

Research Article

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Effect of water-absorbent polymer balls in internal curing on punching shear behavior of bubble slabs

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Abstract: The punching shear capacity of bubbled slabs is one of the main problems due to its decreased thickness; when there is inadequate curing, the problem becomes more critical, causing the building's structural performance to deteriorate and exposing it to the risk of collapse. This study aimed to investigate the effect of using water-absorbent polymer balls in internal curing on the punching shear behavior of bubble slabs. Six concrete slabs were cast (1,000 mm × 1,000 mm × 70 mm). The main variables in this study are the type of slab (solid and bubble), type of curing (water and air), and ratio of water-absorbent polymer balls (5 and 10%). Studying the performance use of polymer balls and recycled plastic balls together and in normal strength concretes is limited. Also, investigating their behavior can provide insight into the efficiency of using these materials to improve concrete structures. Results showed that the most effective ratio for using polymer balls in internal curing is 5%, which had a good effect on the ultimate load, the first crack load, deflection, and crack pattern compared to the water-curing sample (reference sample). The water-absorbent polymer balls used in this study can absorb water when added to a concrete mixture. They release the water absorbed and subsequently contract, forming voids that are equivalent in size to the balls. This process facilitates internal curing while reducing the weight of concrete through the air voids left by the balls after they are dry.

Keywords: bubbled slab, internal curing, plastic balls, polymer balls, punching shear

1 Introduction

Internal curing has gained significant interest in recent years due to its importance in enhancing the strength and performance of concrete structures. It can be defined, according to ACI, as the process by which cement hydration continues due to the existence of internal water that is separate from the water used for mixing [1]. It facilitates water supply to concrete, promoting hydration and thus enhancing the overall performance of concrete structures. The thorough filling of pores in concrete with hydration compounds effectively decreases shrinking and cracking and enhances long-term strength [2]. Internal curing has proven promising in concrete production by lowering the effects of temperature sensitivity and autogenously shrinkage in concrete while enhancing its fracture resistance and improving economics by minimizing overall expenses over the life span [3,4]. In recent years, bubbled-reinforced concrete slab systems have been used in Europe. These slabs are a recent innovation in lightweight concrete construction that has been offered to the industry [5]. Introducing voids in the form of hollow plastic bubbles between the stress zone and the neutral axis of a reinforced concrete slab may prevent the consumption of unneeded concrete [6]. This system has several benefits: greater flexibility in project layouts, reduced self-weight by up to 35% compared to an equivalent solid slab, increased spacing between columns by up to 50% compared to solid slabs, and reduced logistics of transporting materials [7]. It also contributes to reducing carbon dioxide emissions and preserving the environment [8]. Generally, the bubble slab comprises a lower layer of reinforcing mesh, plastic spheres, and an upper layer of reinforcing mesh [9]. Punching shear capacity is the main problem faced with these slabs due to the small thickness, which can cause the structure to collapse if not handled properly [10]. When implemented without beams, punching failure at the connection point between slabs and columns is possible [11,12]. It can lead to sudden and catastrophic failures if not

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addressed appropriately, so this problem requires exploring innovative methods, such as internal curing, to improve its structural performance [11]. Water-absorbent polymer balls are effective internal curing agents for concrete, which are small spherical balls used in cement mortar and concrete. Adding it to cement mortar and concrete improves several characteristics, such as workability, increasing compressive and flexural strengths, and reducing water absorption and penetration of carbonation and chloride ions. All previous improvements depend entirely on the size of polymers to be added and their dosages [13]. Water-absorbent polymer balls have recently been studied and are expected to serve as internal water sources. It can absorb up to hundreds of its weight from pure water [14]. It has been classified as intelligent materials due to changes in characteristics; when exposed to water, they swell, and when exposed to drying later, they shrink reversibly. These fundamental properties can be used effectively in concrete [15].

Ahmed in 2017 [16] studied the compressive strength of the concrete containing polymer balls. The mixture was prepared with and without (reference) polymer balls and was subjected to water and air curing using several ratios of polymer balls (5, 10, 15, and 20%) of the weight of cement. The test was under compression load. Results showed that the optimal ratio for using polymer balls in concrete, which had a noticeable effect on the compressive strength, was 5% in water and air curing.

