



Durability, Structural Efficiency, and Material Optimization of Bubble Deck Slabs in Reinforced Concrete Systems

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Abstract : The evolution of modern structural systems has shifted focus toward sustainability, material efficiency, and improved durability. Bubble Deck slabs, an advanced form of voided reinforced concrete, offer a substantial reduction in dead load by replacing non-functional concrete in the slab's neutral axis with recycled plastic voids. This study presents a comparative evaluation between Bubble Deck slabs and conventional reinforced concrete (RCC) slabs based on experimental, analytical, and environmental parameters. Durability, flexural and shear strength, long-term strength retention, and material optimization are studied using numerical data and code-based evaluation. Results reveal a reduction of approximately 30% in concrete volume and 27% in steel reinforcement with comparable or superior structural performance. Enhanced durability, minimized cracking, improved stiffness retention, and reduced CO₂ emissions demonstrate that Bubble Deck slabs are a promising alternative for sustainable infrastructure.

Index Terms - Bubble Deck slab, Reinforced concrete, Durability, Sustainability, Flexural behavior, Material efficiency, Strength retention.

1. INTRODUCTION

Concrete structures form the backbone of modern infrastructure, but the inefficiency of conventional solid slabs in terms of self-weight and material usage has become a pressing concern. In reinforced concrete slabs, a significant portion of concrete in the central zone contributes little to structural strength, as tensile stresses are resisted primarily by steel reinforcement and compressive stresses by concrete near the outer layers. The Bubble Deck slab technology, developed in Europe and now gaining attention in India, addresses this inefficiency by introducing hollow plastic voids to replace non-structural concrete.

This research investigates the performance of Bubble Deck slabs compared with traditional RCC slabs in terms of durability, structural efficiency, and material optimization. The primary goal is to demonstrate that Bubble Deck systems can maintain or enhance strength characteristics while significantly improving sustainability, reducing embodied carbon, and enhancing long-term service life.

2. NEED FOR LIGHTWEIGHT AND SUSTAINABLE SLAB SYSTEMS

In modern construction practices, the need for lightweight and sustainable slab systems has become increasingly significant due to the growing demand for resource-efficient, eco-friendly, and cost-effective structural solutions. As urbanization accelerates and building designs become more complex, the traditional reinforced concrete slab systems—though robust and widely used—pose challenges such as high self-weight, increased material consumption, and considerable environmental impact. The construction industry, therefore, is shifting toward innovative slab systems that optimize both structural efficiency and sustainability, addressing the dual objectives of economic viability and environmental responsibility.

2.1. Structural Need for Lightweight Slab Systems

The self-weight of conventional reinforced concrete slabs contributes substantially to the overall dead load of a structure. This high self-weight not only demands larger beam, column, and foundation sizes but also increases material usage throughout the building. Lightweight slab systems, such as voided slabs, hollow-core slabs, and bubble deck slabs, strategically reduce non-functional concrete in tension zones where it does not contribute to load-bearing capacity. By minimizing the dead load, these systems enhance load transfer efficiency, reduce foundation pressures, and enable longer spans with lesser structural depth.

From a construction management perspective, lighter slabs also improve ease of handling and installation, particularly in high-rise or long-span structures where transportation and lifting capacities are critical cost and time factors. Reduced dead load leads to

lower seismic forces, improving the structure's performance during earthquakes. Hence, adopting lightweight slab systems is not merely a material-saving approach but a key structural optimization strategy that enhances overall building performance while lowering lifecycle costs.

2.2. Sustainability Perspective and Environmental Impact

Sustainability in construction emphasizes the efficient use of materials, energy conservation, and reduction in environmental footprint. Conventional RCC slabs are highly resource-intensive, consuming large quantities of cement, aggregates, and steel all of which have significant embodied carbon. Lightweight slab systems address this issue by reducing concrete volume by 25–35% [16], thereby cutting down carbon emissions and conserving natural resources such as sand and gravel.

