



Flexural behavior of sustainable reactive powder concrete bubbled slab flooring elements

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ABSTRACT

Voided slabs are reinforced concrete slabs in which voids allow to reduce the amount of concrete. The bubbled deck slab is a new and sustainable biaxial floor system to be used as a self-supporting concrete floor. The use of voided slabs leads to decrease the consumption of materials and improve the insulation properties for enhancing the objectives of sustainability. This study presents an investigation into the flexural behavior of sustainable Reactive Powder Concrete RPC bubbled slab flooring elements. Six one-way slabs were cast and tested up to the failure. The adopted variables in this study are: the volumetric ratio of steel fibers, type of slab; bubbled or solid, placing of reinforcement and thickness of slab. The effect of each variable on the ultimate load, deflection and strain has been discussed. The results show that increasing the percent of steel fibers from 1% to 2% in solid and bubbled slabs decreases the deflection by (18.75%) and (50%) respectively. As well as, the deflection increases by (41%) for bubbled slab compared to the solid slab. The slabs reinforced with top and bottom steel meshes show less deflection than slabs reinforced by only bottom steel mesh.

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1. Introduction

Reinforced concrete slab is defined as the member that used in floors and roofs of buildings and as the decks of bridges. The floor system of a structure can take many forms such as in-situ solid slabs, ribbed slabs or precast units. Slabs may span in one direction or in two directions and they may be supported on monolithic concrete beams, steel beams, walls or directly by the structure's columns by Lee and Burnett (2008).

Sustainability means conserving natural resources and improving the quality of life for people through the use of natural resources and energy in a manner that enable the next generation to live in peace at the same time as the current generations are enjoying and not restricted (Clough et al., 2006; Ochsendorf, 2011; Cole et al., 2005).

Various attempts have been developed in the past to reduce the weight of concrete slabs, with maintaining the flexural strength of the slab. Reducing the slab weight would reduce deflection and make larger span

lengths achievable. Not all the internal concrete can be replaced, where concrete in the top zone of the slab is necessary to form the compression block for flexural strength, and concrete in the tension zone of the slab needs to bond with reinforcement to make the reinforcement effective for flexural strength. Also, the top and bottom faces of the slab need to be connected to work as a one unit and ensure the transfer of the stresses (Mosley and Bungey, 2012; Marais, 2009).

The voided reinforced concrete slab system, also known as Bubbled Deck Slab system, has recently been presented in Europe. It was invented by Danish engineer, Jorgen Breuning. This system consists of hollow plastic balls cast into the concrete to create a grid of void forms inside the slab by Fuchs (2006) and Klein (2006).

Research over the past periods had yielded a new organization of highly resilient concrete called Reactive Powder Concrete (RPC), now labeled and classified as Ultra High Performance Concrete (UHPC). RPC is one of the latest generations in concrete technology by Therresa et al. (2008).

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RPC possesses Ultra-high static and dynamic strength, high fracture capacity, low shrinkage and excellent durability under harsh conditions. The microstructure of RPC is improved by accurate gradation of all particles in the mix to achieve maximum compactness by Yunsheng et al. (2008).

2. Highlights

Minimization of the amount of concrete, providing the required span, overcoming concrete weakness in tension, monolithic and simple behavior with continuous and uniform forces distribution, enhancing heat and sound insulation etc. are the main reasons for the use of voided slabs. This paper presents an experimental study of the combination of the biaxial bubbled slabs technique with the use of reactive powder concrete as high performance concrete for sustainable roofing elements.

3. Experimental Program

Six, one-way RPC slabs with a rectangular cross-sectional area of (416mm) width, (100 and 125mm) depth and (1700mm) length were cast to study the effect of adopted parameters.

3.1. Materials of reactive powder concrete

RPC consists of the following materials shown in Table 1.

3.2. Materials for voided slabs

Materials listed in Table 2 are used in this experimental work for reinforcing and forming bubbled and solid slabs.

Table 1. Properties of materials of RPC.