Hussen and Mohammed in 2022 [17] investigated the impact of water-absorbent polymer balls on the structural performance of reinforced concrete beams. Four reinforced concrete beams were casted with dimensions of 150 mm × 200 mm × 1,500 mm, a compressive strength of 50 MPa, and a ratio of polymer balls (0, 1, 2, and 3%). These beams were tested under two-point loads. The findings indicated that the maximum load capacity was increased by 2.0, 3.0, and 7.14% for the 1, 2, and 3% ratios of polymer balls, respectively, compared to the reference beam. It was also shown that the 3% ratio of polymer balls had more influence than the other ratios. It significantly impacted the deflection.

Ramalingam *et al.* in 2022 [18] studied the effect of water-absorbing polymer balls as internal concrete curing agents to assist hydration. A concrete mixture with polymer ball ratio of 2.5 and 5% of cement weight and exposed to air and water curing and the mixture without polymer balls (reference) were tested under compressive force. The results showed that the compressive strength of air-cured samples with 2.5 and 5% polymer balls was 30.37 and 28.74 MPa, respectively, and about 99–94.2% of the water-cured sample (reference). The tests also showed that air-curing samples expanded and water-curing samples shrunk. Also, air-curing

concrete samples containing polymer balls showed more strength than water-curing concrete samples over 84 days. From previous literature, it can be concluded that polymer balls have been used in concrete. However, using polymer balls in bubble slabs subjected to air and water curing has not been studied and compared until now. Although prior research has provided insight into the behavior of polymer balls used in concrete using a variety of techniques, there are still knowledge gaps in the following areas:

- Evaluating the efficiency of internal curing by using water absorbent polymer balls on punching shear behavior of the bubble.
- Evaluating the efficiency of internal curing on punching shear behavior of bubbled slabs in normal strength concrete.
- Evaluating the performance of structure bubbled slabs under different curing conditions (water and air).

In conclusion, this study provides added value through water-conserving, reducing the duration of the project, and spending on electricity and fuel, where the concrete of normal strength has been developed that does not require external curing; this, in turn, reduces the project's total cost.

2 Experimental work

2.1 Details of samples

Six concrete slabs were cast, with dimensions of 1,000 mm × 1,000 mm × 70 mm. One slab was solid (control slab), and the rest were bubbled slabs with 160 plastic balls inside them, which were manufactured from recycled plastic with a diameter of 40 mm. The diameter of the ball to the depth of the slab ratio (D/T) was 57.14%. The details of the test slabs are shown in Figure 1.

All slabs are reinforced with two layers of reinforcement; the yield strength of the reinforcing mesh was 390 MPa, and the ultimate strength was 470 MPa. The concrete mixture includes water-absorbent polymer balls with a ratio of 5 and 10% from the weight of the cement. After being submerged for 24 h to absorb the water and swell, they were incorporated into the mixtures, as shown in Figure 2. The samples differed regarding the type of slab, type of curing, and ratio of water-absorbent polymer balls, as shown in Table 1. The six slabs were made using normal-strength concrete. Table 2 shows the mixing ratio.

The characteristics of the raw materials utilized in producing normal concrete strength are listed in Tables 3–5.

