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Experimental and Theoretical Design of Reinforced Bubble Deck Concrete (RBDC) Slab: A Review

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ABSTRACT

Slabs are vital for supporting loads and forming the foundation for structures' floors and roofs, classified as one-way or two-way based on deflection characteristics. A recent innovation in construction, the Reinforced Bubble Deck Concrete (RBDC) slab, integrates spherical or elliptical hollow bubbles within the slab for reinforcement, reducing concrete usage without compromising structural integrity. This unconventional approach diverges from traditional methods. The manuscript thoroughly reviews existing literature on the design and testing of Reinforced Bubble Deck Concrete slabs, aiming to explore their diverse characteristics as observed in international research studies. Findings demonstrate that these slabs offer a sustainable and cost-effective alternative to traditional floor slabs. Their capacity to reduce weight while maintaining strength suggests they could revolutionize construction practices, potentially replacing conventional floor slabs in various projects.

1. Introduction

The slab is essential in construction projects as it plays a vital role in creating functional spaces. Not only that, but the slab also stands out as one of the primary components that require a substantial amount of concrete. According to Harshit *et al.,* [1], the Reinforced Bubble Deck Concrete (RBDC) slab is an innovative construction method that employs recycled plastic balls to reduce the weight of concrete slabs. This can lead to significant savings in material and time and a reduction in environmental impact. Consequently, this substantially reduces the structural self-weight, leading to

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a lighter slab that is typically 30 to 50% lighter. As a result, the self-weight, deflection, moments, and force reactions are likewise reduced [2,3].

RBDC slabs are made by placing the spherical or elliptical balls in the middle of the slab before pouring concrete. The balls create voids, decreasing the slab's weight without affecting its strength or stiffness. RBDC slabs can be installed up to 20% faster than traditional concrete slabs, requiring less material and energy. This makes them a more sustainable option for construction. RBDC slabs have been used in various projects worldwide, including high-rise buildings, bridges, and stadiums. The RBDC slab is composed of three primary components, which are concrete and steel reinforcement, with a particular emphasis on the crucial inclusion of plastic balls as the principal material. The plastic balls are made from recycled high-density polyethylene (HDPE). HDPE is a robust, long-lasting material that exhibits non-reactive properties when in contact with concrete and steel.

According to Ali *et al.,* [4], the concrete utilized to fill the slab must possess a strength greater than M30. Opting for a self-compacting concrete variation is a valuable advantage as it guarantees proper compaction in all areas of the slab, including those that are typically difficult to access. Moreover, it is recommended to employ aggregates smaller than 15 mm in this concrete mix. The steel reinforcement is used to provide strength and stiffness to the slab. The type and amount of reinforcement used will depend on the specific design of the slab. The plastic balls can be recycled and reused, and the concrete and steel can be recycled at the end of the slab's life. This paper seeks to conduct a comprehensive review of previous research endeavors focusing on the design and testing of RBDC slab applications, aimed at enhancing the collective understanding of this innovative technology.

This paper presents a literature review centered on design and testing studies carried out by a select group of researchers. The databases employed for sourcing materials were Science Direct and Scopus. Furthermore, supplementary publications were sought on Google Scholar by referencing the bibliographies of the incorporated studies. All articles obtained by the keyword “Bubble Deck Slab” and “Voided Slab” were screened thoroughly to avoid redundancy. There is a total of 12 studies that were chosen as the main paper to be reviewed. Table 1 shows the summary of the previous studies extracted in this paper.

Table 1
Summary of Previous Study

Author, Year	Methodology	Shape of Void Former	Size of Void Former (mm)	Slab Thickness (mm)
Arati *et al.,* [2]	Experimental: Full-Scale Structural Testing	Elliptical	240 x 180	230
Md Mustafeezul *et al.,* [3]	Finite Element Analysis	Spherical	270 x 180	230
Zalena *et al.,* [12]	Systematic Review Study	-	-	-
Yahya *et al.,* [13]	Experimental: Static Load Testing with a maximum load of 2000 kN	Spherical	40 Ø	80
Jasna *et al.,* [14]	Finite Element Analysis: ANSYS software	Spherical & Elliptical	S: 150 Ø E: 240 x 180	230
Maha *et al.,* [15]	Experimental: Static Load Testing with a maximum load of 1000 kN	Oval	80 x 80 x 40	100
Nor *et al.,* [16]	Experimental: Static Load & Punching Shear Loading Testing	Spherical	180 Ø	230
Sameer *et al.,* [19]	Finite Element Analysis: ANSYS Workbench	Spherical	80	150
Ritesh *et al.,* [20]	Experimental: Three Point Load Deflection Test & Ultrasonic Pulse Velocity Test	Spherical	60 Ø	125
Hussain *et al.,* [21]	Experimental: Four-Point Cyclic Load Test	Spherical	70	120
N A Muhammad *et al.,* [22]	Experimental: Area loading Test	Spherical	180	235
Anusha M. *et al.,* [23]	Finite Element Analysis: Abaqus Software	Spherical	90	150

2. Design and Structural System of Reinforced Bubble Deck Concrete (RBDC) Slab

In the 1990s, the RBDC slab system was innovated by a German professor, Jorgen Bruening. Distinguished for its superior sustainability compared to conventional concrete construction methods, this system curtails both material usage and associated expenses, along with diminishing energy consumption and CO2 emissions [5]. The technology also plays a role in reducing construction waste and mitigating severe construction-related pollution, as noted in [6]. The versatility of the RBDC slab system is demonstrated by its application in diverse building types across Malaysia, encompassing residential, commercial, and industrial structures. This adaptability arises from the system's capacity to adjust various design parameters to align with the unique requirements of different projects.