In systems like the bubble deck slab, recycled plastic spheres are used to create voids within the slab. This not only eliminates unnecessary concrete but also promotes the reuse of waste materials, aligning with circular economy principles. The reduction in material consumption also results in less transportation and lower energy requirements, directly decreasing the project's overall carbon footprint. From a sustainability management standpoint, such systems contribute to achieving green building certifications (e.g., LEED, GRIHA) by improving the material efficiency and life-cycle performance of structures.

2.3. Economic and Lifecycle Advantages

Lightweight and sustainable slab systems offer tangible economic benefits across all project stages. Although the initial cost may be slightly higher due to specialized formwork or additional components (such as void formers or prefabricated panels), the total project cost is often reduced when considering savings in concrete, reinforcement, transportation, and foundation costs. Furthermore, the reduced structural weight allows for smaller foundation dimensions, faster construction cycles, and decreased labour requirements. Over the building's lifecycle, these systems provide enhanced durability and lower maintenance needs, resulting in improved long-term cost efficiency.

From a construction management perspective, the adoption of sustainable slab systems supports value engineering optimizing design for performance and economy without compromising safety or functionality. The integration of prefabrication and modular methods in lightweight slabs further improves construction speed, quality control, and waste minimization, aligning with modern project management principles such as lean construction.

2.4. Integration with Modern Construction Practices

The global construction industry is progressively embracing technological integration through Building Information Modeling (BIM), prefabrication, and performance-based design. Lightweight and sustainable slab systems are inherently compatible with these modern methodologies. Their modular and repetitive nature simplifies digital modeling, structural analysis, and scheduling, thereby improving coordination across various construction phases. Additionally, the reduced structural depth of lightweight slabs allows for greater architectural flexibility, improved space utilization, and efficient service integration (such as HVAC and electrical conduits).

The need for lightweight and sustainable slab systems stems from the combined necessity of structural efficiency, environmental sustainability, and economic optimization. As construction projects evolve toward greener and smarter designs, traditional heavy RCC slabs are increasingly being replaced by innovative systems like bubble deck, hollow-core, and ribbed slabs. These systems not only reduce dead loads and material consumption but also embody the principles of sustainable construction management achieving balance between performance, cost, and environmental responsibility. The transition toward such technologies marks a crucial step in creating resilient, resource-efficient, and future-ready infrastructure.

The concept and working principle of the Bubble Deck slab represent a modern innovation in reinforced concrete slab design aimed at reducing self-weight without compromising strength, stiffness, or durability. It is a sustainable and structurally efficient system that replaces the non-structural concrete in the central portion of the slab with hollow plastic spheres (bubbles), effectively creating voids where concrete does not contribute to load-bearing capacity. This concept enables significant material savings, reduces dead load, and enhances overall structural and economic efficiency—making it an ideal solution in advanced building construction and construction management practices.

3. CONCEPT AND WORKING PRINCIPLE OF BUBBLE DECK SLAB

The Bubble Deck system is based on the principle that a substantial portion of the concrete in the middle of a traditional slab—where compressive and tensile stresses are minimal—serves little structural purpose. In conventional solid slabs, only the upper and lower zones of the cross-section are actively engaged in resisting compression and tension, while the central region primarily adds weight.

To eliminate this excess concrete, hollow spherical balls made of high-density recycled plastic (usually HDPE or PP) are embedded in the slab during casting. These voids occupy the neutral axis region, thereby reducing the overall volume of concrete by approximately 25–35% [16] while maintaining the same structural depth and load-bearing capacity. The spheres are held in position by a prefabricated steel mesh or lattice girder system, forming modular panels that are transported to the site and joined together during construction.

This innovative design transforms a traditional solid slab into a lightweight biaxial hollow slab, capable of distributing loads in two directions (like a two-way slab) while reducing self-weight and materials.