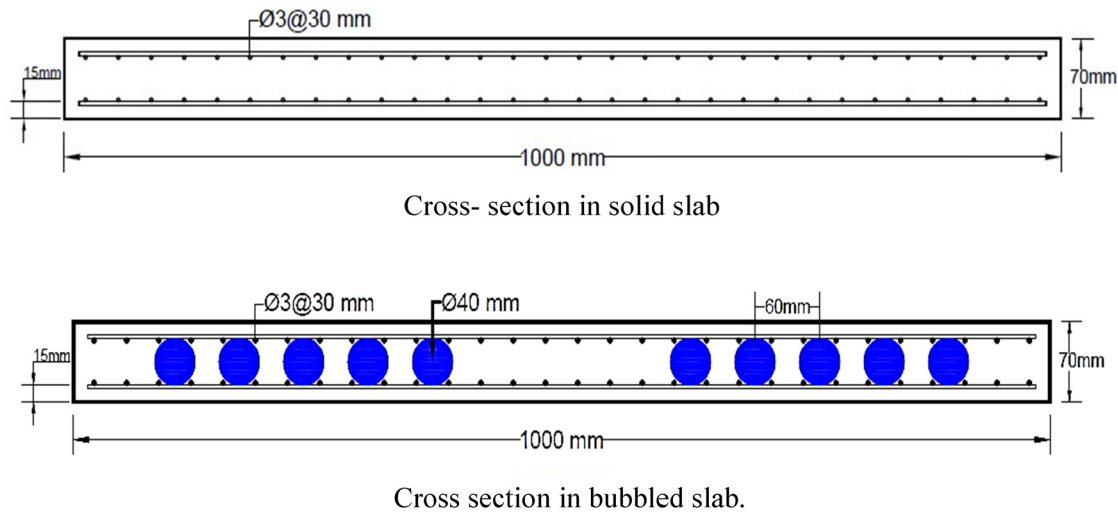


Figure 1: Details of the samples. Upper panel: cross-section of the solid slab; lower panel: cross-section of the bubbled slab.



Figure 2: Water-absorbent polymer balls.

Table 1: Details of test slabs

Number of samples	Labeling	Type of slab	Ratio of polymer balls %	Type of curing
1	RSW	Solid	—	Water
2	RBW	Bubbled	—	Water
3	RBA	Bubbled	—	Air
4	BP5A	Bubbled	5	Air
5	BP10A	Bubbled	10	Air
6	BP10W	Bubbled	10	Water

R: reference, S: solid, B: bubble, A: air curing, W: water curing, and P: polymer ball.

In this mixture, the mixing process is carried out using a rotary mixer. Initially, dry sand was added to the mixture,

and 0.5 L of water was added to dampen the sand. Subsequently, gravel and sand were blended for 1.5 min. Later, the cement was placed in the mixer, and each dry material was combined for 1 min to guarantee the uniformity of the mixture. After that, water was introduced in three stages, and a 3-min mixing procedure was performed. The mixer was stopped, manually repositioned, and continued mixing for three more minutes. This stage ensures uniformity in the mixture [19]. Polymer balls were added to the mix in the two layers. Each slab was cast from one concrete batch; nine standard cylinders with dimensions of 150 mm × 300 mm were taken from each slab to determine the mechanical properties of the concrete.

All slabs and associated cylinders were subjected to different curing conditions, such as water and air, for 28 days. Table 6 lists the mechanical properties of concrete, and Figure 3 shows the methodology used to conduct this study.

2.2 Test setup

Before testing, the slab was thoroughly cleaned and painted on both sides to ensure the visibility of cracks during the testing process. The slab is positioned on simple supports. Below each slab, a 0.01 mm dial gauge was placed. Concentrated load was applied at the midpoint of the slab. The slabs were tested using a hydraulic testing machine (EPP300MFL), and the system had a max capacity of 30 tons. The load was incrementally applied in 5 kN increments. The load at the first crack, as well as the ultimate load, together with their respective deflections at the

Table 2: Properties of the mixture

Mix notation	Average nominal compressive strength f_c (MPa)	w/c	Cement (kg/m ³)	Water (L/m ³)	Sand (kg/m ³)	Gravel (kg/m ³)
NSC	30	0.45	400	180	600	1,200

Table 3: Composition and physical properties of the cement used

Oxide	Content, Wt (%)	Limit of IQS 5/1984 [20]
SiO ₂	20.87	—
Al ₂ O ₃	4.15	—
Fe ₂ O ₃	3.39	—
SO ₃	2.57	<2.80%
CaO	63.11	—
MgO	2.7	<5.0%
Loss on ignition	3.72	<4.00%
Lime saturation factor	0.95	(0.66–1.02)%
Insoluble residue	0.69	<1.5%

Table 4: Properties of the fine aggregate

Sieve size (mm)	Passing (%)	IQS No.45/1984 [21]
10	100	100
4.75	90.5	90–100
2.36	76.3	75–100
1.18	58.1	55–90
0.60	35.51	35–59
0.30	11.64	8–30
0.15	1.93	0–10

