which followed ASTM-A615 [6], were evaluated (ρ1=0.007, ρ2=0.011, ρ3=0.0179). The details of the bottom reinforcement for all slabs are shown in figure 1. The slab samples were separated into four groups, each one contained two slabs, as shown in figure 1, and each group discussed a different variable. Table 1 shows all slab details with different parameters.

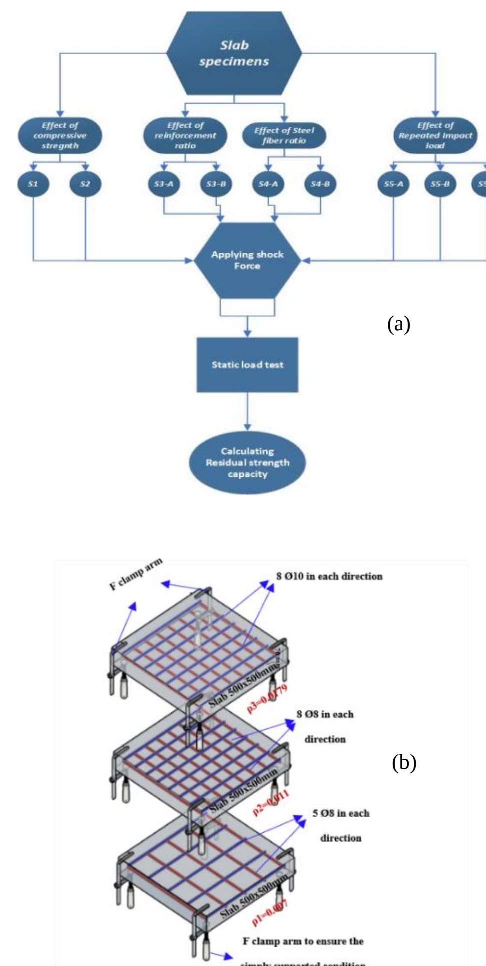


Figure 1. (a) Experimental program; (b) slabs details.

Table 1. Slab specimen's details.

Group	Name	Reinforcement ratio	Compressive Strength (kN)	Vf% (Steel fiber ratio)
Effect of compressive stregnth	S1	ρ1=0.007	33	NA
	S2	ρ1=0.007	83	1%
Effect of steel reinforcement ratio (G5)	S3-A	ρ2=0.011	83	1%
	S3-B	ρ3=0.0179	83	1%
Effect of steel fiber ratio (G6)	S4-A	ρ1=0.007	92	1.5%
	S4-B	ρ1=0.007	102	2%
Effect of number of blows (G7)	S5-A	ρ1=0.007	83	1%
	S5-B	ρ1=0.007	83	1%

2.2. Materials and mix proportions

Several components were used, such as silica fume with a 20% ratio, steel fiber mixed with concrete with various ratios (1, 1.5, and 2% by volume) based on ASTM A 820M [7], and water to cement ratio of 0.20, so that the mechanical properties of concrete varies depending on the percentages of steel fiber. Ordinary Portland cement (OPC) was used for all mix proportions from Aljaser brand [8], and the fine aggregate was categorized as very fine sand since the maximum size is 0.15 mm that met the B.S.882:1992 [9]. It is necessary to utilize ordinary tap water that is clean and free of harmful concentrations of oils, acids, alkalis, salts, and organic components, as well as other impurities. The silica fume utilized in this research is produced by the Sika Company. Sika Company also provided the short steel fiber that was employed in all slab samples. To achieve the required mechanical qualities, various experimental mixtures were used [10, 11].

Table 2. Concrete proportions are used in the mixture.

Mix	Cement (kg)	Fine aggregate (kg)	Coarse aggregate (kg)	Silica fume (%)	Steel fiber (%)	Superplasticizer (%)	W/C (%)
NC	564	690	787	NA	N/A	0.4	0.4
1	920	995	N/A	20%	1	6	0.20
2	920	995	N/A	20%	1.5	6	0.20
3	920	995	N/A	20%	2	6	0.20

All materials were meticulously and perfectly weighed. Following that, the mixing procedure proceeded normally, with the fibers being added at the conclusion. The fibers were gradually introduced during the mixer's rotation. To cast the samples, plywood molds were created. Figure 2 illustrates the mold after the reinforced steel meshes have been placed and the mold after casting. After 2 days of molding, the molds were opened and the specimens cured for three days at 60°C, then 25 days at 25°C.

