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Static and cyclic behaviour of Bubble Deck slab with plastic balls

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Research Paper

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Bubble deck slab technology offers an innovative approach for crafting concrete slabs that combine lightweight properties with efficiency. This system incorporates voids within the system. The primary purpose of voids is to minimise the self-weight of a slab considering its structural integrity. This enables extended spans and decreases the load on the supporting structures. This study investigated the static and progressive cyclic load behaviours of concrete in which plastic balls were used as void makers below the neutral axis in various proportions. Bubble deck slabs were evaluated alongside conventional concrete under both loading conditions, and the results were analysed to assess the impact of varying void percentages. In addition to the primary investigations, a detailed analysis of the load–deflection curve behaviour and stiffness degradation of the slabs was conducted.

Key words:
static load, progressive cyclic load, plastic balls, percentage of voids, ultimate load, load–deflection curve

Prethodno priopćenje

Anni Anto G., Murugan M.

Ponašanje “Bubble Deck” ploča pod statičkim i cikličkim opterećenjem

Tehnologija “Bubble Deck” ploča nudi inovativan pristup za izradu betonskih ploča koje kombiniraju malu težinu s učinkovitošću. Ovaj sustav obuhvaća šupljine unutar konstrukcijskog elementa. Primarna je svrha šupljina smanjenje vlastite težine ploče uz očuvanje njene nosivosti. To omogućava veće raspone i smanjuje opterećenje nosive konstrukcije. Ovo istraživanje ispitivalo je ponašanje betona pod statičkim i rastućim cikličkim opterećenjem, pri čemu su plastične kuglice korištene za stvaranje šupljina ispod neutralne osi u različitim omjerima. “Bubble Deck” ploče uspoređivane su s klasičnim armiranim betonom pod oba opterećenja, a rezultati su analizirani radi procjene utjecaja različitih postotaka šupljina. Uz osnovno istraživanje provedena je i detaljna analiza ponašanja dana krivuljom odnosa opterećenja i progiba, kao i degradacije krutosti ploča.

Ključne riječi:
statičko opterećenje, rastuće cikličko opterećenje, plastične kuglice, postotak šupljina, granično opterećenje, krivulja opterećenje-progib

1. Introduction

Bubble deck slab technology is an advanced construction method that focuses on enhancing the efficiency and effectiveness of concrete slabs [1]. The core concept of bubble deck technology involves embedding void formers or bubbles in the core of a concrete slab. The inserted voids decrease the amount of concrete required, thereby reducing the self-weight of the slab while maintaining its load-carrying capacity [2, 3]. The intentional reduction in concrete volume is designed to minimise the self-weight of the structure, enabling the use of smaller, more cost-effective supporting columns and foundations [4]. This approach also enables the design of extended spans between supports.

This technology affords enhanced design flexibility, permitting the creation of expansive column-free areas and extended spans [5, 6]. This capability is particularly advantageous for commercial and residential structures [7]. Conventional reinforcement bars are integrated with the bubble deck system to manage the tensile stresses and maintain structural integrity.

A primary advantage is the reduction in the slab weight, which decreases the load on the supporting structures and foundations [8]. This material efficiency not only curtails construction costs but also enhances sustainability by reducing resource consumption [3, 9]. Bubble deck slabs typically offer enhanced thermal and acoustic insulation owing to their reduced mass [8, 10].

In structural engineering, concrete is primarily engineered to resist compressive forces, while steel addresses tensile forces. Therefore, concrete is not required in the tension zone of a slab located below the neutral axis [11]. Voids are introduced in areas where concrete is not required, thereby allowing for weight reduction and material efficiency. A cover is necessary to protect the reinforcement and ensure the durability of the concrete. Load transfer can be achieved through the voids using an arch action while inserting bubbles into the slabs. The arch action helps distribute loads more efficiently between the support points, creating a stronger, rigid slab with less concrete [10].

The arch action provided by the void-creating material allows the slab to span longer distances with less material, making it an efficient design choice. This also leads to material savings, which can be significant in large-scale projects, reducing both the environmental impact and cost.

Various materials have been used to create voids in bubble deck slabs, including waste pipes, plastic balls, PET bottles, foam, glass bottles, and cardboard [12, 13]. The use of recycled plastic and other sustainable materials in construction helps reduce the need for new plastic production, addressing the growing issue of plastic waste, which poses a significant environmental threat [14, 15]. Although non-biodegradable, plastic balls reduce waste during construction, with future recycling innovations addressing disposal concerns. In voided slabs, specific sections of concrete are replaced with eco-friendly alternatives such as coconut shells, effectively reducing the overall weight while maintaining structural integrity. Different shapes of inert bubbles, such as elliptical, cylindrical, spherical, concave, cubic, and reinforced bubbles, have also been incorporated to optimise structural performance [16, 17].