According to Vishal *et al.,* [7], the RBDC slabs consist of two concrete layers, a bottom, and an upper section, linked by vertical ribs. The slab's reinforcement comprises two mesh layers, one on the lower and one on the upper sides. These mesh layers are interconnected after the hollow plastic balls (made of high-density polyethylene, or HDPE) have been positioned. The HDPE spheres are integrated into the concrete structure, with their arrangement tailored to suit the project's specifications and positioned between the layers of reinforcement. The HDPE balls exhibit no chemical reactivity with either the concrete or the reinforcement, boasting sufficient rigidity and strength to shoulder loads during the concrete pouring and subsequent construction stages. The primary effect of these plastic spheres is to alleviate the deck's dead load while preserving its deflection characteristics and bending strength, even when compared to a solid slab of equivalent thickness. These balls, which are hollow in nature, contribute to the slab's reduced weight without compromising its structural integrity. The slabs are typically designed as biaxial flat slabs, with hollow plastic balls available in two configurations: elliptical and spherical bubble shapes.

The RBDC slab is also called a voided biaxial slab by utilizing these plastic bubbles as voids. The RBDC slab efficiently reduces the concrete volume by around 30% within the slab and up to 20% in the supporting structural elements. This reduction is attained by eliminating superfluous concrete from the central region, which does not provide structural benefits [4]. As a result, it decreased the dead load, and the decreased dead load of the building contributed to a more cost-effective long-term response. As the structure's resistance is directly influenced by the concrete depth, the shear and punching shear resistance of the Bubble Deck floor are notably lower compared to a solid deck. However, this reduction in weight yields numerous advantages that engineers should carefully consider when selecting the building's structural system. By strategically substituting non-essential concrete sections with hollow plastic void formers, plastic voided slabs attain comparable load-bearing capabilities as solid slabs while eliminating surplus concrete. Figure 1 shows the cross-sectional diagram of a typical RBDC slab showing significant elements.

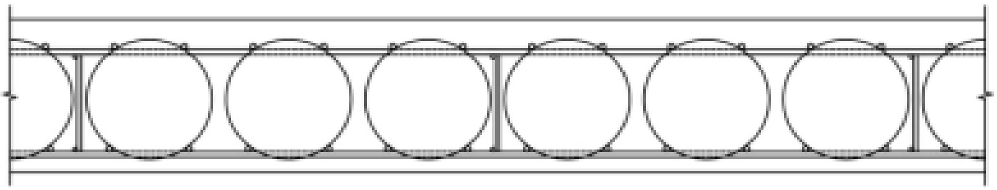


Fig. 1. Cross-sectional diagram of a typical RBDC slab showing major elements [8]

According to Tina Lai *et al.,* [9], the RBDC slab system employs hollow plastic spheres to decrease the weight of the reinforced concrete slab, presenting a lightweight structural solution. The balls are placed at the neutral axis of the slab, which is the point where the tensile and compressive forces are equal. This effectively eliminates the concrete at the neutral axis, which can reduce the slab's weight by up to 30% compared to a conventional slab system. Hence, the RBDC slab offers numerous benefits compared to traditional concrete slabs. These advantages include lower overall costs, reduced material consumption, improved structural efficiency, decreased construction duration, and eco-friendly nature [10]. As a result, engineers and researchers worldwide have taken a keen interest in this innovative technology. Figure 2 shows the illustration of the RBDC slab.

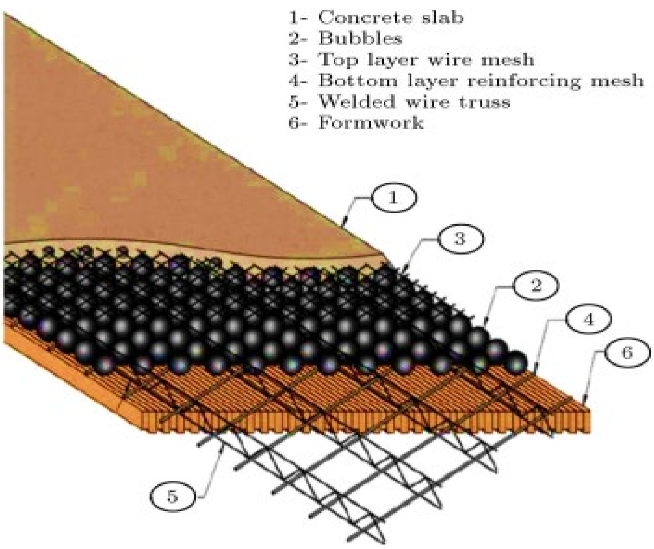


Fig. 2. The illustration of RBDC slab [8]

Regarding the design aspect, several crucial factors determining the load capacity of Bubble Deck slabs have been identified. In a study conducted by Natalia *et al.,* [11], sensitivity analysis and numerical homogenization techniques were employed to demonstrate the substantial impact of the slab's geometry, material composition, and the arrangement of air voids on its stiffness and load-bearing capacity. Furthermore, the shape of the void formers emerged as a critical determinant of load capacity.

Several studies have investigated different types of void formers and their impact on the properties of these slabs. It is crucial to analyze and determine the ideal shape for the void formers to achieve optimal performance in Bubble Deck slab systems. Previous studies have extensively examined different shapes of void formers used in RBDC slabs. Table 2 shows the summary of the previous study reviewed in this paper.