2.3. Drop weight test

To conduct the impact tests on all samples, an impact rig was constructed. The impact rig was made of a supporting steel structure, an impactor frame, and a vertical guide tube to ensure the central contact, as illustrated in figure 2. The slab was then placed into the steel frame and the cable that was holding the projectile was released, allowing the projectile to fall freely from 2.1m with a velocity of 6.42m/s.

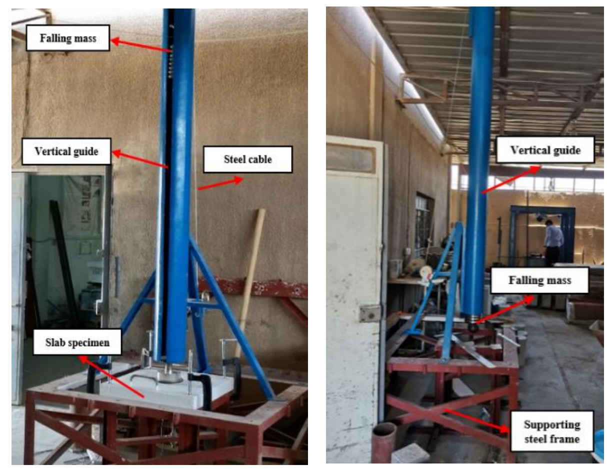


Figure 2. Drop weight test rig.

2.4. Residual strength test

After the drop weight was evaluated for all slabs, reinforced concrete slab specimens were subjected to a static load to determine their residual strength capacity. The test was performed in the laboratory of the University of Karbala, Iraq, using a flexural testing machine with a capacity of 500 kN. The boundary condition was simply supported by the f clamp arm. The load was applied progressively to the slab's midspan using a hydraulic load cell, while displacements were recorded using an LVDT sensor mounted under the midspan. Figures 3 and 4 depict all of the static test machine's details.

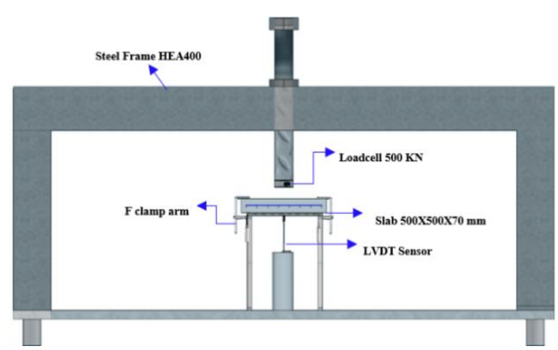


Figure 3. Static test machine.

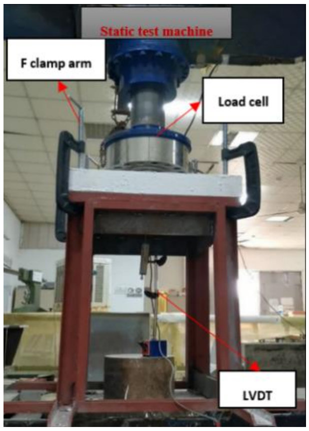


Figure 4. Placing the slab sample in the test rig.