The strength of bubble deck concrete with cubic concave bodies is lower than that using spheres owing to the differences in shape and stress distribution. Spheres allow for uniform load transfer and minimise stress concentrations, resulting in better structural performance. In contrast, cubic concave bodies create sharp edges and localised stress points, leading to weaker bonding with concrete and reduced overall strength [16]. Larger voids remove more concrete from the load-bearing section, significantly reducing the strength and stiffness of the slab and leading to a greater decrease in the ultimate load capacity. In contrast, increasing the number of smaller voids distributes the reduction more evenly, causing less impact on the overall structural integrity [18]. For optimal performance, using balls at 50 % of the slab thickness is recommended, as it maintains the ultimate strength while minimising reductions in stiffness, ductility, and toughness [19].

Various load tests, such as cyclic loading, harmonic loading, and impact loading, have been conducted on ordinary concrete slabs [20]. However, despite extensive research on bubble deck slabs, gaps remain in the understanding of their behaviour under different loading conditions. Limited research has been conducted on their performance under cyclic loading, including stiffness degradation and failure mechanisms. The optimal void percentage for balancing the weight reduction and strength has not yet been well established. The static and cyclic loading effects have not been sufficiently compared, making it unclear how voids influence the load–deflection behaviour, failure modes, and stiffness over time. More studies are needed to understand these aspects and improve the design of bubble deck slabs. In this study, arch-shaped voids were created by incorporating varying percentages of recycled plastic balls into bubble deck slabs, thereby minimising plastic waste and promoting sustainable construction. The slabs were then subjected to static and progressive or incremental cyclic loading, and the ultimate loads were compared with those of conventional concrete.

Prior research has mainly focused on doubly reinforced bubble deck slabs in which voids are created by removing concrete from the middle of the slab through the introduction of voids. This study introduces a novel approach by strategically placing plastic balls below the neutral axis to optimise material usage while maintaining structural efficiency. Unlike previous studies that focused primarily on static loading, this study investigated the effects of cyclic loading on bubble deck slabs by analysing the stiffness degradation and load–deflection behaviour. It also explored the role of

Table 1. Properties of the used 53 grade Ordinary Portland Cement (OPC)

Name of the tests	Results obtained	Requirement of IS 12269-2013
Fineness [m²/kg]	257	Not less than 225
Specific gravity	3.14	-
Standard consistency [%]	29	-
Soundness [min] (by Le-Chatelier expansion)	1.0	Not more than 10
Initial setting time [min]	40	Not less than 30
Final setting time [min]	520	Not more than 600
Compressive strength at 3 days [MPa]	36.50	Not less than 27
Compressive strength at 7 days [MPa]	45.17	Not less than 37
Compressive strength at 28 days [MPa]	55.25	Not less than 53

Table 2. Coarse aggregate properties

Properties	Test results	Requirement of IS 12269-2013
Maximum size of aggregate [mm]	20	-
Shape	uglat	-
Water absorption [%]	0.70	-
Specific gravity	2.71	-
Bulk density [kg/m³]	1637	-
Aggregate impact value [%]	14.08	< 45 %
Crushing strength [%]	10.23	< 45 %
Flakiness index [%]	5.72	< 40 % (combined)
Elongation index [%]	8.03	

plastic voids in enhancing the arch action and improving load redistribution. Additionally, this study identified the optimum void percentage that balances weight reduction with structural integrity, contributing to the development of more efficient and sustainable slab designs.

2. Material properties

Indian Standard (IS) codes, Eurocodes, and ASTM follow similar structural principles, including safety factors, material properties, and load considerations. They share common testing procedures and use a limit-state design approach for concrete structures. However, in mix design and durability guidelines, IS codes differ from the others [21]. In this study, IS codes were adopted for material testing, mix design, slab casting, and slab testing. The material properties of cement concrete are crucial for obtaining proper integrity and longevity of structures. The following raw materials were used to cast the slab, and all materials met the IS requirements.

2.1. Cement

Ordinary Portland cement (OPC) of grade 53, which meets the requirements of Indian Standard specification IS 12269:2013, was used to cast the slab. The physical properties of the cement are listed in Table 1.

2.2. Coarse aggregate

Crushed stone from a quarry was used as coarse aggregate, consisting of 60 % of aggregate with a maximum size of 20 mm and 40 % with a size of 12.5 mm. The aggregate satisfied the requirements of IS 2386 (Part 1): 1963 and is presented in Table 2.