Table 5: Properties of the coarse aggregate

Sieve size (mm)	Passing (%)	IQS No.45/1984 [21]
19.5	100	100
12.5	94.45	90–100
9.5	50.93	40–70
4.75	9.27	0–15
2.36	0.01	0–5

center of the slab, were both observed and documented. The slabs in the current study had a length of 1,000 mm, which exceeded the maximum capacity of the testing machine, which was 450 mm. Consequently, a custom-made supporting structure is fabricated and used inside the testing apparatus to achieve the necessary width of the slab. The test slabs were subject to a focused load by

Table 6: Mechanical properties of the concrete

Labeling	Compressive strength of the cylinder (MPa)	Splitting tensile strength (MPa)	Modulus of elasticity (GPa)
RSW	32	4.1	27.5
RBW	32	4.1	27.5
RBA	26.5	3.1	24.7
BP5A	32	4.0	27.6
BP10A	30	3.8	27.1
BP10W	28	3.4	26.6

placing a solid square steel shaft with a dimension of 100 mm × 100 mm over its center.

3 Test results and discussion

3.1 Ultimate load

The ultimate load of the tested slabs is presented in Figure 4, which is a crucial indicator of structural performance. Generally, the results of the ultimate load show a decrease when the voids are inserted into the concrete slab. The bubbled slab (RBW) exhibits a decrease in ultimate loads compared to the solid slab (RSW) by about 4.35%. This decrease results when the plastic balls are in the concrete slabs at the middle depth, with minimal stress. Also, the tests show a decrease in ultimate loads in the bubbled slab of RBA compared to the RBW by about 18.2%. This is due to the complete hydration process in addition to the increasing porosity of concrete and increasing stress development. BP5A and BP10A have strengths of about 100 and 95.5% from RBW, respectively, attributed to an increase in the degree of hydration process resulting from polymer balls, which leads to an increase in hydration products that fill the concrete voids. BP10W exhibited a reduction in the ultimate load. Compared to the RBW of about 13.6%, an increase in the water contents causes a decrease in values. Tables 7 and 8 present the results obtained.

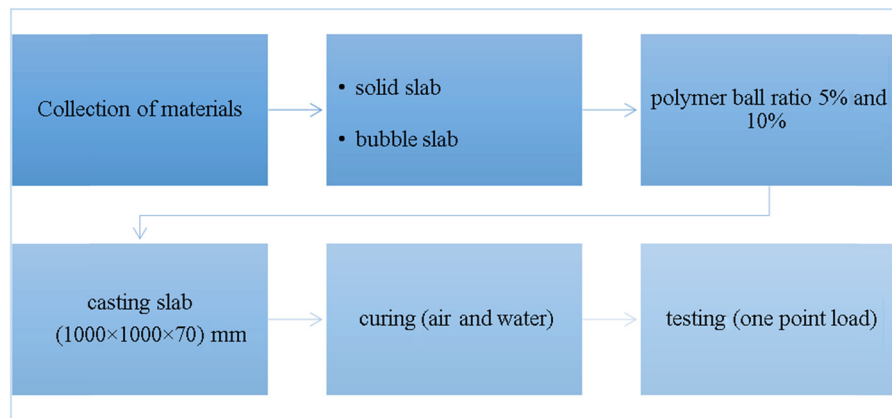


Figure 3: Methodology used in this study.



Figure 4: Ultimate load results.

3.2 First crack load

The first crack occurs in all slabs at applied loads of 29, 27, 18, 26.5, 25, and 21.5 kN for slabs RSW, RBW, RBA, BP5A, BP10A, and BP10W, respectively. The RBW slab exhibits a reduction in the first crack load compared to the solid RSW slab of about 6.9%. This decrease occurs due to the presence

Table 8: Derived information of the tested slabs

Labelling	Failure mode	Failure Angle (°)	Failure area (mm)
RSW	Punching	17.8	88,452
RBW	Punching	17.1	88,598
RBA	Punching	16.4	90,854
BP5A	Punching	17.2	88,543
BP10A	Punching	15.4	221,342
BP10W	Punching	15.1	226,493

of plastic balls and the decrease in concrete. The first crack load of RBA was about 66.7% due to its inadequate curing. The first crack loads of BP5A, BP10A, and BP10W were about 98.1, 92.6, and 79.6%, respectively. From RBW, this indicates that the internal curing provided by polymer balls led to an improved first crack load.