Table 2
Summary of Related Research Reviewed

Author	Methodology	Findings
Arati *et al.,* [2]	Experimental: Full-Scale Structural Testing	The Bubble Deck arrangement provides significantly enhanced flexural strength, stiffness, and shear capacity, amounting to a minimum of 70% improvement, even when employing the equivalent quantity of concrete and reinforcement as in a solid slab. This results in a concrete saving of 30-50% compared to a solid slab while maintaining comparable performance. Using hollow elliptical balls, the Bubble Deck system can attain an improved load-bearing capacity compared to hollow spherical balls.
Zalena *et al.,* [12]	Systematic Review Study	Opting for HDPE hollow elliptical balls in the Reinforced Bubble Deck Concrete (RBDC) slab offers superior load-bearing capacity and reduced overall weight, making it a more advantageous choice than spherical balls.
Yahya *et al.,* [13]	Experimental: Static Load Testing with a maximum load of 2000 kN	When assessing the impact of the concrete removal ratio on the structural performance of Reinforced Bubble Deck Concrete (RBDC) slabs, it was observed that slabs featuring spherical balls outperformed those with elliptical balls when the ratio of bubble diameter to slab thickness remained consistent.
Jasna *et al.,* [14]	Finite Element Analysis: ANSYS software	The load-bearing capacity of a Reinforced Bubble Deck Concrete (RBDC) slab equipped with elliptical balls surpasses that of a Bubble Deck slab incorporating spherical balls.
Maha *et al.,* [15]	Experimental: Static Load Testing with a maximum load of 1000 kN	Comparing Reinforced Bubble Deck Concrete (RBDC) slabs with spherical and elliptical balls under identical bubble diameter to slab thickness ratios, the former exhibits a superior load-bearing capacity by approximately 3.7% and 9.7%, respectively.
Nor *et al.,* [16]	Experimental: Static Load & Punching Shear Loading Testing	This study investigated how the application of area loading influences the bending capabilities of Reinforced Bubble Deck Concrete (RBDC) slabs, considering them as single-supported slabs. The findings show that the RBDC slabs, which contained HDPE hollow spherical plastic bubble balls, exhibited improved flexural performance compared to the conventional slabs.

2.1 Shape of Void Former

The RBDC slabs are a structural slab variant that incorporates void formers, such as spherical or elliptical balls, intending to reduce the slab's self-weight without compromising its load-bearing capacity. The choice between spherical and elliptical balls in Bubble Deck slabs has been researched and discussed. As per findings by Natalia *et al.,* [11], literature reviews have indicated that Bubble

Deck slabs utilizing elliptical balls demonstrate enhanced load-carrying capacity and reduced weight compared to their spherical ball counterparts. However, this assertion is contradicted by an independent investigation conducted by Yahya *et al.,* [13], which examined the impact of the concrete elimination ratio on the structural behavior of reinforced bubble deck concrete slabs. Their research revealed that, under equivalent ratios of bubble diameter to slab thickness, RBDC slabs with spherical balls exhibit superior load-bearing capacity compared to those employing elliptical balls. The experimental study involves eight specimens of RBDC slab with dimensions of 45 mm x 45 mm x 80 mm. The specimens are divided into two groups. The initial collection of four samples is employed to examine the impact of eliminating standard-strength self-consolidating concrete (SCC) from the concrete mixture. Meanwhile, the second set is utilized to study the consequences of removing high-strength SCC from the concrete mixture.

Based on the experimental findings [13], increasing the number of balls within standard-strength SCC leads to a decrease in the initial fracture load, ranging from 8.3% to 15.5%, and the ultimate load, ranging from 3.98% to 12.15%. The results from the experiments also revealed that altering the number of balls in high-strength SCC results in a decline of the initial crack load by 2.5% to 8.92% and a reduction in the ultimate load by 5.95% to 16.19%. Additionally, when the number of balls is increased, there is a noted decrease in the stiffness of the slab. The findings [13] also revealed that bubble deck slabs with spherical balls were more efficient at carrying loads than those with elliptical balls, even with the same amount of concrete reduction.

Conversely, in an experimental investigation conducted by Arati *et al.,* [2] on an RBDC slab system incorporating elliptical balls made from high-density polypropylene (HDPE), it was established that the performance of Bubble Deck slabs is significantly influenced by the ratio of bubble diameter to slab thickness. The study encompassed a range of bubble diameters from 180 mm to 450 mm, with slab depths varying between 230 mm and 600 mm. Nominal gap diameters were set at 180 mm, 225 mm, 270 mm, and 315 mm. A comprehensive experimental study was conducted within a full-scale structural testing laboratory to study the attributes of the Bubble Deck system using traditional spherical balls. There are five samples of RBDC slab, designated as A.BD.2, A.BD.3, A.BD.4, B.BD.2, and B.BD.3. All these samples share identical dimensions of 1900 mm x 800 mm x 230 mm. Labels A and B represent the concrete strengths of B25 and B35, respectively. Two steel beams supported the samples. The force is applied at the center of the slabs using a hydraulic jack capable of handling a maximum load of 1000 kN. The force will be incrementally raised until the appearance of cracks is observed. Table 3 shows the experimental result obtained [2].

Table 3
Experimental Results [2]

Slab	Ultimate Loading, P_u (kN)	Deflection, Δ_u (mm)	Type of Failure
A.BD.2	175	16.15	Shear
A.BD.3	185	21.06	Bending
A.BD.4	195	23.04	Bending
B.BD.2	180	15.18	Shear
B.BD.3	200	20.22	Bending

From this study [2], the conclusions obtained showed that the Bubble Deck arrangement provides significantly enhanced flexural strength, stiffness, and shear capacity, amounting to a minimum of 70% improvement, even when employing the equivalent quantity of concrete and reinforcement as in a solid slab. The Bubble Deck system offers a notable benefit in terms of cost reduction by the potential to achieve extended spans with fewer supporting elements. Not only that, but through the utilization of hollow elliptical balls, the Bubble Deck system can attain an improved load-bearing capacity compared to hollow spherical balls.