2.3. Fine aggregate

Sand from a local quarry was used to cast the concrete. The manufactured sand (M-sand) has a particle size smaller than 4.75 mm. Tests on fine aggregates were performed, and the results were compared with the requirements specified in IS 2386 (Part 1), 1963, as listed in Table 3.

Table 3. Properties of fine aggregates

Properties	Test results	Requirement of IS 2386-1963
Specific gravity	2.67	-
Fineness modulus	4.62	-
Water absorption [%]	1.5 %	< 3 %
Bulk density [kg/m³]	1518	-
Surface texture	Glatka	-
Grading zone	Zona III	Zona I. II ili III

2.4. Water

Clean, potable, and locally available drinking water was used to prepare the concrete. The pH of the water was 7.1

2.5. Reinforcing bars

Reinforcing bars with a diameter of 8 mm and grade Fe550 were used in both the longitudinal and transverse directions. The stress–strain behaviour of a reinforcing bar is shown in Figure 1.

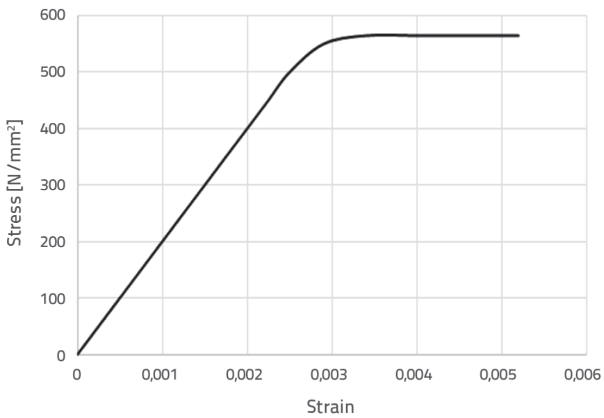

Figure 1. Stress–strain curve of Fe550 rod

2.6. Plastic balls

Small spherical plastic balls with diameters of 30 and 40 mm, made of chemically inert polyethylene, were used to cast the bubble deck slab.

2.7. Mix proportion

The concrete slabs were casted using C 20/25 concrete grade. The mix proportions were designed in accordance with IS 456:2000 and IS 10262:2009 standards. The following mix proportions were determined based on the design:

Cement	Fine aggregate	Coarse aggregate		Water
		12.5 mm	20 mm	
1	1.92	1.39	2.09	0.50

2.8. Compressive strength of concrete cube

The compressive strength at 28 days, measured using standardised cube specimens (150 × 150 × 150 mm), was 33.42 MPa. The stress–strain curve for the C 20/25 concrete grade is shown in Figure 2.

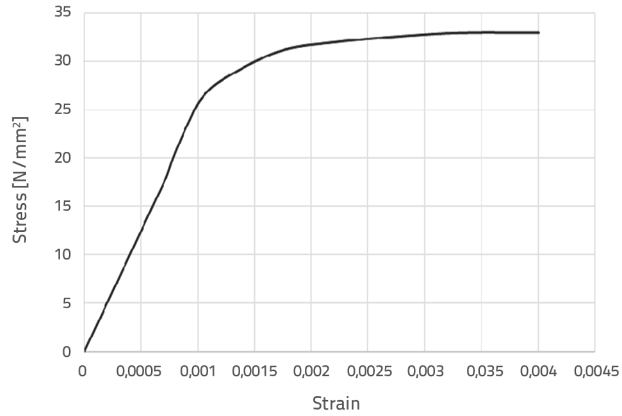

Figure 2. Stress–strain curve of C 20/25 concrete grade

3. Fabrication details

Concrete slabs measuring 600 × 450 × 100 mm were utilised with varying percentages of concrete replacement in the tension zone at 0 %, 10 %, 20 %, 30 %, and 40 % of the total concrete volume.

Total volume of concrete slab = 600 x 450 x 100 mm = 2.7 x 10^7 mm^3. 10 % replacement of concrete in tension zone = 2.7 x 10^6 mm^3, 20 % = 5.4 x 10^6 mm^3, 30 % = 8.1 x 10^6 mm^3, and 40 % = 1.08 x 10^7 mm^3.

Plastic balls were used to replace 10 %, 20 %, 30 %, and 40 % of the total concrete volume.

3.1. Fabrication of conventional concrete slab

The slabs were cast using plywood moulds with dimensions of 600 × 450 × 100 mm. A 20 mm-thick layer of C 20/25 concrete grade was laid as the bottom cover. A steel reinforcement consisting of 8 mm diameter steel rods was placed in a grid pattern with 140 mm spacing in both directions, as shown in Figure 3. After the reinforcement was set up, concrete was poured and compacted to ensure the elimination of voids.