3.3 Load deflection

When a reinforced concrete slab is gradually exposed to increasing loads, deflection increases linearly, exhibiting

Table 7: Results of the tested slabs

Labeling	First crack load		Service load		Ultimate load		FC/UL (%)	Crack width (mm)
	Load (kN)	Central deflection (mm)	Load (kN)	Central deflection (mm)	Load (kN)	Central deflection (mm)		
RSW	29	0.6	69	2.3	115	7.5	25.2	0.6
RBW	27	0.7	66	2.2	110	7.7	24.5	0.62
RBA	18	0.65	54	2.4	90	6.6	20	0.8
BP5A	26.5	0.5	66	2.4	110	8.0	24	0.61
BP10A	25	0.68	63	2.4	105	8.2	23.8	0.63
BP10W	21.5	0.8	57	2.5	95	7.3	22.6	0.65

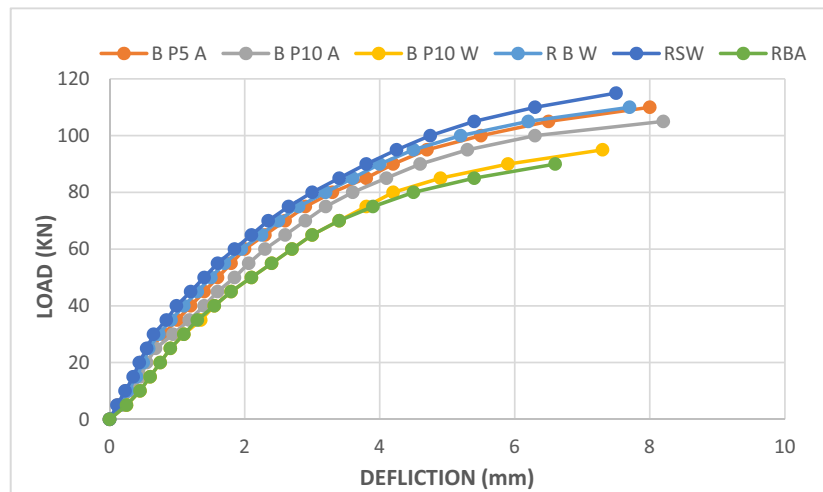
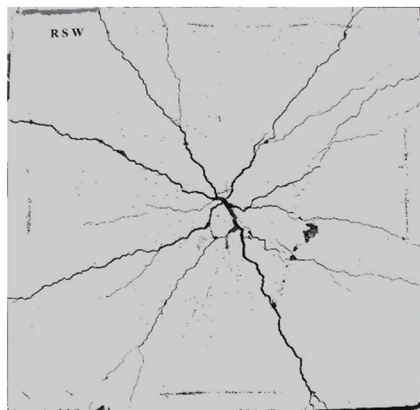
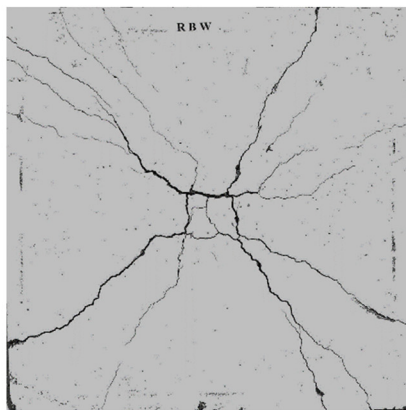


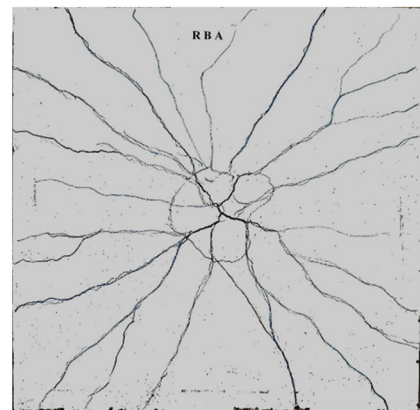
Figure 5: Load-deflection relation.