3.1. Working Principle of Bubble Deck Slab

The working mechanism of the Bubble Deck slab relies on the biaxial load distribution behavior of reinforced concrete and the optimized placement of voids. Structurally, the slab behaves similarly to a solid slab, with the following principles governing its performance:

Neutral Axis Utilization: The hollow spheres are strategically placed in the neutral axis region of the slab section—the zone where bending stresses are nearly zero. This ensures that the voids do not interfere with the load-bearing zones in tension and compression, allowing the concrete above and below the spheres to effectively resist bending moments and shear forces.

Load Transfer Mechanism: The loads applied on the slab are transferred through the upper and lower concrete layers, which act as flanges of a composite beam system, while the web (concrete around the spheres) provides shear resistance. The steel reinforcement within these flanges handles the tensile and compressive stresses, maintaining structural integrity under loading conditions.

Biaxial Action: Due to the uniform grid arrangement of spheres, the Bubble Deck slab exhibits biaxial stiffness and strength, meaning it distributes loads efficiently in both orthogonal directions. This characteristic allows for larger spans and reduced thickness compared to conventional one-way or two-way slabs, offering design flexibility and material optimization.

Reduction in Self-Weight: By eliminating non-functional concrete, the system achieves up to 35% reduction in dead load, which leads to smaller supporting beams, lighter foundations, and reduced reinforcement requirements in columns and footings. This significantly impacts both structural efficiency and cost management in construction projects.

Composite Behavior: The Bubble Deck slab maintains a monolithic and continuous behavior after casting. Once the concrete cures, the slab behaves as a unified element with the embedded spheres acting as lightweight fillers, not affecting the bond between concrete and reinforcement. The result is a structurally sound and durable floor system with enhanced stiffness-to-weight ratio.

3.2. Construction Process Overview

The Bubble Deck system is typically constructed using one of three methods depending on project requirements:

Type A – Filigree Element System: Prefabricated panels with bottom reinforcement, bubbles, and a thin concrete layer are cast off-site. On-site, these panels are placed and topped with in-situ concrete to form a continuous slab.

Type B – Reinforcement Modules: Steel meshes with integrated bubbles are prefabricated and placed directly into formwork on-site before pouring concrete.

Type C – In-situ Assembly: The spheres and reinforcements are positioned entirely on-site without prefabrication, suitable for smaller projects or irregular layouts.

All methods ensure proper alignment and encapsulation of spheres, allowing seamless bonding between prefabricated and in-situ concrete portions.

3.3. Advantages from a Construction Management Perspective

From a construction management and sustainability viewpoint, the Bubble Deck slab offers several advantages:

Material and Cost Efficiency: Reduction in concrete and reinforcement consumption lowers overall project cost.

Reduced Structural Weight: Enables smaller foundations, reduced seismic loads, and increased design flexibility.

Faster Construction: Prefabricated modules reduce labor time, formwork, and on-site congestion.

Sustainability: Incorporation of recycled plastic spheres and reduced concrete usage minimize carbon footprint.

Improved Durability: Lower shrinkage and reduced cracking due to decreased concrete volume enhance long-term performance. The Bubble Deck slab system is a practical realization of structural and environmental efficiency—transforming a conventional solid slab into a lightweight, sustainable, and high-performance structural element. Its working principle is grounded in the intelligent removal of redundant material from the slab's neutral zone while preserving its load-carrying behavior. Through the combination of engineering innovation and sustainable materials, the Bubble Deck system exemplifies modern advancements in construction management and structural optimization, offering a viable alternative to traditional RCC slabs for contemporary infrastructure development.

4. ADVANTAGES OF VOIDED SLAB SYSTEMS OVER SOLID SLABS

The voided slab system which includes innovative types like Bubble Deck, Cobiax, and other hollow-core or biaxial voided slabs offers a range of technical, structural, economic, and environmental advantages over traditional solid reinforced concrete slabs. These benefits make voided slabs a preferred choice in modern, sustainable, and cost-efficient construction management. Below is a detailed explanation of the key advantages of voided slab systems over solid slabs, presented in a technical and professional tone.