3. Results and discussion

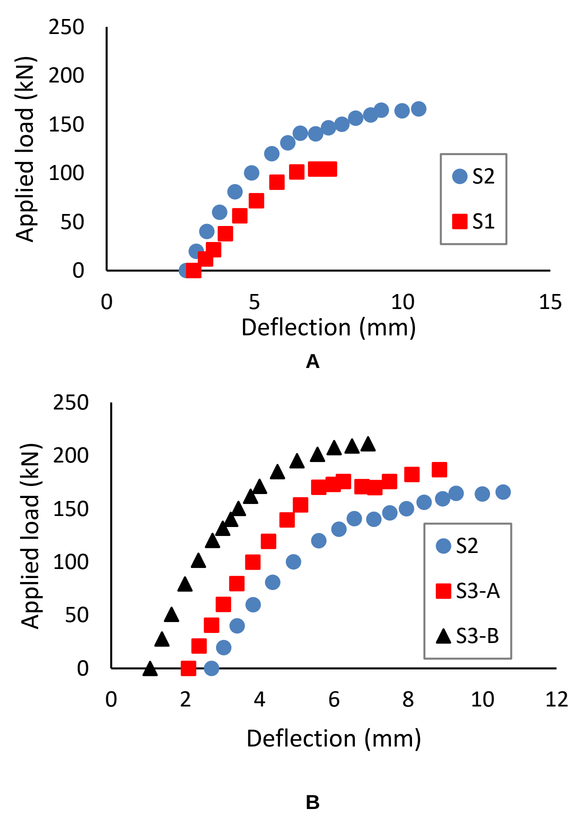
After the impact tests were finished, all slab specimens were tested under static load, as shown in figure 6. An LVDT was installed at the center of the bottom face of slab spacemen to evaluate central displacement. Residual capacity strength, deflection, and strain in reinforcement were all measured and displayed. Table 3 displays the values of the maximum static load, deflection, first crack load, and maximum strain for all slabs.

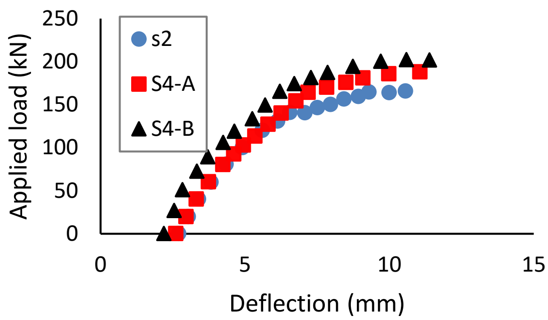
Table 3. Concrete proportions used in the mixture.

Group	Slab	Residual stregnth capacity (kN)	Maximum defection (mm)	First crack load (kN)	Maximum strain
Control	S1	104.26	4.58	15	0.00149
	S2	165.88	7.861	25	0.00168
Effect of steel reinforcement ratio	S3-A	187	6.76	33	0.00187
	S3-B	211.27	5.87	41	0.00175
Effect of steel fiber ratio	S4-A	188.1	8.46	36	0.0025
	S4-B	201.76	9.2	44	0.00225
Effect of number of blows	S5-A	164.41	6.96	25	NA
	S5-B	157.37	7.07	22	NA

3.1. Residual static load -displacement history

Static load-displacement histories for all slabs are shown in figure 5, which are used to investigate the effects of the shock load on the strength capacity of the slab. All the deflection values were started from the residual deflection of the impact load test. It was observed that the utilization of reactive powder concrete improves the mechanical properties of concrete when comparing slab S2-RPC to slab S1-NC-normal concrete. The increase in failure load was 59.1%, while the central deflection was increased by 5.59%. Increasing steel reinforcement in the tension zone improved the moment resistance of concrete slabs. When the reinforcement ratio was raised from ρ=0.007 to ρ=0.0179, there was an improvement in the failure load of 27.36%, whereas the deflection exhibited a reduction of 25.33%. Three slab samples with 1, 1.5, and 2% steel fiber ratio were subjected to static load to display the behavior of reactive powder concrete slabs under this kind of load and investigate the effect of the impact load on the slab's strength capacity. For slab S4-B, VF=2%, as compared to slab S2-RPC, VF=1%, the failure load was improved by 21.63% and the deflection was increased by 17.03%. Two slab samples with two and four drops of falling mass were tested under static load to show the attitude of reinforced reactive powder concrete slabs with various drop numbers under static load. For slab S5-A, Dr=2, when compared with slab s2-RPC, Dr=1, a reduction by 0.89% in the failure load was observed. The deflection was decreased by 10.06% and steel strain was reduced by 4.76%. For slab S5-B, Dr=4, when compared with slab S2-RPC, Dr=1, the failure load was decreased by 5.13%, while the deflection was reduced by 10.06%. Figure 6 shows the strain–time history for all slabs under different parameters. The strain in the x-axis started from the residual strain from the impact test. All slabs exposed to residual load tests had their crack pattern being identified, as illustrated in Figure 9. The utilization of reactive powder concrete reduced the number and length of cracks because of the existence of steel fiber, enhancing the concrete's mechanical characteristics. The quantity and width of cracks were reduced by improving the steel fiber and reinforcing ratio. When slab samples were repeatedly hit, the amount and depth of cracks increased.