3.2. Fabrication of bubble deck slab with balls

Plywood moulds with dimensions of 600 × 450 × 100 mm were prepared for casting the bubble deck concrete slabs. A 20 mm thick layer of concrete was poured into the mould to provide adequate reinforcement protection, and the reinforcement mesh was placed on top of this cover layer, as shown in Figure 3. The necessary number of balls corresponding to the specified replacement percentage was uniformly placed on top of the concrete. To secure the balls in place, a fibre mesh was tied to the reinforcement mesh, as shown in Figure 4. The remaining portion of the mould was then filled with concrete and carefully compacted to remove any trapped air.

Figure 3. Casting conventional concrete slab

Figure 4. Casting of slab with balls

The slabs were demoulded after 24 h and submerged in water for 28 days to ensure adequate cement hydration. The curing water was maintained at a temperature of 27 °C ± 2 °C, with 100 % relative humidity (fully immersed curing). After curing, the slabs were dried at a normal atmospheric temperature of 35 °C before testing.

4. Test on slabs

4.1. Static test on slabs

The load-bearing capacity of both conventional and bubble deck slabs, incorporating balls, was tested using a flexure testing machine The flexure testing machine used for testing has a loading accuracy within ±1 %, in compliance with IS 1828 standards. The slabs were supported at both ends and subjected to monotonic loading at their centre until failure, as illustrated in Figure 5. The beam had a support span of 600 mm, with the load applied 500 mm away from each support. The load was gradually applied at a rate of 0.2 to 0.5 kN/s until failure.

For each incremental load applied, the central deflection was recorded to analyse the load–deflection behaviour of the slab. With an increase in load, cracks began to form on the tension side of the slab. Despite the cracks, the slab continued to bear additional loads owing to the reinforcement.

The first cracking load and maximum load before failure were recorded and are listed in Table 1.

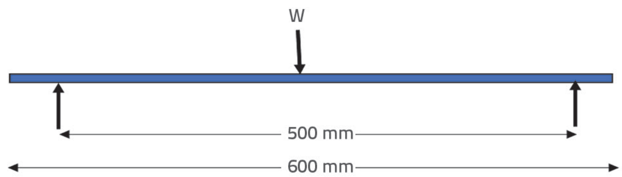

Figure 5. Load and support specifications of slab

The slabs exhibited a progressive reduction in both the first cracking load and ultimate load. The first cracking load, marking the onset of visible cracks, varied between 40.8 and 24.21 kN, indicating a steady decline. Likewise, the ultimate load, which defines the maximum load-bearing capacity before failure, dropped from 55.02 to 42.92 kN, highlighting a decreasing trend in structural strength.

Figure 6 illustrates the gradual reduction in the ultimate load capacity of the slabs as the proportion of plastic balls increased. This trend suggests that the presence of voids in the tension zone introduced by the balls marginally weakened the ability of the slabs to withstand higher loads before failure.

As presented in Table 4, when 20 % of the concrete in the tensile zone was replaced, the reduction in the load-carrying capacity remained below 8 %, indicating only a slight decrease in strength. This suggests that slabs with 20 % replacement ratio perform similarly to solid slabs, making them a promising alternative for construction. Similar observations have been reported in previous studies. A review indicated that bubble deck slabs retained 75 % of the load-bearing capacity of traditional reinforced concrete slabs [22].

Table 4. Ultimate load values of conventional and bubble deck slabs with balls in the static test

Slab number	Percentage of replacement of concrete in tension zone	First cracking load [kN]	Ultimate load [kN]	Percentage decrease in ultimate load compared to conventional concrete [%]
1	0 %	40.8	55.02	0.00
2	10 % balls	37.65	54.1	1.67
3	20 % balls	33.84	50.68	7.89
4	30 % balls	29.52	47.3	14.03
5	40 % balls	24.21	42.92	21.99

Another study found that the strength variation between conventional and bubble deck slabs was negligible [23]. Additionally, research indicated that reducing the concrete volume by 15 % resulted in an 11.5 % decrease in the ultimate load capacity, whereas an 18 % reduction led to a 15.93 % decrease compared with that of solid slabs [24].
Furthermore, another study demonstrated that bubble deck slabs could withstand up to 80 % of the stress borne by conventional slabs, with only slight differences in deformation [25].

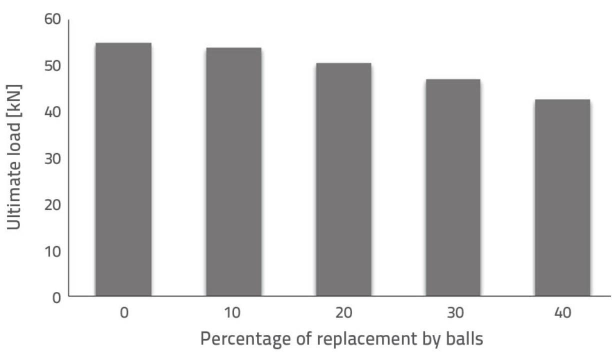

Figure 6. Ultimate load of bubble deck slab with balls in static test

The bubble deck slabs primarily failed owing to mid-span concrete crushing, with initial flexural cracks in the constant moment region. Shear cracks were also observed near the supports, with some extending diagonally toward the loading points as the load increased. The presence of plastic balls affected crack propagation but maintained structural integrity until failure.