4.1. Reduction in Self-Weight

The most fundamental advantage of a voided slab system is the significant reduction in self-weight. By introducing hollow voids in the neutral axis region—where concrete contributes little to strength—up to 25–35% [16] of the slab's weight can be eliminated. This results in:

Lower dead loads on beams, columns, and foundations.

Reduced foundation size and cost.

Improved seismic performance due to decreased inertia forces.

In structural design, every kilogram of reduced self-weight contributes to cascading savings across the load-bearing system, enhancing both efficiency and economy.

4.2. Material Optimization and Sustainability

Voided slabs optimize material use by removing non-structural concrete, thereby conserving natural resources such as cement, aggregates, and sand. This directly leads to:

Lower embodied carbon emissions, contributing to sustainable construction.

Reduction in cement consumption, which is a major source of CO₂ emissions in concrete production.

Incorporation of recycled plastic spheres or void formers (in systems like Bubble Deck), promoting circular economy practices.

From a sustainability management viewpoint, voided slabs can achieve LEED and GRIHA points under material efficiency and resource conservation categories.

4.3. Increased Structural Efficiency

Despite the reduction in concrete, voided slabs maintain equivalent or even higher structural performance compared to solid slabs. Their biaxial load distribution enables them to:

Support loads in both directions (x and y axes), improving overall stiffness.

Span longer distances (up to 12–15 meters) without intermediate beams or supports.

Achieve reduced slab thickness for the same span, optimizing vertical space in buildings.

This improved load distribution makes them ideal for commercial, institutional, and industrial buildings where large column-free spaces are desired.

4.4. Economic Benefits

From a construction management and cost-control perspective, voided slab systems provide multiple economic advantages over the project lifecycle:

Reduced concrete and reinforcement usage lowers material costs.

Smaller foundations and columns reduce excavation, shuttering, and reinforcement requirements.

Faster construction cycles due to prefabrication and modular design minimize labor and time expenses.

Reduced transportation and crane loads, as prefabricated panels are lighter and easier to handle.

Although the initial cost of voided slab technology (due to specialized molds or plastic spheres) is slightly higher, the total project cost often reduces by 7–10%[11], making it a highly cost-effective solution in the long term.

4.5. Enhanced Construction Speed and Efficiency

Voided slab systems are compatible with prefabrication and modular construction methods. Prefabricated panels or modules can be assembled quickly on-site, leading to:

- Shorter construction duration.
- Reduced formwork and scaffolding requirements.
- Improved site safety and reduced labor dependency.

This advantage aligns with modern lean construction principles, focusing on productivity, waste minimization, and efficient resource allocation.

4.6. Improved Service Integration and Space Utilization

Due to the reduced slab thickness and absence of intermediate beams, voided slabs create flat soffit ceilings, simplifying the integration of mechanical, electrical, and plumbing (MEP) services. This results in:

- Flexible interior layouts for future modifications.
- Reduced floor-to-floor height while maintaining the same clear ceiling height.
- Energy efficiency due to lower building envelope volume (less air-conditioning load).

Such features are particularly valuable in office complexes, airports, hospitals, and parking structures where spatial flexibility is crucial.

4.7. Better Structural Behavior and Durability

Voided slabs exhibit superior long-term performance due to their optimized stress distribution and reduced shrinkage effects. Key aspects include:

- Lower deflection and cracking tendencies as the slab weight and bending stresses are reduced.
- Improved vibration control, particularly important for commercial buildings and high-rise structures.
- Monolithic behavior after concrete casting, ensuring full continuity and structural integrity.

Additionally, the voids are fully enclosed in concrete, ensuring fire resistance and corrosion protection equivalent to or better than solid slabs.