Material	Property
Cement	Ordinary Portland Cement Type-I (AL-Maas) by Iraqi Specification, No. 5 (1984).
Sand	Natural sand from Al-Ukhaider region with maximum size of (600 μm) by Iraqi Specification, No.45 (1984), and B.S. 882. (1992).
Silica Fume	A gray colored material was produced by Sika Company, Turkey by ASTM C 1240 (2005).
Steel Fibers	Micro golden straight steel fibers of (13mm length and 0.22mm diameter).
Super Plasticizer	Glenium 51 manufactured by BASF Construction Chemicals, Jordan by ASTM C494 (2004).
Water	Ordinary tap water

Table 2. Materials for voided slabs.

Material	Property
Steel Bars	Deformed steel bars of (4mm diameter) having (560MPa) yield strength.
Balls	Plastic balls used were made by embodying high density polypropylene (HDPE) with a diameter of (75mm).

3.3. Mix proportion

Two mixes were used in this study with the same quantities and percentages of RPC components and two different ratios of micro steel fibers (1% & 2%) as shown in Table 3.

3.4. Preparation of bubbled slab

- Steel reinforcement layer of (4 mm) bar diameter and (50 mm \times 50 mm) openings was placed in their correct position at the bottom with cover equal to (25mm).
- Balls of (75 mm) diameter were placed over the steel reinforcement layer at spacing of (25 mm) between balls in both transverse and longitudinal directions.

- For bubbled slab with bottom steel reinforcement only, the balls tied to the reinforcement layer by steel wire to prevent balls floating while concrete pouring.
- For bubbled slab with top and bottom steel reinforcement, the top reinforcement layer placed over the balls and then tied to the bottom layer by steel wire as shown in Fig. 1.

4. Specimen Details

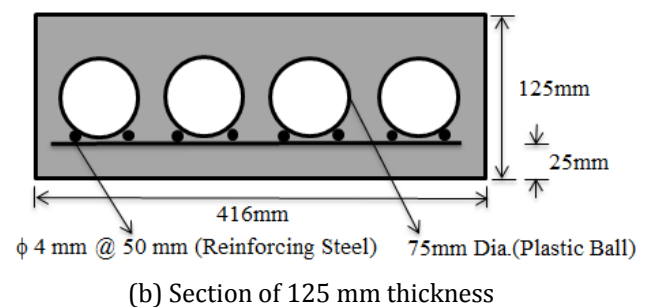
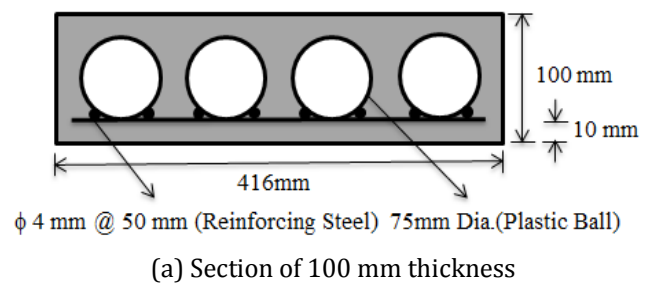
Six rectangular RPC specimens were cast to study the flexural behavior of sustainable reactive powder concrete voided slabs. Details of slab specimens are shown in Table 4 and Figs. 2-3.

Table 3. Concrete mixes.

Cement kg/m ³	Sand kg/m ³	Silica Fume % of (cement weight)	w/c	Super Plasticizer % of (cementitious materials)	Steel Fiber %
1000	1000	8	0.25	6	1 & 2

Table 4. Details of tested slabs.

Slab Coding	Details
S-1-B-125	Solid Slab, 1% Steel Fiber, Bottom Reinforcement and 125 mm Thickness
S-2-B-125	Solid Slab, 2% Steel Fiber, Bottom Reinforcement and 125 mm Thickness
BS-1-B-125	Bubbled Slab, 1% Steel Fiber, Bottom Reinforcement and 125 mm Thickness
BS-1-TB-125	Bubbled Slab, 1% Steel Fiber, Top and Bottom Reinforcement and 125 mm Thickness
BS-2-TB-125	Bubbled Slab, 2% Steel Fiber, Top and Bottom Reinforcement and 125 mm Thickness
BS-1-TB-100	Bubbled Slab, 1% Steel Fiber, Bottom Reinforcement and 100 mm Thickness