4.2. Load vs deflection in static test

The bubble deck slabs exhibited greater deflection than the solid slabs under a given load owing to the presence of voids, which reduced their overall stiffness and load-bearing capacity, as presented in Table 5. This reduction in material made the slabs more flexible, causing them to bend more than the solid slabs when subjected to the same applied load. Similar observations indicated that the reduction in flexural stiffness caused voided slabs to exhibit a more flexible load–deflection behaviour than solid slabs, with the stiffness decreasing by 11.1 % to 23.7 % [18]. Another study observed that bubble deck slabs showed 5.88 % greater deflection than solid slabs, which was attributed to the reduced stiffness owing to the presence of hollow sections [26]. The load–deflection graphs for conventional concrete and concrete with varying ball percentages are shown in Figure 7.

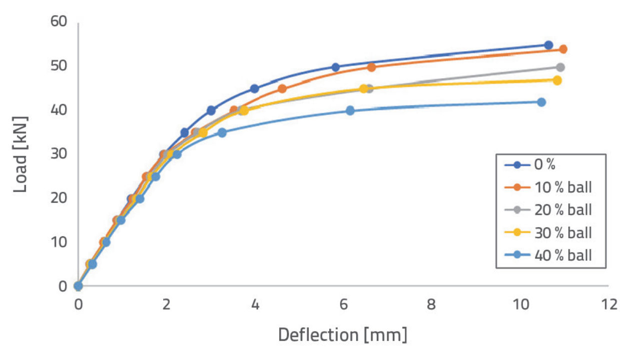

Figure 7. Load–deflection graphs of conventional concrete and bubble deck slab with balls

Initially, the load–deflection curve was straight, indicating that the material behaved elastically, and the slab returned to its original shape once the load was removed. As the load increased, the material reached a point at which it started to bend or stretch permanently, causing the curve to become less straight.
The curve reached its highest point at the maximum load that the material can handle. Beyond this point, the material began to weaken or break, leading to a decrease in its ability to carry loads.

Table 5. Load vs deflection

Load [kN]	Central deflection [mm]				
	0 %	10 % balls	20 % balls	30 % balls	40 % balls
0	0	0	0	0	0
5	0.28	0.27	0.29	0.3	0.32
10	0.59	0.58	0.62	0.62	0.65
15	0.9	0.89	0.95	0.96	0.99
20	1.22	1.25	1.32	1.34	1.41
25	1.56	1.55	1.64	1.67	1.76
30	1.94	1.96	2.02	2.12	2.23
35	2.42	2.66	2.72	2.84	3.26
40	3.01	3.53	3.68	3.76	6.17
45	3.98	4.62	6.58	6.46	10.48 (for 42.92 kN)
50	5.83	6.64	10.91 (for 50.68 kN)	10.83 (for 47.3 kN)	-
-	10.64 (for 55.02 kN)	10.98 (for 54.1 kN)	-	-	-

4.3. Progressive cyclic test on slabs

The slabs were simply supported at both ends and subjected to monotonic loading at their centre until failure, as explained in the static test. The support span was 600 mm, with the load applied 500 mm from each support. The slab was placed on a testing platform, supported at both ends, and subjected to cyclic loading, which involved the repeated application and removal of the load over time, inducing alternating stress and strain. A preload was initially applied to ensure proper system engagement and eliminate any slack. In the progressive cyclic loading procedure, the load was gradually increased in 10 kN increments. It was first applied from a minimum value of zero up to 10 kN, and then reduced back to zero. This cycle was repeated with increasing load levels, 20 kN, 30 kN, and so on, until the slab ultimately failed.