Additionally, while the spherical shape is commonly used for void formers in bubble deck slabs, recent studies by Jasna *et al.,* [14] have indicated that elliptical balls offer superior load-carrying capacity and reduced weight compared to spherical balls. However, it is essential to note that this claim contradicts the findings of a study by Maha *et al.,* [15]. As reported by Maha *et al.,* [15], bubble deck slabs with spherical balls exhibit superior load-bearing capacity compared to those employing elliptical balls, with an approximate advantage of 3.7% and 9.7%, respectively, when maintaining an equal ratio of bubble diameter to slab thickness. Figure 3 illustrates the cross-sectional of spherical and elliptical hollow plastic bubbles.

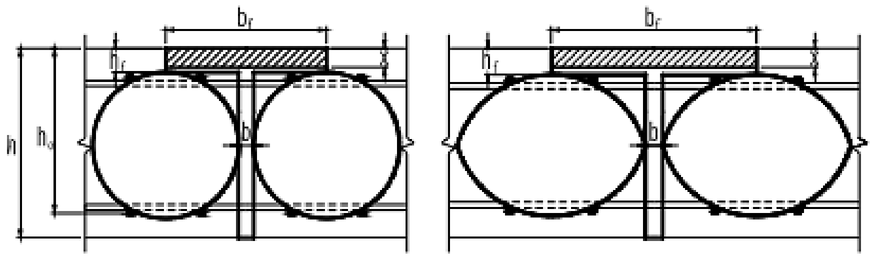


Fig. 3. The illustration of the cross-sectional of spherical and elliptical hollow balls [10]

In the context of flexural performance, Nor *et al.,* [16] investigated the influence of distributed area loading on RBDC slabs, contrasting their behavior with traditional reinforced concrete slabs. This study investigated how the application of area loading influences the bending capabilities of RBDC slabs, considering them as single-supported slabs. The square deck slabs utilized had dimensions of 1200 mm x 1200 mm for both width and length, with a thickness of 230 mm. Within the RBDC slab specimens, 36 hollow spherical plastic bubble balls, each with a diameter of 180 mm and composed of HDPE, were strategically positioned. This strategic placement significantly reduced the overall self-weight of the RBDC slabs. The primary aim of this study is to compare the experimental findings regarding the bending performance of the RBDC slab with those of a conventionally reinforced concrete slab with simple support, both subjected to static area loads [16]. The experimental results encompass various aspects, including flexural strength, bending stiffness, load-deflection behavior, crack propagation, and crack pattern of both slab types under the applied loads [16]. The findings show that the RBDC slabs, which contained HDPE hollow spherical plastic bubble balls, exhibited improved flexural performance compared to the conventional slabs [16].

Indeed, the shape of the void formers in RBDC slabs can also affect the structural behavior. The choice between spherical and elliptical balls in RBDC slabs depends on various factors such as load-carrying capacity, weight reduction, and flexural performance. While some studies suggest that elliptical balls offer advantages in load-carrying capacity and weight reduction, others argue that spherical balls provide better load-bearing capacity. Further research is needed to understand the comparative performance of bubble deck slabs with different void former shapes fully utilizing a different testing method.

2.2 Structural Properties of Reinforced Bubble Deck Concrete (RBDC) Slab

RBDC slabs represent an innovative structural system that employs void formers, like spherical plastic bubble balls, to effectively diminish the slab's self-weight while preserving its load-bearing capacity. These slabs have gained attention in structural engineering due to their potential for weight reduction, improved construction efficiency, and sustainability. Designing and constructing efficient and sustainable structural systems have been paramount in civil engineering. Among the innovative solutions, the bubble deck slab has garnered significant attention due to its unique structural properties and potential to revolutionize traditional concrete slab design. Various factors, including the geometry and material properties of the void formers, the concrete mix design, and the overall slab configuration, influence the structural properties of RBDC slabs. The behavior of these slabs under different loading conditions, such as area loading and punching shear, is crucial for evaluating their structural performance and ensuring their safety and durability.

2.2.1 Shear resistance and punching shear

Incorporating hollow HDPE bubbles into an RBDC slab leads to a noticeable reduction in its shear resistance compared to a traditional solid slab. As per both theoretical studies and practical test results, it has been established that the shear strength of a structure is contingent on the effective mass of the concrete. Compared to a solid deck, the estimated shear capacity ranges between 72-91%. A safety factor 0.6 is applied to this shear capacity for safety calculations, considering an equivalent solid deck's height. This approach ensures a substantial safety margin. Areas exposed to high shear loads, such as those surrounding columns, necessitate specialized attention during the design process, mirroring the considerations for a solid slab [17]. Regarding load-carrying capacity, reinforced bubble deck concrete slabs have demonstrated higher capacities than conventional concrete deck slabs [18]. The inclusion of shear connectors allows the composite deck slabs to carry significantly more load.

2.2.2 Strength in compression and bending capacities

The structural properties of RBDC slabs, particularly their strength in compression and bending capacities, have been extensively studied. These studies have provided valuable insights into the behavior and performance of these slabs. The design of the RBDC slab is strategically aimed at eliminating a substantial amount of concrete from the central core, an area where the slab experiences minimal flexural stress. Remarkably, despite containing only 66% of the concrete volume due to incorporating HDPE balls, the RBDC slab maintains an impressive 87% bending stiffness compared to an equivalent solid slab of similar strength. As a result, the deflection observed in the RBDC was marginally greater than that in the solid slab. Nevertheless, the significant reduction in the self-weight of the solid slab is counterbalanced by the slightly reduced stiffness, leading to the RBDC slab exhibiting a superior load-bearing capacity [19].