**Fig. 1.** Preparation of bubbled slab.**Fig. 2.** Front view of reinforced bubbled slab.

5. Test Instrumentation and Measurement

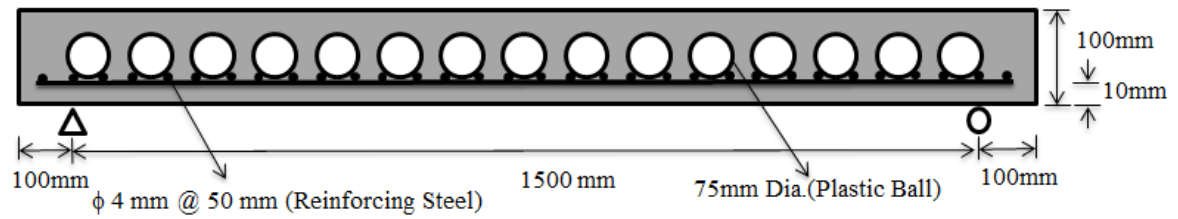
5.1. Load measurement

A universal hydraulic machine with (300 ton) capacity is used for specimens testing. All slabs were tested after (28) days as simply supported under two-point load, with a clear span of (500 mm) which is kept constant for all tests. The specimens are supported on steel rollers (50 mm) diameter. The load is distributed to two point loads by using steel blocks (40 mm thickness, 60 mm width and 416 mm length) which are placed on the top

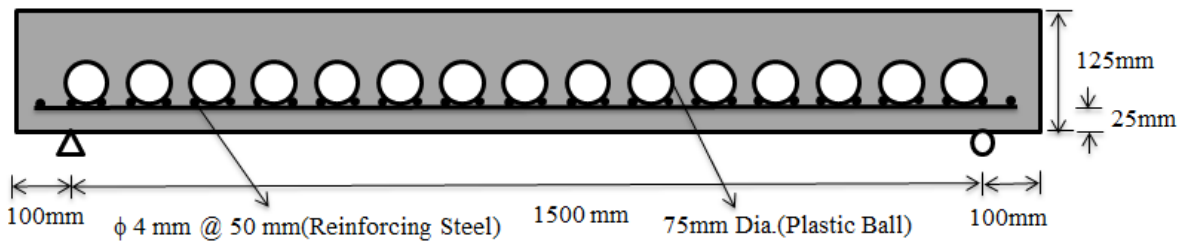
surface of the slab at both loading points to prevent local crushing of the concrete, as shown in Fig. 4. All tests were carried out under the condition of load step of (5 kN) for all specimens.

5.2. Deflection measurement

The deflection measurement is taken underneath midpoint. One dial gauge of (0.01mm) sensitivity is mounted on a steel frame was placed in the center of the bottom face of each specimen, as shown in Fig. 5.



(a) Section of 100 mm thickness



(b) Section of 125 mm thickness

Fig. 3. Side view of reinforced bubbled slabs.**Fig. 4.** Preparation of testing slab specimen.**Fig. 5.** Deflection measurement.

5.3. Concrete strain measurement

Concrete strain has been measured using electrical micro strains. Each specimen has two strain locations, the first in the center of the compression face (top surface) and the second in the center of the tension face (bottom surface). The strain wires were connected to a data logger instrument with movable ram memory for saving data and then transported to the computer in excel form.

6. Results and Discussion

As mentioned before, the objective of this paper is to study the flexural behavior of voided slab (bubbled slabs) made with RPC. Effects of steel fibers volumetric ratio, placing of reinforcement and type of slab on flexural behavior of RPC in terms of first cracking load, ultimate flexural load, maximum deflection, load-deflection and stress-strain curves were recorded and discussed below.

6.1. General behavior

RPC slabs tests showed that the general behavior of all slabs under flexural loading can be described as fol-

lows: at the early stage of loading, the first cracks appeared at the bottom of the mid span in the tension zone, the load in this stage is known as first crack load. With increasing loads, these cracks became wider and going upwards, also other cracks developed in the same zone. Further loading made the cracks to spread and extend faster; some of them reached the compression zone until the failure occurred at ultimate load capacity.