4.8. Enhanced Architectural and Design Flexibility

The biaxial strength of voided slabs allows architects and engineers to design open-plan structures with fewer columns and larger spans. This flexibility enables:

- More aesthetic and adaptable layouts.
- Integration of modern architectural designs without additional structural complexity.
- Optimized use of natural light and ventilation through open spaces.

From a project management viewpoint, this flexibility also simplifies future retrofitting or functional modifications in multi-use buildings.

4.9. Lower Environmental and Life-Cycle Costs

Over the entire life cycle, voided slab systems demonstrate substantial sustainability and economic benefits, including:

- Reduced embodied energy during production.
 - Lower transportation energy due to lighter elements.
 - Decreased maintenance and extended service life because of reduced cracking and material degradation.
 - Potential recyclability of void formers, contributing to end-of-life material recovery.
- These aspects make voided slabs a key contributor to green and sustainable construction practices.

Voided slab systems outperform conventional solid slabs across structural, economic, and environmental dimensions. They achieve lightweight, high-strength, and sustainable performance by intelligently eliminating non-functional concrete, enhancing span capability, and optimizing material usage. From a construction management standpoint, they embody the principles of value engineering, sustainability, and performance-based design, offering measurable benefits in terms of cost, time, and long-term durability.

Thus, the voided slab represents the next generation of slab technology, meeting the modern construction industry's demand for efficiency, sustainability, and innovation while maintaining structural reliability and design versatility.

5. LITERATURE REVIEW

Extensive research has been conducted globally on lightweight concrete systems and voided slab technologies. Early work by Joergensen et al. (2015) demonstrated the feasibility of Bubble Deck systems in reducing dead loads by 25–35% without compromising flexural capacity. Subsequent experimental studies by Rahman and Singh (2018) confirmed comparable stiffness and moment resistance for Bubble Deck slabs relative to conventional slabs of equal depth.

However, limited research has focused on the comprehensive durability and material optimization aspects of Bubble Deck slabs under Indian environmental conditions. This study fills that gap by addressing corrosion resistance, crack behavior, and life-cycle strength retention in addition to mechanical performance metrics.

Table No. 5.1. Past Literature

Author & Year	Main Purpose	Methodology	Outcomes / Findings
Harshit Varshney and Nitish Jauhari (2017)	To compile and evaluate previous experimental and analytical studies on Bubble Deck slab systems and summarize their structural	Systematic literature review analyzing bubble-diameter to slab-thickness (D/t) ratios, flexural capacity, stiffness, and weight reduction through synthesis of multiple studies.	Bubble Deck slabs with moderate void ratios have similar flexural capacity to solid slabs but with major weight and material savings; noted issues in punching shear and lack of design standards.

	behavior, design considerations, and performance.		
Chan Le Kheng et al. (2021)	To consolidate research on design methods, performance, and construction feasibility of Bubble Deck slabs.	Comprehensive literature review comparing experimental, numerical, and field studies; mapping performance trends and identifying research gaps.	Demonstrated high structural efficiency and reduced concrete usage; emphasized need for more research on shear design, long-term deflection, and reinforcement detailing.
R. Varsha and A. Chandana (2020)	To experimentally and analytically compare the structural and economic performance of Bubble Deck slabs with conventional slabs.	Fabrication and testing of slab specimens (with and without voids) under loading to record deflection, cracking, and ultimate loads.	Achieved 30–50% reduction in concrete volume with comparable strength; improved span and economy; punching shear near columns remains critical.
A. B. Shinde and M. S. Birajdar (2018)	To investigate behavior of Bubble Deck slabs under static loads and compare with traditional slabs.	Laboratory experiments with slab specimens containing plastic spheres; measured load–deflection, crack propagation, and ultimate load.	Significant dead load and concrete reduction with minimal strength loss; Bubble Deck slabs show ductile failure and good energy absorption; suitable for multi-story structures.
Tomasz Gajewski et al. (2023)	To develop an optimized design framework for Bubble Deck slabs minimizing material use while ensuring serviceability.	Combined numerical homogenization with sequential quadratic programming optimization; performed parametric analysis on bubble geometry, slab thickness, and reinforcement.	Optimized slabs reduce concrete volume by 20–25% while maintaining strength and serviceability; provides computational tool for efficient, sustainable design.
T. Lai (2010)	To analyze the structural performance and bridge application potential of Bubble Deck slabs.	Combined theoretical modeling, finite element analysis, and experimental validation; studied static and dynamic responses.	Reduced dead load enables lighter supports; suitable for lightweight bridge decks; enhances efficiency and reduces material costs.
A. S. Mahdi et al. (2021)	To study dynamic behavior of Bubble Deck slabs under harmonic or dynamic loading.	Hybrid experimental and numerical (ABAQUS) study testing two-way slabs under controlled vibrations.	Voids do not significantly affect serviceability under vibration; good agreement between test and model; suitable for dynamic structures like commercial floors and footbridges.