The ultimate load capacity of the control slab (0 % replacement) was recorded as 47.28 kN, which served as the benchmark, as listed in Table 6. With 10 % replacement, a slight reduction to 46.25 kN was observed, amounting to a 2.18 % decrease. Increasing the replacement to 20 % led to a more pronounced decline, reducing the ultimate load to 42.85 kN (9.37 % reduction). At 30 % replacement, the load capacity decreased further to 39.85 kN, reflecting a 15.71 % decrease. The most substantial reduction was observed at 40 % replacement, where the ultimate load reached 35.52 kN, representing a 24.87 % decrease compared with the control slab.
An increase in the percentage of voids within the tension zone resulted in a gradual decrease in the ultimate load capacity of the slabs, as shown in Figure 8. When up to 20 % of the concrete was replaced, the reduction in the load-bearing capacity remained within 10 %, suggesting that the

Table 6. Ultimate loads of conventional and bubble deck slabs with balls in the cyclic tests

Slab number	Percentage of replacement of concrete in tension zone using balls	Ultimate load [kN] in cyclic test	Percentage decrease in ultimate load compared to conventional concrete [%]
1	0 %	47.28	0.00
2	10 % balls	46.25	2.18
3	20 % balls	42.85	9.37
4	30 % balls	39.85	15.71
5	40 % balls	35.52	24.87

structural performance was still within an acceptable range. However, when the replacement exceeded 30 %, a notable decrease in the strength was observed, indicating that a higher percentage of voids negatively affected the ability of the slab to withstand cyclic loading. Further research is required on the cyclic behaviour of bubble deck slabs, as most existing studies focus on static loading.

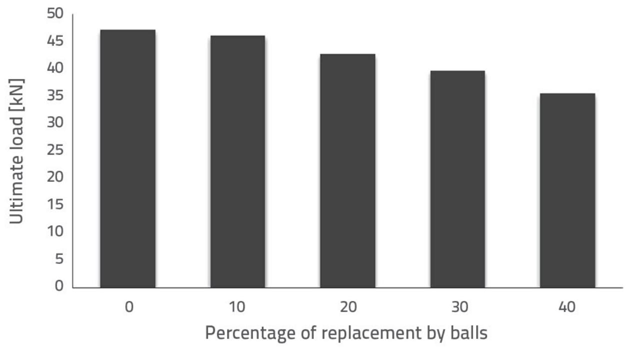

Figure 8. Ultimate load of bubble deck slab with balls in the cyclic tests

4.4. Load vs. deflection in progressive cyclic test

The slabs were subjected to cyclic loading to simulate real-world conditions. The resulting load–deflection behaviour was analysed and compared with that of conventional concrete slabs to evaluate the consequences of replacing part of the concrete volume below the neutral axis with balls on the overall bending performance of the bubble deck slabs.

The load–deflection hysteresis curves for conventional concrete and concrete with varying percentages of balls under cyclic load testing are shown in Figure 9. In the incremental cyclic test, the conventional concrete withstood more cycles than the bubble deck concrete slab, and as the percentage of voids increased, the number of cycles decreased. Conventional concrete and slabs with 10 % and 20 % void replacements underwent five cycles, whereas those with 30 % and 40 % void replacements underwent four cycles.

In conventional concrete, the maximum load reached was 47.28 kN, with a corresponding deflection of 11.02 mm. For the 10 %-voided slab, the peak load was 46.25 kN, accompanied by a deflection of 10.18 mm. For the 20 %-voided slab, the maximum recorded load was 42.85 kN, with a deflection of 8.76 mm. The 30 %-voided slab carried a maximum load of 39.85 kN, resulting in a deflection of 7.24 mm. The 40 %-voided slab achieved a maximum load of 35.52 kN, with a corresponding deflection of 7.12 mm.

The initial slope of the load–deflection curve shows the stiffness of the slab before cracking or undergoing significant plastic deformation, with a linear segment representing elastic behaviour. As the loading progressed, microcracks formed, leading to a gradual reduction in the stiffness and making the curve nonlinear near the yield point. Under cyclic loading, hysteresis loops developed owing to the energy dissipation from cracking and friction within the slab. With each cycle, the loop area increased, indicating greater energy dissipation from the accumulated damage. After several cycles, particularly at higher loads, the deflection did not fully return to zero, indicating plastic deformation. Eventually, the slab reached significant yielding, where the deflection increased sharply with a minimal load, marking the onset of failure with a sudden decline in load capacity.