2.2.3 Durability

Durability is a crucial aspect of RBDC slabs, and several studies have investigated different factors that contribute to their long-term performance. One crucial factor is the choice of void formers. The voids' geometry, arrangement, and shape significantly impact the reduction of self-weight in bubble deck slabs [11]. Optimal design parameters related to the voids are crucial for achieving desired structural performance [11]. Studies have shown that different shapes of void formers, such as spherical, elliptical, or donut-shaped, can affect the load-bearing capacity and behavior of the slabs [12]. Furthermore, bubble deck slabs' structural behavior and load-carrying capacity have been studied to ensure their long-term durability. The results have shown increased ultimate load capacity and decreased deflection compared to solid slabs [13]. The stiffness and load-bearing capacity of bubble deck slabs are influenced by factors such as the height of the slab, the geometry of the voids, and the type of reinforcement used [11].

3. Testing and Analysis of Reinforced Bubble Deck Concrete (RBDC) Slab

The RBDC slab is a construction method that almost wholly removes concrete from the non-structural areas at the center of a slab—this significant reduction in concrete results in a substantial decrease in dead weight. Researchers on RBDC slabs conducted numerous studies under various conditions. In recent years, there has been growing interest in employing RBDC slabs as a potential substitute for traditional floor slabs, underscoring their increasing prominence in the construction industry. This literature review aims to provide an overview of the testing and analysis aspects of RBDC slabs. Table 4 shows the summary of previous research reviewed in this chapter.

Table 4
Summary of Related Research Reviewed

Author	Methodology	Findings
J. Jamal *et al.,* [14]	Finite Element Analysis: ANSYS Software	The load-bearing capacity of a Bubble Deck slab equipped with elliptical balls surpasses that of a bubble deck slab incorporating spherical balls. Regarding performance, the utilization of spherical and elliptical balls in M30 grade concrete for the bubble deck slab outperforms the same balls in M25 grade concrete. Bubble deck slabs exhibit weight savings of approximately 33.15% for a single spherical ball and 34.90% for a single elliptical ball.
Sameer A. *et al.,* [19]	Finite Element Analysis: ANSYS Workbench	The study showed that the Bubble Deck slab outperformed the conventional concrete slab. The voided deck experienced significantly lower maximum stresses and internal forces, approximately 40% less than those observed in the solid slab. This study illustrates that this Bubble Deck design will yield improved outcomes in terms of long-term performance and durability, especially in the context of predominant gravitational and uniform loading conditions.
Ritesh *et al.,* [20]	Experimental: Three Point Load Deflection Test & Ultrasonic Pulse Velocity Test	Compared to the conventional slab, the Bubble Deck slab exhibited the ability to support 90% of the load capacity of the latter. Also, the Bubble Deck slab exhibited a notable 25% reduction in weight compared to the traditional slab.
Hussain *et al.,* [21]	Experimental: Four-Point Cyclic Load Test	The insertion of balls completely modified the load-deflection responses. In the case of solid slabs, the behaviors were characterized by three distinct phases: elastic, inelastic, and plastic plateau. Despite this difference, the behaviors of solid and bubble slabs were quite similar during the initial two phases. The results revealed that the presence of the balls led to an abrupt shear mode failure in the slabs, irrespective of the a/d ratio.
N A Muhamad *et al.,* [22]	Experimental: One-Point Load Test	The findings obtained that implementing the continuous Bubble Deck design leads to a reduction in the concrete volume, consequently resulting in a decrease in the overall weight of the slab. In parallel, this design modification also enhances the load-bearing capability when contrasted with conventional slabs. The conventional slab displays reduced deflection in contrast to the Bubble Deck slab, and the elasticity of the latter is contingent upon the number of bubbles integrated into the slab structure. In terms of weight, the conventional slab is heavier than the Bubble Deck slab.
Anusha M. *et al.,* [23]	Finite Element Analysis: Abaqus Software	The load-bearing capacity of the Bubble Deck slab demonstrates a better performance than that of the traditional slab. The utilization of sphere balls in the Bubble Deck slab results in a weight reduction of approximately 10.55%.

3.1 Experimental Testing of Reinforced Bubble Deck Concrete Slab

A recent study by Ritesh *et al.,* [20] worked on the design and experimental analysis of RBDC slabs to investigate the ultimate load-carrying capacity, strength, and porosity of conventional and Bubble Deck slabs. The study also sought to obtain the economic benefits of both slabs. In the study, both slabs were cast in the same size, 500 mm x 500 mm x 125 mm, undergoing destructive and non-destructive tests, which were a load-deflection test and an ultrasonic pulse velocity test, respectively. The specimens were tested under a three-point load test during the load-deflection test [20]. The hydraulic jack had a maximum load capacity of 2000 kN, incrementally raised in 5 kN intervals. The hydraulic jack was calibrated to exert a force equivalent to the slab's self-weight.

The ultrasonic pulse velocity (UPV) test aims to identify the quality of the concrete structure. A total of eight readings, which consist of indirect and direct readings, were taken. A velocity lower than 3.0 Km/sec signifies inferior quality, while a velocity higher than 4.40 Km/sec signifies good quality. This study's findings and conclusions stated that the investigation involved employing a loading frame to apply a uniformly distributed load (UDL) across the slab, aiming to determine its maximum load-bearing capacity and deflection. Compared to the conventional slab, the Bubble Deck slab exhibited the ability to support 90% of the load capacity of the latter. Figure 4 shows the Load-Deflection curve obtained from the study.