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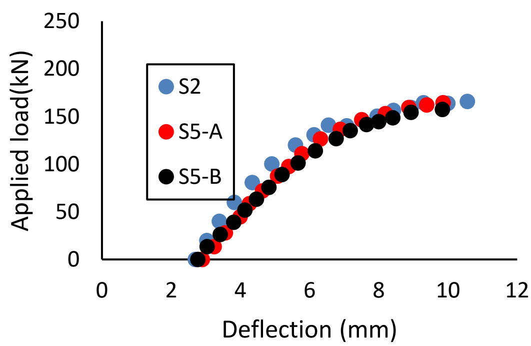

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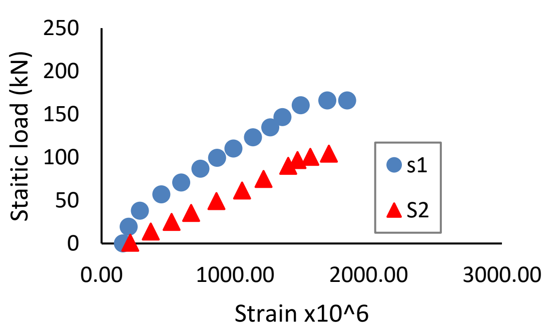
Figure 5a-d. Load-displacement curves for all slabs.



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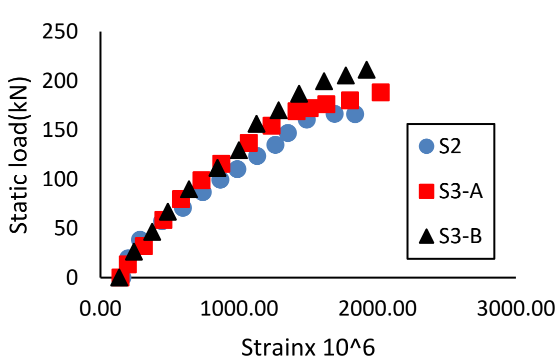

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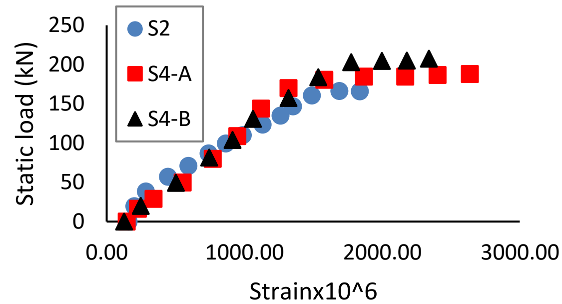

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Figure 6a-c. Load-strain curves for all slabs.

3.2. First crack load

The value of the first crack load for the S1 slab was 15 kN, whereas for the conventional RC slab, S2, it was 25 kN. The use of reactive powder concrete increased the first crack load by 66.67% as compared to normal concrete. Increasing the percentage of reinforcement in the tension zone increased the first crack load. For slab S3-A, as compared to slab S3-B, the first crack load was increased by 24.24%. The percentage of steel fiber in the mixture was very effective in improving the first crack load. For slab S4-A, as compared to slab S4-B, the first crack load was increased by 22.23%. When the slabs were subjected to repeated drop weight, the first crack load decreased due to the reduction in stiffens of the slabs. For slab S4-A, as compared to slab S4-B, the first crack load was reduced by 12%. Figure 7 shows a comparison between the first crack load and the ultimate load for all slabs.

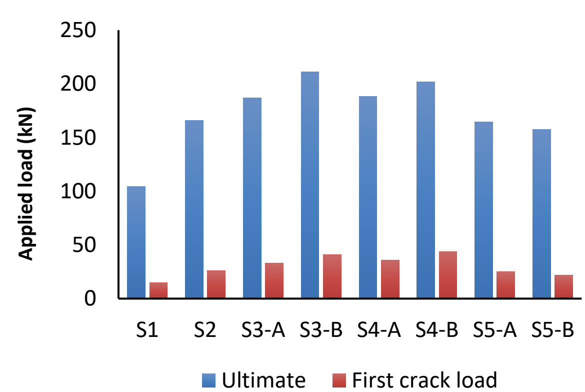

Figure 7. Comparison of first crack load and ultimate load.