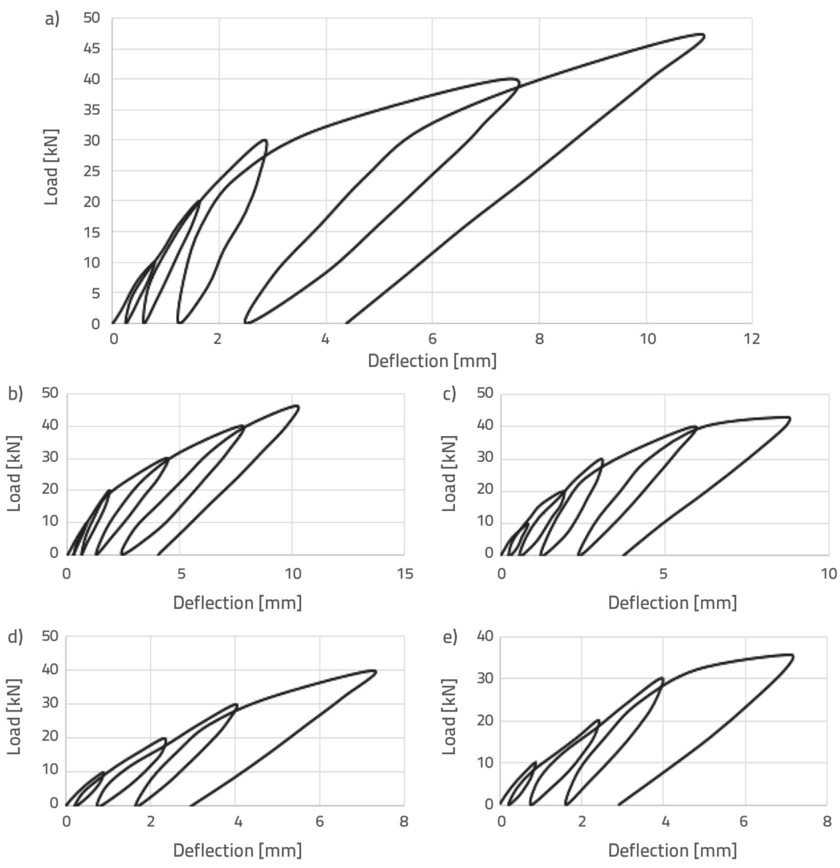

Figure 9. Load–deflection graph in the progressive cyclic test: a) classic concrete; b) 10% balls; c) 20% balls; d) 30% balls; e) 40% balls

Table 7. Stiffness degradation in the cyclic test

Conventional concrete				
Cycle no	Peak load [kN]	Displacement [mm]	Stiffness [kN/mm]	Stiffness degradation [%]
1	10	0.78	12.82	0
2	20	1.62	12.35	3.70
3	30	2.85	10.53	17.89
4	40	7.47	5.35	58.23
5	47.28	11.02	4.29	66.53

10 % replacement by balls				
Cycle no	Peak load [kN]	Displacement [mm]	Stiffness [kN/mm]	Stiffness degradation [%]
1	10	0.85	11.76	0
2	20	1.85	10.81	8.07
3	30	4.41	6.80	42.15
4	40	7.75	5.16	56.11
5	46.25	10.18	4.54	61.37

20 % replacement by balls				
Cycle no	Peak load [kN]	Displacement [mm]	Stiffness [kN/mm]	Stiffness degradation [%]
1	10	0.84	11.90	0
2	20	1.91	10.47	12.01
3	30	2.95	10.17	14.54
4	40	5.92	6.76	43.22
5	42.85	8.76	4.89	58.89

30 % replacement by balls				
Cycle no	Peak load [kN]	Displacement [mm]	Stiffness [kN/mm]	Stiffness degradation [%]
1	10	0.89	11.24	0
2	20	2.33	8.58	23.63
3	30	4.02	7.46	33.61
4	39.85	7.24	5.50	51.03

40 % replacement by balls				
Cycle no	Peak load [kN]	Displacement [mm]	Stiffness [kN/mm]	Stiffness degradation [%]
1	10	0.88	11.36	0
2	20	2.42	8.26	27.25
3	30	3.97	7.56	33.48
4	35.52	7.12	4.99	56.08

4.5. Stiffness degradation in cyclic test

The cyclic test resulted in a reduction in slab stiffness with each consecutive cycle. Table 7 presents the gradual reduction in the stiffness of the material or structural element as it undergoes repeated loading and unloading cycles. As the number of cycles increased, the percentage of stiffness degradation increased continuously. In conventional concrete, the stiffness was found to degrade continuously from 12.82 to 4.29 kN/mm after five loading cycles. With 10 % of voids, the stiffness progressively degraded over all cycles, dropping from 11.76 to 4.54 kN/mm after five loading cycles. In the case with 20 % of voids, the stiffness steadily decreased from 11.9 to 4.89 kN/mm upon completion of five cycles. With 30 % of voids, the stiffness reduced from 11.24 to 5.5 kN/mm at the end of four cycles. In the presence of 40 % of voids, the stiffness decreased from 11.36 to 4.99 kN/mm at the end of four cycles.
In the bubble deck slabs with plastic balls subjected to progressive cyclic loading, the stiffness progressively degraded with each cycle. Initially, the slab exhibited high stiffness, as indicated by the steep initial slope of the load–deflection curve. However, as the cyclic loading continued, the microcracking and accumulated damage within the slab gradually reduced its stiffness.
In regions prone to earthquakes and subjected to fatigue loading, bubble deck slabs tend to experience progressive stiffness reduction over time. This deterioration is influenced by the percentage of void-forming balls used in the slab. A higher concentration of these voids can weaken the bond between the cement paste and the surrounding materials, potentially compromising energy dissipation and resistance to crack propagation. Therefore, strategic design modifications are essential to enhance the long-term performance and durability of slabs under cyclic loading conditions.