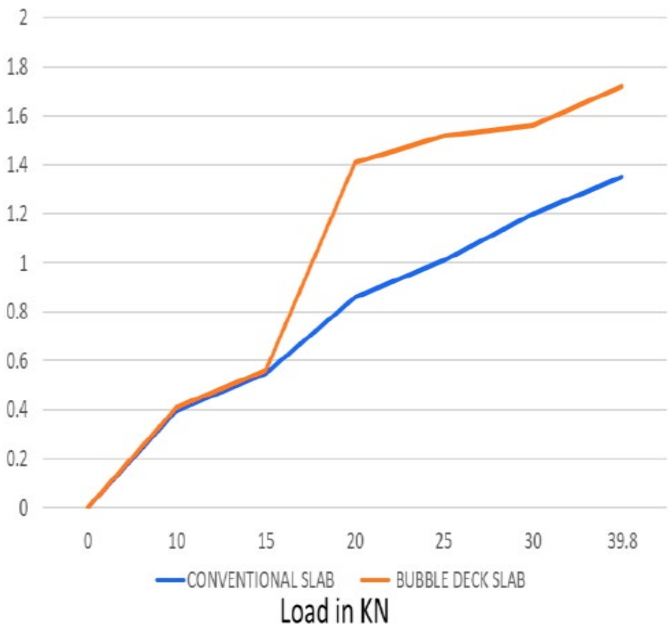


Fig. 4. Load-Deflection Curve [20]

Also, the RBDC slab demonstrated a weight reduction of 25% compared to the conventional slab. UPV results for both types of slabs fell within the categories of good and excellent. The deflection measurements were observed at 1.72 mm for the Bubble Deck slab and 1.35 mm for the conventional slab, both at a load of 39.8 kN. These deflection values remained within the permissible limit of 20 mm. Lastly, the reduction in the self-weight of the slab contributed to a cost reduction of 17.83% [20]. Table 5 shows the properties and nominal strength of slabs tested in the studies [20].

Table 5

Properties and Nominal Strengths of Slabs [20]

Group	Slab	Type	a/d ratio	Nominal Strength	
				Flexural, Pf, kN	Shear, Ps, kN
1	S2	Solid	2	116	36
	S3.5		3.5	66	36
	S5		5	46	36
2	B2	Bubble	2	116	29.5
	B3.5		3.5	66	29.5
	B5		5	46	29.5

In a study conducted by Hussain *et al.* [21], a comparative investigation was undertaken to assess the behavior of Bubble Deck slabs compared to solid slabs under the influence of limited repeated four-point loads. The primary objective was to experimentally analyze how RBDC slabs performed under varying a/d ratios, employing six slab strips of identical dimensions. Among these, three were solid slabs, while the remaining three were RBDC slabs featuring 70 mm-diameter balls. All slabs underwent four-point cyclic loading with a/d ratios of 2, 3.5, and 5. The experimental results of the RBDC slabs were compared with those of the solid slabs, and within each type of slab, the outcomes were further compared to highlight the influence of the a/d ratio.

In this study, the findings and conclusion were as follows [21]:

i. The presence of balls changed the way that slabs fail. Previously, slabs would fail in a ductile mode through combined flexural-shear or pure flexural failure. However, the presence of balls caused slabs to fail in a brittle shear manner, regardless of the a/d ratio.
ii. The load-bearing capacity of slabs increased as the loads were placed closer to the supports. This is because the concrete struts, formed when the load is applied, are more robust when closer to the supports. The peak strength of S2 was 1.9 and 2.6 times that of S3.5 and S5, respectively. This means that S2 could support 1.9 to 2.6 times more load than S3.5 and S5, respectively. In the bubble slabs, the B2 failed at loads about 2.3 and 2.5 times that of B3.5 and B5, respectively. The bubble slabs' strengths were 22-35% below those of solid samples.
iii. The insertion of balls completely modified the load-deflection responses. In solid slabs, the behaviors were characterized by three distinct phases: elastic, inelastic, and plastic plateau. However, the plastic plateau phase was absent in the responses of the bubble slabs. Despite this difference, the behaviors of solid and bubble slabs were quite similar during the initial two phases.
iv. The service stiffness of slabs decreased as the a/d ratio increased. The service stiffness of a solid slab decreased by 37.8% when the a/d ratio was increased from 2 to 5. The service stiffness of voided slabs decreased by 40% under the same conditions. However, the presence of balls in the voided slabs did not significantly affect the service stiffness, with the decline not surpassing 15%.
v. The ductility decreased when the a/d ratio was increased from 2 to 3.5, but then increased when the a/d ratio was increased to 5. This unclear trend may be because of the slabs were loaded in different ways at different a/d ratios. The ductility of bubble slabs did not significantly change with the a/d ratio. This is because bubble slabs failed in a brittle shear mode, meaning they failed suddenly and without warning. The ductility index of bubble slabs was 39-64% smaller than that of solid slabs.
vi. By incorporating 32 balls with a diameter of 70 mm, the RBDC slabs achieved material savings of approximately 18% compared to the solid slab. This reduction in constituent

materials contributed to the enhanced sustainability of the voided slabs compared to conventional ones. As a result of these material savings, the voided slabs exhibited reductions of about 14% in CO2 emissions and 10% in consumed embodied energy.

3.2 Finite Element Analysis of Reinforced Bubble Deck Concrete (RBDC) Slab

The finite element method is commonly utilized to examine structural performance, including parameters such as overall displacement, directional deformation, and equivalent stress. Jamal *et al.,* [14] conducted a finite element analysis (FEA) study on the structural behavior of bubble deck slabs using spherical and elliptical balls using the finite element analysis software ANSYS. The bubble deck slab with spherical and elliptical balls was going under a uniformly distributed load while maintaining appropriate boundary conditions. The concrete grade used was M25 and M30 concrete grade. The study assessed Total deformation, Directional deformation, and Equivalent stress (Von Mises stress). Subsequently, a comparison was drawn between the outcomes of bubble deck slabs with spherical balls and those with elliptical balls.