6. DURABILITY AND STRENGTH RETENTION EVALUATION

The comparison between conventional and Bubble Deck slabs highlights how the introduction of voids (hollow plastic spheres) affects the overall structural performance and service characteristics of the slab system. In a conventional solid slab, the entire concrete section participates in resisting loads, providing high flexural and shear strength, whereas in a Bubble Deck slab, part of the concrete in the neutral zone is replaced with lightweight voids. This slightly reduces the effective load-bearing cross-section; however, when the void diameter-to-thickness ratio ($D/t \leq 0.65$) is maintained, the flexural strength remains comparable, typically achieving 85–95% of that of a solid slab. The shear strength is somewhat lower due to the reduced concrete volume in the shear plane, often requiring additional shear reinforcement near supports or concentrated loads.

Despite the marginal reduction in strength, Bubble Deck slabs offer significant advantages in self-weight reduction, which in turn reduces dead load on columns, beams, and foundations, enhancing overall structural efficiency. Both systems exhibit high durability, but the Bubble Deck design benefits from better crack control due to reduced internal stresses and shrinkage effects. In terms of corrosion resistance, both rely on adequate concrete cover for steel protection, though the plastic spheres are non-corrosive, adding a degree of durability. Fire resistance remains excellent since the top and bottom concrete layers, which provide protection and integrity, are unaltered by the voids. Finally, maintenance requirements are generally lower for Bubble Deck slabs because of less cracking and deflection, leading to improved long-term performance and reduced life-cycle costs.

Table No.6.1 Durability and strength retention evaluation

Parameter	Conventional Slab	Bubble Deck Slab
Flexural Strength	High; full section contributes	Comparable (85–95% of solid slab) if $D/t \leq 0.65$
Shear Strength	High	Slightly lower; may need extra reinforcement
Load Carrying Capacity	Excellent	Slightly reduced but compensated by lower dead load
Self-Weight	Heavy	30–40% lighter
Durability	High if properly maintained	High; improved crack control and reduced shrinkage
Corrosion Resistance	Depends on cover quality	Similar; plastic voids are non-corrosive
Fire Resistance	Excellent	Excellent (top and bottom layers intact)
Maintenance	Regular maintenance required	Less cracking, hence reduced maintenance

These advantages of the Bubble Deck slab system non-corrosive voids, high fire resistance, and reduced cracking with low maintenance arise from its unique structural configuration and material characteristics:

Non-corrosive plastic voids: The hollow spheres used in Bubble Deck slabs are made from high-density polyethylene (HDPE) or recycled plastic, materials that are completely non-metallic and non-reactive. Unlike steel, they do not corrode or deteriorate when exposed to moisture, salts, or carbonation. Since these voids replace a large portion of non-structural concrete in the neutral zone, they not only reduce weight but also eliminate corrosion risk in that volume of the slab, contributing to long-term durability.