4.6. Comparison of ultimate load in static and cyclic tests

As the replacement percentage increased, the load-bearing capacity of the slab decreased under both test conditions, as listed in Table 8. Under cyclic loading, the reduction in strength compared with that under static loading ranged from 14.1 % to 17.2 % owing to the voids created by the ball replacements, which weakened the concrete cross-section and stiffness.

Table 8. Comparison of ultimate loads in static and cyclic tests

Slab number	Percentage of replacement of concrete in tension zone using balls	Ultimate load [kN]		Percentage decrease in cyclic test compared to static test [%]
		Static test	Cyclic test	
1	0 %	55.02	47.28	14.1
2	10 % balls	54.1	46.25	14.5
3	20 % balls	50.68	42.85	15.4
4	30 % balls	47.3	39.85	15.8
5	40 % balls	42.92	35.52	17.2

Figure 10 shows a sharp drop in the ultimate load under cyclic loading, particularly at higher replacement levels. The bubble deck slabs failed sooner in the cyclic tests because of the accumulated damage from repeated loading. Unlike static loading, where failure occurs under a steadily increasing load, cyclic loading accelerates fatigue, stiffness loss, and microcrack growth over multiple cycles.

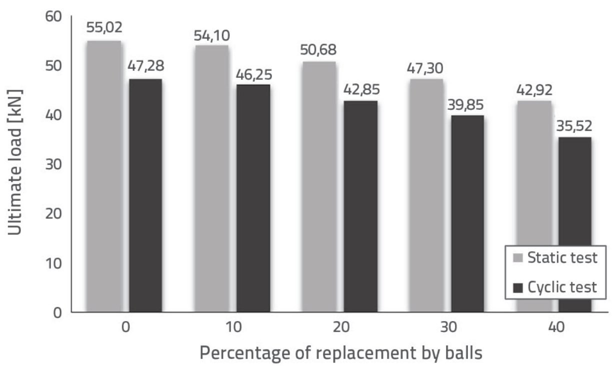

Figure 10. Comparison of ultimate loads in static and cyclic tests

5. Conclusion

Singly reinforced bubble deck slabs represent a contemporary construction method, in which voids are introduced into a concrete slab by incorporating plastic balls at varying percentages of 0 %, 10 %, 20 %, 30 %, and 40 %. The conclusions of this study are as follows:

- The cost of bubble deck slabs was more efficient compared with that of ordinary concrete slabs.
- This approach supports the use of recycled materials such as plastics, contributing to more sustainable construction practices.
- The performance of the bubble deck slabs was evaluated under both static and cyclic loading conditions to assess the impact of different void percentages on the structural behaviour.
- Because the voids reduced the stiffness and load capacity, the bubble deck slabs deformed more under the load than the solid slabs in the static test.
- In the cyclic loading tests, the fact that slabs with up to 20 % plastic ball replacement successfully endured five cycles indicated that these slabs maintained their structural integrity for a considerable number of load cycles. However, the observed gradual increase in stiffness degradation with an increase in the number of cycles is typical of materials undergoing fatigue, where repeated loading leads to progressive weakening of the structure.
- In the incremental cyclic tests, up to 20 % replacement of concrete with plastic balls resulted in a less significant reduction in the bending strength of the bubble deck slabs.
- In the bubble deck concrete slabs with plastic balls, the difference between the results obtained from the static and cyclic tests was quantified as a percentage ranging from 14 % to 17.2 %. This percentage indicates the extent to which the slab performance differs under static loading conditions compared to cyclic loading. The observed discrepancies highlighted the impact of load type on the structural behaviour of the slabs, emphasising that cyclic loading could lead to increased deformation and potential stiffness degradation over time, which is critical for assessing long-term durability and serviceability.
- Increasing the replacement of concrete with plastic balls by up to 20 % resulted in a reduction in the load-carrying capacity of less than 10 % in both the static and cyclic tests, and the change was deemed negligible. This decrease has little effect on the strength or stability of the concrete slab.
- However, the structural performance of the slab significantly diminished when the void percentage exceeded 20 %, highlighting the detrimental impact of excessive voids on the load-bearing capacity.

In summary, bubble deck concrete with up to 20 % plastic ball replacement reduces weight with minimal impact on strength and stiffness, making it viable for practical use.

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