6.2. Load-deflection relationship

Deflection is measured at the center of the tension face of the tested slabs (at the mid span) by means of (0.01mm) dial gauges. The readings were recorded for each load increment. In general, the deflection increases linearly with the load in an elastic stage when the concrete slab is subjected to a gradual load increase. After the cracks start developing, deflection of the slab increases at a faster rate. After cracks have developed in the slab, the load-deflection curve is approximately linear up to the yielding of flexural reinforcement after which the deflection continues to increase without an appreciable increment in load. Table 5 shows the deflection values at the first and ultimate loading stages and Fig. 6 shows the load deflection curves of tested slabs at different loading stages.

Table 5. Deflection of first and ultimate cracking load.

Slab Coding	First Cracking Load (P_{cr}) kN	Cracking Deflection (Δ_{cr}) mm	Ultimate Load (P_u) kN	Ultimate Deflection (Δ_u) mm
S-1-B-125mm	25	1.8	78.5	18
S-2-B-125mm	42.5	2.1	87.5	35
BS-1-B-125mm	17.5	1.2	37.5	11.3
BS-1-TB-125mm	24	1.65	52.5	12.5
BS-2-TB-125mm	62.5	6.5	92.5	10.95
BS-1-TB-100mm	12.5	1.8	27.5	10.5

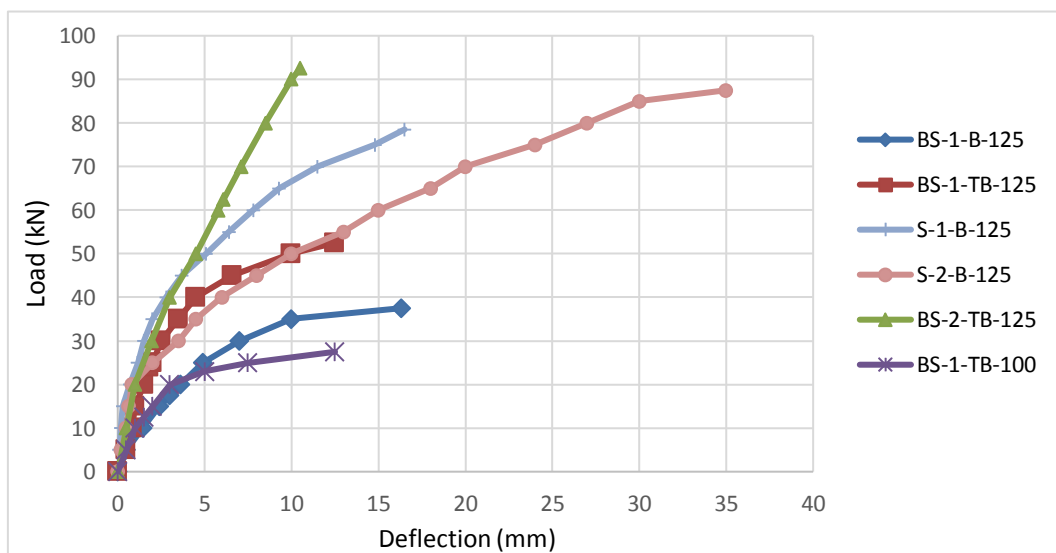


Fig. 6. Load-deflection relationship for tested slabs.

6.2.1. Effect of steel fiber ratios

The effect of the increasing steel fiber ratio from (1% to 2%) for solid slabs (S-1-B-125) & (S-2-B-125) of (125 mm) thickness with bottom reinforcement leads to increase the ultimate load capacity for slab (S-2-B-125) by (10%) and showing a significant increase in ductility while the deflection decreased by (18.75%) compared to slab (S-1-B-125) at the same stage of loading close to the first crack loading. Increasing the ratio of steel fiber in bubbled slabs (BS-1-TB-125) & (BS-2-TB-125) of (125 mm) thickness with top and bottom reinforcement lead to increase the ultimate load capacity for slab (BS-2-TB-125) by (43%) while the deflection decreases by (50%) compared to slab (BS-1-TB-125) as shown in Fig. 6. The increase in first crack and ultimate loads by increasing the steel fiber ratio results from restriction growing and expanding of the cracks also transition the tensile stress to concrete and surrounding cracks and result in increasing in load capacity.