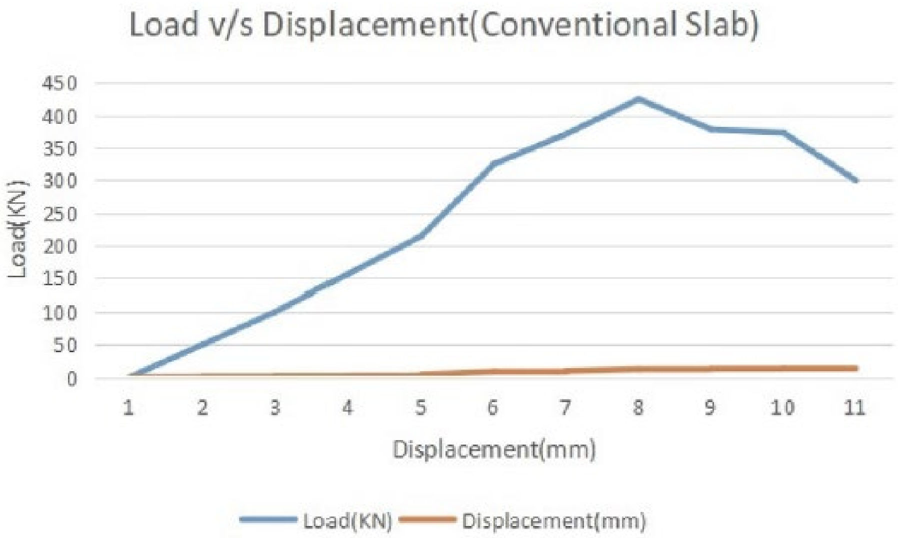
In this study [13], five three-dimensional bubble deck slabs with sphere balls of 150 mm diameter using the size of 1250 mm x 1250 mm x 230 mm and five three-dimensional bubble deck slabs with elliptical shape balls of 180 mm x 240 mm using deck size of 1730 mm x 1350 mm x 230 mm were modeled in ANSYS software. Both slab types were presumed to be constructed from High-Density Polyethylene (HDPE). The analysis obtained was an RBDC slab incorporating spherical balls and utilizing M30 grade concrete sustained stress of approximately 31.831 MPa under a uniformly distributed load of around 350 kN, resulting in a deflection of 2.9428 mm.

Also, the RBDC slab incorporating elliptical balls and employing M30 concrete managed a stress of roughly 35.14 MPa with the same load, leading to a deflection of 3.5375 mm. It can be observed that the RBDC slab featuring elliptical balls exhibited superior load-bearing capacity when compared to the bubble deck slab utilizing spherical balls. Not only that, the performance of RBDC slabs containing spherical and elliptical balls made from M30 grade concrete surpasses that of bubble deck slabs containing spherical and elliptical balls made from M25 grade concrete.

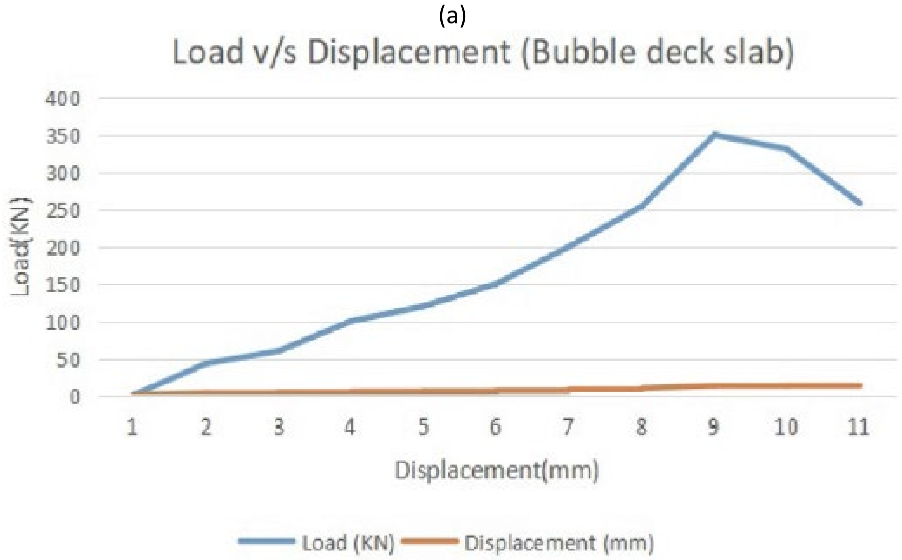
On the other hand, Sameer *et al.,* [19], conducted an analytical study of conventional slab and bubble deck slab under various support and loading conditions. The study [19] was conducted by using ANSYS Workbench 14.0 software. This research aimed to analyze the behavior of both slab types. The slabs are presumed to have primarily supported end conditions when undergoing static uniformly distributed load (UDL). The outcome of the analysis revealed the overall deflection and Von-Mises's stress experienced by both slabs when subjected to uniformly distributed loads, considering various end conditions [19].

The study [18] showed that the RBDC slab outperformed the conventional concrete slab. The RBDC slab experienced significantly lower maximum stresses and internal forces, approximately 40% less than those observed in the solid slab. This reduction can be attributed to the reduced dead load from incorporating HDPE spheres instead of concrete. The RBDC slab exhibited a slightly greater deflection, accompanied by a stiffness reduction attributed to the voids' presence. Nevertheless, this impact will be mitigated by the overall reduction in stress within the slab. This study [18] illustrates that this Bubble Deck design will yield improved outcomes in terms of long-term performance and durability, especially in the context of predominant gravitational and uniform loading conditions.

A recent study by Anusha *et al.,* [23] utilized finite element analysis to model the structural behavior of the RBDC slab by utilizing the Abaqus software. The dimension of the conventional slab was 900 mm x 600 mm with 150 mm thickness, while the dimension of the RBDC slab was 2000 mm x 2000 mm with the same 150 mm thickness. A total number of 100 plastic spheres with a diameter of 90 mm was used. Figure 5 shows the load-displacement curve of conventional and RBDC slabs.