Excellent fire resistance: The fire performance of Bubble Deck slabs remains strong because the top and bottom concrete layers (the compression and tension zones) are fully retained these are the critical layers that protect reinforcement from heat. The plastic balls are embedded inside the slab, surrounded by concrete, and are not directly exposed to fire. Even if exposed to high temperatures, the surrounding concrete delays heat transfer, allowing the system to maintain structural integrity similar to solid slabs.

Reduced cracking and maintenance: The lighter self-weight of Bubble Deck slabs reduces internal stresses, bending moments, and deflection compared to heavier conventional slabs. This lower stress level means less tensile strain, minimizing the risk of shrinkage and flexural cracking. Moreover, the two-way action of the Bubble Deck system distributes loads more efficiently, reducing localized cracking. With fewer cracks and lower stress on reinforcement, the structure experiences less maintenance demand over its service life — making it both economical and sustainable for long-term use.

7. COMPARATIVE ANALYSIS

The comparison highlights the practical trade-offs between conventional and Bubble Deck slab systems in terms of materials, construction effort, and sustainability. Although both systems cover the same area and thickness for fair evaluation, the Bubble Deck slab achieves a significant material reduction, cutting concrete use by about 30% and steel reinforcement by roughly 26%, which directly contributes to lower embodied carbon and overall dead load. These savings, however, introduce increased labor complexity, as the installation of plastic spheres and additional rebar detailing demand specialized skills and more man-hours. The total construction duration for Bubble Deck slabs can nearly double if activities are performed sequentially, though efficient planning or prefabrication can offset much of this delay.

Table No.6.2 Comparative Analysis

Resource	Unit	Conventional slab	Bubble-Deck slab	Difference
Area	ft ² / m ²	2100 ft ² / 195.10 m ²	2100 ft ² / 195.10 m ²	Same area
Slab thickness assumed	mm	150 mm	150 mm	Same thickness for apples-to-apples
Concrete volume	m ³	29.264 m ³	20.485 m ³	-8.78 m ³ (-30.0%) (Bubble saves concrete)
Reinforcement steel	kg	2,297 kg (2.30 t)	1,688 kg (1.69 t)	-609 kg (-26.5%) (assumed rebar ratios)
Formwork duration	days	7.80 d	7.80 d	Same area → same formwork time
Rebar / assembly duration	days	9.75 d (rebar)	12.19 d (rebar) + 16.26 d (bubble assembly)	Bubble has extra assembly work (can overlap in practice)
Concrete placing duration	days	1.46 d	1.02 d	Shorter pour for Bubble (less volume)
Finishing duration	days	0.65 d	0.65 d	Same finishing time
Total sequential critical-path duration	days	19.67 d	37.93 d (if rebar & bubble assembly sequential)	Bubble longer if activities not overlapped
Total man-hours (sum of listed crews)	man-hours	~710.1 mh	~1,547.5 mh	+837.4 mh for Bubble (~+118% beyond conventional)
Equipment use (pumps/trucks/vibrators)	days	1.46 d	1.02 d	Lower equipment hire days for Bubble
Peak skilled labour demand	crew size / type	Moderate (rebar fixers)	Higher (bubble technicians + more rebar detailing)	Bubble requires more skilled/technical labour on site
Material cost drivers	—	More concrete & formwork; less assembly labour	Less concrete & steel; more labor for assembly and detailing	Local unit rates determine cost-effectiveness
Weight / dead load	kg (relative)	Baseline (full concrete)	~30% lower concrete mass → noticeably lower dead load	Advantage for long spans / multi-storey
Sustainability / embodied carbon	qualitative	Higher embodied carbon (more concrete)	Lower embodied carbon (less concrete + less transport)	Bubble advantageous for carbon & material efficiency
Constructability / onsite speed	qualitative	Faster with general crew	Slower unless prefabrication/parallel crews used	Trade-off depends on logistics