6.2.2. Effect of voids

The presence of voids in slabs has great effect on ultimate load capacities and deflection values. The effect of bubbles in the slab (BS-1-B-125) compared with solid slab (S-1-B-125) with the same ratio of steel fiber, thickness and reinforcement decreases the ultimate load capacity by (52%) and the deflection by (41%) at the same stage of loading as shown in Fig. 6. The bubbled slab (BS-1-TB-100) has the least value of ultimate load (27.5 kN) as shown in Table 5 with minimum material used. By simple calculation, the equivalent distributed design live load that can be computed from the maximum applied moment is (12 kN/m²) for the same slab length.

6.2.3. Effect of slab thickness

The increasing in thickness by 25% in slab (BS-1-TB-125) compared with slab (BS-1-TB-100) with 1% steel fiber ratio and same reinforcement led to increase the ultimate load capacity by (48%) while the deflection decreased by (40%) at the same stage of loading as shown in Fig. 6. The increase in deflection for a specimen of (100mm) thickness is caused by the reduction of stiffness which gives rise to a significant increase in deflection values.

6.2.4. Effect of steel reinforcement

The increase of reinforcing ratio, as well as the presence of compression reinforcement decreases the deflection and increase the load capacity. Although the slab is simply supported, the additional top steel for slab (BS-1-TB-125) contributes in increasing the ultimate load capacity by (29%) and decrease the deflection by (57%) compared to slab (BS-1-B-125) at the same stage of loading. This may be because of slightly increasing in the moment arm or by releasing of the top reinforcement role in the thin voided slab.

6.3. Stress-strain relationship

Concrete strain is measured by micro strain gauges which are placed in the center of tension and compression faces for each specimen. Fig. 7 shows the variation of strain for tested slabs at different loading stages and for compressive and tensile strains. It can be seen that the concrete compressive and tensile strain is small at the elastic stage as loading is applied, and then it increases after the first crack when loading is continued. Positive values in the diagrams refer to tension strain and negative values refer to compression strain. In most cases of reinforced concrete with high tensile steel fibers, the fiber does not reach to the ultimate strength and the failure occurs by pulling out the fibers.

6.3.1. Effect of steel fiber ratios

Fig. 7 shows that bubbled slab (BS-1-TB-125) and solid slab (S-1-B-125) have larger compressive and tensile strains than (BS-2-TB-125) and (S-2-B-125) respectively. This decrease in compressive and tensile strains attributed to the increasing in the percent of steel fibers from 1% to 2% would increase the bonding in bubbled and solid slabs with 2% than slabs with 1% steel fiber ratio and this lead to reduce strains in compression and tension.

6.3.2. Effect of voids

Bubbled slabs show compression and tensile strains larger than solid slab. The increase in strain for bubbled slab attributed to that the voids (balls) occupying significant space from the total volume. Lesser amount of concrete used in the bubbled slab than a solid slab leads to decrease the stiffness and increase the compression and tension strains as shown in Fig. 7.

6.3.3. Effect of slab thickness

The compression and tension strains increase when the thickness decreases from (125 to 100 mm) for bubbled slabs at the same stage of loading as shown in Fig. 7.

From the results of previous comparisons, it seems that the thickness has large effects mainly in each of the first cracking and ultimate loads, deformation and strains in both tension and compression.

6.3.4. Effect of steel reinforcement

The additional top reinforcement postpones the appearance of cracks and increases the ultimate load capacity, thereby the strains in compression and tension decreases in slabs of double reinforced.

6.4. Crack patterns and flexural failure mode of tested slabs

In general and for all the specimens, the cracks appear at the bottom surface of the concrete slabs and grow upward through loading stages. The first crack could not be

distinguished because it is internal crack and after seconds it appears in the middle of the slab and grows gradually across the width of the slab. Then the other cracks developed to the right and left of the first crack. Increasing the applied load, the displacement of slabs begins to

increase at higher degree as more loads are applied and the ultimate crack occurs in the bottom face along the width of specimens. The ultimate failure crack shown in Fig. 8 and flexural failure modes of the slabs are shown in Figs 9(a-f).