(a)



(b)

Fig. 5. Load-Displacement Curve for (a) Conventional Slab (b) Bubble Deck Slab [23]

The load-displacement curve indicates that the RBDC slab sustained a peak load of 350 kN with a deflection of 12.6 mm, and it supported fewer loads than conventional slabs. Based on the analytical study [23], the load-bearing capacity of the RBDC slab demonstrates a better performance when compared to the traditional slab. The utilization of sphere balls in the RBDC slab results in a weight reduction of approximately 10.55%.

The RBDC slab system analysis reveals several significant findings. Incorporating bubble deck floors in construction lowers the slab's self-weight and demands specialized design proficiency [11]. The optimal selection of geometry, materials, and the arrangement and size of air voids in RBDC slabs can ensure high cross-section stiffness while minimizing the slabs' self-weight.

All in all, extensive research has been conducted on designing, testing, and analyzing reinforced bubble deck concrete slabs. Key design parameters, including the slab height and void geometry, significantly influence the load-bearing capacity of these slabs. Through experimental programs and finite element analysis, valuable insights into these slabs' structural behavior and performance have been gained. Moreover, the incorporation of innovative materials has enhanced their durability and sustainability. As a result, the findings from these studies contribute to the advancement of more efficient and practical designs for RBDC slabs, paving the way for improved construction practices and sustainable infrastructure solutions.

4. Conclusions

Based on the comprehensive analysis of existing literature, the following conclusions are outlined:

i. The RBDC slab system revolutionized traditional slab design by incorporating spherical or ellipsoidal void formers made from lightweight materials within the concrete slab. These voids reduce the self-weight of the slab, creating a grid-like structure of solid ribs.
ii. The RBDC slab technology is a ground-breaking approach that eliminates concrete from the center of floor slabs, reducing dead weight and increasing floor efficiency using recycled hollow plastic balls. This innovative prefabricated construction method has gained popularity and is increasingly applied in numerous industrial projects worldwide, particularly in constructing multi-storeyed buildings. By significantly reducing loads on columns, walls, foundations, and other building components.
iii. The RBDC slab technology optimizes the overall structural design. Furthermore, the design and testing of RBDC slabs have been extensively studied and reviewed in recent years. This comprehensive paper review delved into RBDC slab technology, focusing on its design and testing aspects. The analysis of various research papers and studies has provided valuable insights into this innovative construction method's structural behavior and performance.
iv. The design of RBDC slabs revolves around the strategic placement of hollow plastic balls within the concrete, resulting in a reduced dead weight and optimized load distribution. These slabs achieve a remarkable reduction in concrete volume by incorporating void formers while maintaining a high load-carrying capacity. The literature review has shown that this unique design approach improves structural performance and contributes to significant cost savings during construction.
v. Testing of Bubble Deck slabs has been an area of intense research, employing various experimental programs and numerical simulations. The sensitivity analysis and finite element studies have further reinforced the system's effectiveness, highlighting its enhanced flexural capacity, stiffness, and shear resistance compared to conventional solid slabs.
vi. The slabs exhibit enhanced flexural capacity, stiffness, and shear capacity of at least 70% compared to solid slabs with the same concrete and reinforcement. The efficient load distribution through the solid ribs ensures a high load-carrying capacity while achieving a substantial concrete economy of 30-50%.
vii. The RBDC slab system contributes to sustainability by reducing concrete consumption and, consequently, the environmental impact of concrete production. The lightweight design promotes resource conservation and minimizes transportation-related carbon.
viii. The load and deflection performance of the RBDC slab is higher than the conventional slab.

ix. Not only that, it is essential to be aware of the limitations and potential constraints that can affect the research findings and the application of the RBDC slab technology. There are a few common limitations faced when conducting the review. One of the primary challenges in researching RBDC slabs is the scarcity of long-term data. Since RBDC slab technology is relatively recent, historical performance data is lacking. Consequently, researchers frequently resort to short-term studies or simulations to project long-term behavior, thereby introducing an inherent level of uncertainty. Secondly, laboratory testing of RBDC slabs may not replicate real-world conditions accurately. Factors such as temperature, humidity, and loading dynamics can differ significantly between laboratory settings and actual construction sites. These disparities can lead to variations in results and limit the practical applicability of research findings.
x. Another significant constraint in researching RBDC slabs is geographical variability, design, and construction variability. Building codes, construction practices, and environmental conditions can vary significantly from one region to another. Design and construction practices for RBDC slabs can exhibit substantial variability. What may be acceptable and effective in one location may not hold elsewhere, rendering it challenging to generalize research findings. Lastly, the quality and characteristics of materials, including concrete and the plastic bubbles used in RBDC slabs, can vary widely. This material variability introduces uncertainty into research outcomes. Variations in material properties can impact structural performance and must be considered in any study. Acknowledging these limitations is essential for researchers, industry professionals, and policymakers alike, as it promotes a nuanced understanding of RBDC slab technology and paves the way for its practical and sustainable application in the built environment. Future research efforts should strive to mitigate these limitations to unlock the full potential of RBDC slabs in construction.

All in all, there are several recommendations where future research can contribute to the development and improvement of RBDC slab technology, which is conducting comprehensive structural tests and simulations to better understand the long-term performance and durability of RBDC slabs under different and various loading conditions, research the development of new materials for the plastic bubbles to enhance their strength, durability, and sustainability, explore alternative materials that can replace plastic bubbles, such as biodegradable or recycled materials, to make RBDC slabs more environmentally friendly with variety shape and size and investigate the seismic performance of bubble deck slabs and develop design guidelines for regions prone to earthquakes or other crucial disasters. By focusing on these research areas, the construction industry can advance bubble deck slab technology, making it more efficient, cost-effective, and environmentally friendly while also ensuring its structural integrity and safety.

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