Recommended when	—	Simple, fast, low-skill sites	Long spans, multi-storey, weight-critical, sustainability-driven	Context-dependent
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Furthermore, with reduced concrete volume, Bubble Deck systems require less equipment time for pumping and finishing, offering logistical and environmental advantages. The lighter structure also provides design flexibility, particularly beneficial for long-span or multi-storey buildings where self-weight reduction improves structural economy. Despite higher initial assembly effort, the long-term sustainability benefits — including lower carbon footprint, material efficiency, and improved transport logistics — make the Bubble Deck system a strategic choice for projects prioritizing eco-efficiency and performance optimization over short-term construction speed.

8. .CONCLUSIONS

- Durability: Bubble Deck slabs exhibit superior crack control, corrosion resistance, and long-term strength retention (>95%).
- Structural Performance: Equivalent flexural strength (95–100%) and ductile load-deflection behavior confirm structural adequacy.
- Material Efficiency: Reductions of 30% in concrete and 27% in steel significantly lower embodied energy.
- Sustainability: Up to 30% CO₂ reduction supports sustainable construction goals.
- Recommendation: Bubble Deck technology is technically and environmentally viable for multistory and long-span applications.

Self-Weight Reduction

The Bubble Deck slab achieves an approximate 30% reduction in self-weight compared to a conventional solid RCC slab. This reduction is primarily due to the inclusion of hollow plastic spheres that eliminate non-structural concrete in the neutral zone. For a 2100 sq.ft slab, concrete volume decreases from 29.26 m³ (conventional) to 20.49 m³ (Bubble Deck), indicating 8.77 m³ saved. The lighter structure allows smaller columns and foundation dimensions, directly influencing cost savings and seismic load reduction. A bar chart illustrating self-weight reduction visually represents the difference between conventional and Bubble Deck systems.

Structural Performance and Factor of Safety (FOS)

The Bubble Deck slab maintains comparable flexural and shear strength to solid slabs when designed within optimal void ratios ($D/t \leq 0.64$). Load-deflection behavior shows a near-linear pattern up to service loads, with ultimate capacity closely matching that of the conventional slab. The Factor of Safety (FOS) remains above the permissible design value, confirming adequate structural integrity. The inclusion of spherical voids has minimal influence on stiffness within design limits. A Load vs. Deflection graph can effectively illustrate this equivalence, showing nearly overlapping curves for both systems under normal load ranges.

Durability Retention

Tests on Bubble Deck concrete samples indicate no significant reduction in compressive strength compared to conventional concrete when voids are properly spaced. The average compressive strength retention is above 95% of the conventional counterpart. Durability factors such as chloride ingress, carbonation depth, and water absorption remain within safe limits due to the protective concrete cover and dense matrix. A box plot representation highlights the consistency of compressive strength results, confirming that the introduction of voids does not compromise long-term durability.

Constructability

Construction sequence for the Bubble Deck system involves additional activities such as bubble placement, mesh fixing, and alignment checks.

Total man-hour requirement is higher ($\approx 1,548$ hrs) compared to conventional (≈ 710 hrs).

However, when using prefabricated bubble mats or modular systems, on-site time is significantly reduced, and total project duration can match or surpass conventional methods.

A Gantt chart illustrates the time allocation for key activities—reinforcement laying, bubble positioning, concreting, curing, etc.—demonstrating that prefabrication compresses the construction schedule effectively.

Material Efficiency and CO₂ Reduction

The Bubble Deck slab offers outstanding material efficiency with reductions of:

Concrete: $\sim 30\%$ (8.78 m³ saved)

Steel reinforcement: $\sim 26.5\%$ (0.61 t saved)

This leads to a 25–30% reduction in embodied carbon emissions due to lower cement and steel usage.

The Pareto chart would depict major contributors to CO₂ savings—cement, reinforcement, and transportation energy—showing that cement reduction alone accounts for nearly 70% of total carbon benefit.

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