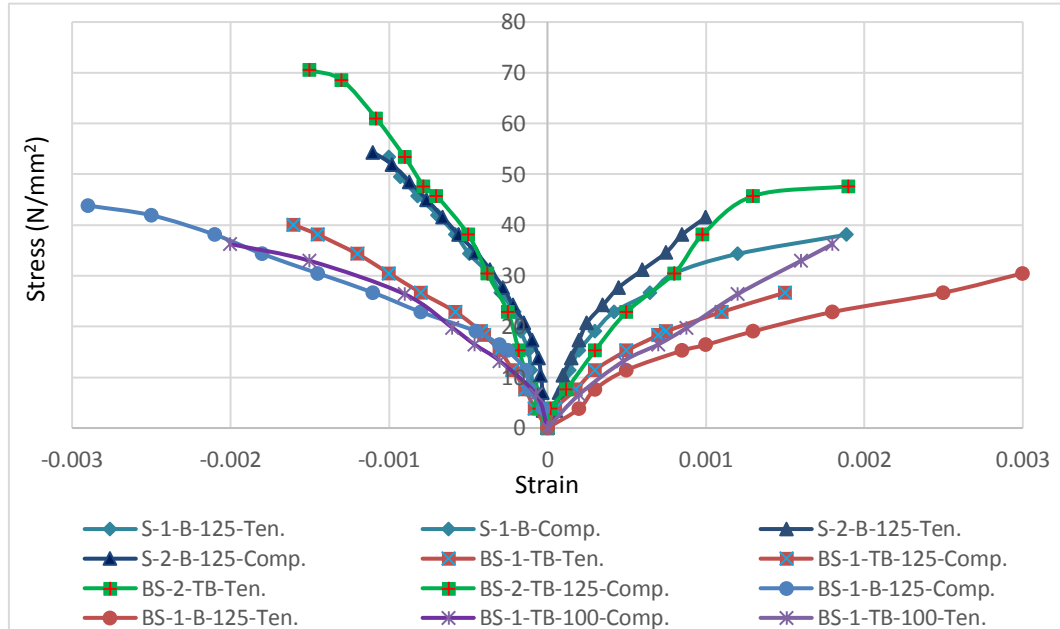


Fig. 7. Stress-strain diagram.



Fig. 8. Ultimate failure crack.

7. Conclusions

Biaxial voided slabs have many advantages over the conventional solid concrete slabs. Minimization of material, reduction of construction, lower cost, green technology, etc., are the main reasons for using these types of slabs. The effect of studied experimental parameters on the load capacity, strain and central deflection may be concluded as follows:

- The effect of the increasing steel fiber ratio improves the ultimate load capacity by (10%) for solid slabs with bottom reinforcement, while the ultimate load capacity increases by (43%) for bubbled slabs with top and bottom reinforcement.
- The deflection Influenced by increasing the steel fiber ratio from by (18.75%) for solid slabs with bottom reinforcement and by (50%) for bubbled slabs with top and bottom reinforcement.
- Increasing the thickness from 100 to 125 mm leads to increase the ultimate load capacity for bubbled slab with top and bottom reinforcement by (48%) while the deflection decreased by (40%).
- Additional top reinforcement in bubbled slabs improved the ultimate load capacity by (29%) and decreases the deflection by (57%).
- Bubbled slabs saving concrete by 18% compared to solid slab which reflects on the primary use of materials and CO2 emissions, so these slabs contribute the main objectives of sustainability.
- Increasing the steel fiber ratios from 1% to 2% shows improving the mechanical properties of RPC: f_{cu} , f'_c , f_{ct} , f_r and E_c by (16.88%, 17.63%, 50%, 39.4% and 11.12%) respectively.
- The study shows that this type of slabs satisfies the sustainability requirements and it is suitable for building which design live loads not exceed 12 kN/m².

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