4. Absorbed energy

The area under the load-deflection curve of impact load is known as the absorbed energy; it was estimated using the Origin pro-2021 program (data analysis and graphing software). The absorbed energy for all slabs under different parameter conditions has been determined and is listed in the

Table 4. The technique of estimating the area under the load-deflection curve is visualized in Figure 8.

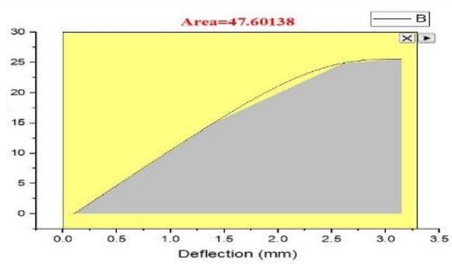

Figure 8. Calculating area under load-Deflection curve.

Table 4. Absorbed energy results.

Group	Slab	Absorbed energy (kJ)
Control	S1	49.6
	S2	59.38
Effect of steel reinforcement ratio	S3-A	52.38
	S3-B	32.89
Effect of steel fiber ratio	S4-A	53.87
	S4-B	58.41
Effect of number of blows	S5-A	55.34
	S5-B	52.51

The absorbed energy (area under impact load-deflection curve) improved with the using of reactive powder concrete. For slab (S1-NC), when compared with slab (S2-RPC), the reduction in the absorbed energy was (16.47%) due to the reduction in slab stiffness leading to reduce the impact force. For slab (S3-A), when compared with slab (S2-RPC), the absorbed energy was reduced by (11.79%). For slab (S3-B), when compared with slab (S2-RPC), a reduction by (44.61%) in the magnitude of absorbed energy was noticed. Improving the steel fiber ratio caused a reduction in the magnitude of absorbed energy. Slab (S2-RPC) When comparing with slab (S4-A), the absorbed energy increase by (10.23%). When the slabs were subjected to repeated impact force, a drop in the magnitude of absorbed energy was noticed. Slab (S5-A) indicated a decrease in the magnitude of the absorbed energy by (6.80 %).

5. Conclusions

This study investigated the influence of concrete type, reinforcement ratio, steel fiber ratio, and repeated impact force on the behavior of reinforced two-way slabs. The residual strength capacity of the slab samples was determined by subjecting them to static load following the impact load test. From this research, it is possible to conclude the following:

1- Adopting reactive powder concrete instead of regular concrete was very effective, where the increase in failure load was 59.1%. Furthermore, the central deflection and strain values were increased by 71.64 and 12.75%, respectively.
2- The static test indicated that using steel fiber increases the post-cracking response of slabs. As the steel fiber ratio increased from 1% to 2%, the slab strength resistance improved by 21.63% because the presence of steel fiber enhanced the tension resistance of the slab.
3- Static testing showed that increasing the reinforcement ratio increased the failure load, while decreasing the deflection. When the reinforcement ratio was increased from ρ=0.007 to ρ=0.0179, the failure load increased by 27.36 % and the deflection decreased by 25.33 %.
4- When the slabs were subjected to repeated drop weight, the residual strength load was reduced as a result of the slabs' reduced stiffness. For slab S5-B, Dr=4, when compared with slab S2-RPC, Dr=1, the failure load was decreased by 5.13%, while the deflection was reduced by 10.06%.
5- The use of reactive powder concrete increased the first crack load by 66.67%, as compared to normal concrete.
6- The percentage of steel fiber in the mixture was very effective in improving the first crack load. When the steel fiber ratio was improved from 1% to 2%, the first crack load was increased by 76%.
7- Increasing the steel reinforcement ratio led to a reduction in the absorbed energy due to the improvement in slab stiffens which led to a reduction in central deflection.
8- Multiple impact forces on the slabs resulted in a reduction in the amount of absorbed energy.

Authors' contribution

All authors contributed equally to the preparation of this article.

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