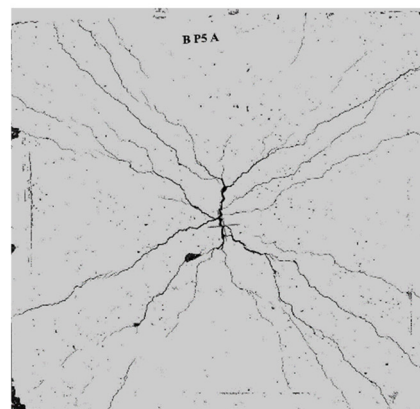
(a)



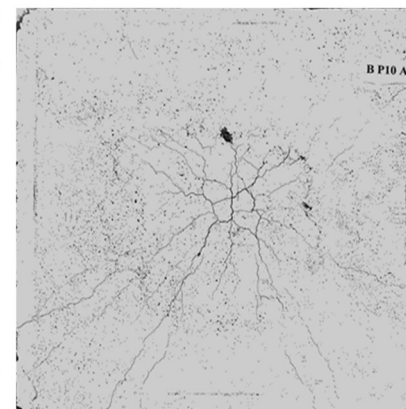
(b)



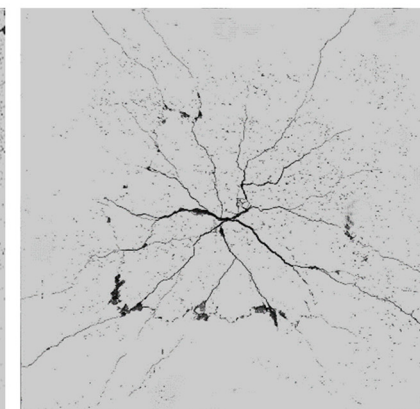
(c)



(d)



(e)



(f)

Figure 6: Crack patterns: (a) RSW, (b) RBW, (c) RBA, (d) BP5A, (e) BP10A, and (f) BP10W.

elastic behavior. First, cracks start to form and the deflection of the slab accelerates. As the cracks in the slab progress, the load–deflection curve shows an essentially non-linear behavior until the flexural reinforcing reaches its yield point. After this point, the deflection continues to increase without significantly increasing the applied load. The deflections resulting from loading do not vary significantly at the early loading levels; nevertheless, the difference became evident at the advanced loading levels. Generally, the deflection in bubble slabs is more significant than that of solid slabs, especially in RBA and BP10W. After the elastic region, cracks were generated, which deteriorated more than others. The slabs BP5A and BP10W also showed an improvement in deflection compared to RBW at the same loading level, in addition to reducing the damage rate, as shown in Figure 5.

3.4 Crack pattern and mode failure

According to fractal theory, a direct relationship exists between the size of a crack (length and width) or the punching area and the computed fractal dimension. In other words, the fractal dimension increases as the crack or hole becomes wider or bigger. Cracks and punching that appear in concrete slabs indicate the degree to which they have failed. The fractal dimension of these cracks may be used as a benchmark to measure the extent of failure.

The failure pattern of all concrete slab samples in this study is through the spread of the cracks. These cracks spread quickly and extend from the column parameter toward the slab edges. When comparing the failure pattern of the specimens in Figure 6, it can be seen that the more severe the failure of the specimen, the larger the fractal dimension value.

4 Conclusions

In summary, the main conclusions are as follows:

1. The ultimate load of bubble slabs containing polymer balls with a ratio of 5% and air curing is about 100% of the ultimate load of the sample water-cured. This was the highest improvement among all the methods of curing studied.
2. The first crack load of bubble slabs containing polymer balls and air-cured was about 98.1% compared to the reference sample water-cured.
3. Adding polymer balls with a ratio of 5% to concrete as an internal curing agent led to the development of normal-strength concrete that did not require external curing.

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Data availability statement: Most datasets generated and analyzed in this study are within the manuscript. The other datasets are available on reasonable request from the corresponding author with the attached information.

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