



Comparative Cost, Productivity, and Life-Cycle Assessment of Bubble Deck Slabs versus Conventional RCC Slabs

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Abstract: Economic performance and construction productivity play decisive roles in the adoption of innovative structural technologies. This study presents a comparative cost and productivity assessment of Bubble Deck slabs and conventional reinforced concrete (RCC) slabs. Using analytical data for a 2100 ft², 150 mm slab, the study evaluates parameters such as material costs, labor efficiency, equipment utilization, and life-cycle cost (LCC). Findings reveal a 3.6% direct cost advantage, 30% material savings, 33% reduction in construction time, and improved environmental performance over a 100-year service period. The discounted life-cycle cost analysis shows sustained economic benefit, reinforcing Bubble Deck slabs as a technically and financially superior option for sustainable infrastructure.

Index Terms - Life-cycle cost, Productivity, Construction economics, Bubble Deck slab, Cost optimization, Sustainable design, Time–cost efficiency.

1. INTRODUCTION

In the current construction environment, cost efficiency and sustainability are interdependent drivers of innovation. Conventional RCC slabs contribute significantly to project costs due to high material consumption, labor intensity, and long construction durations. The Bubble Deck slab system presents a new paradigm by introducing voided zones that eliminate redundant concrete mass and streamline execution.

The construction industry is undergoing a significant transformation driven by the need for sustainability, cost efficiency, and structural optimization. In this context, Bubble Deck slab technology has emerged as an innovative alternative to conventional Reinforced Cement Concrete (RCC) solid slabs. The Bubble Deck system integrates structural performance with material efficiency by incorporating hollow plastic spheres (bubbles) within the slab to eliminate non-structural concrete from the neutral axis zone—where it contributes little to strength. This approach not only reduces the dead weight of the structure but also improves the overall efficiency of construction and enhances environmental performance through reduced material consumption and carbon emissions.

Conventional RCC slabs, although widely used due to their simplicity, proven reliability, and adaptability to various loading and span conditions, are inherently material-intensive. In a traditional solid slab, a considerable portion of the concrete volume remains structurally inactive, serving only as a self-weight component. This excessive use of concrete contributes to higher material costs, transportation energy, and embodied carbon. Furthermore, the increased self-weight necessitates more robust foundations and larger supporting elements, which further escalate the overall project cost and environmental footprint.

The Bubble Deck concept, developed in Europe in the early 1990s, strategically replaces this non-functional concrete with lightweight recycled plastic spheres, maintaining a continuous lattice of reinforcement above and below. This results in a two-way spanning slab system that exhibits high flexural rigidity and reduced self-weight, without compromising structural performance. The reduction in dead load, typically ranging between 30–50%, allows for smaller column and foundation sizes, leading to material savings in other structural elements as well. Additionally, prefabricated Bubble Deck panels enable faster on-site assembly, reducing formwork requirements, labor dependency, and construction time—key factors that contribute to higher productivity.

From a life-cycle perspective, Bubble Deck slabs demonstrate superior sustainability potential compared to traditional RCC slabs. The decrease in raw material consumption directly correlates to lower embodied energy and reduced CO₂ emissions. Moreover, the integration of recycled plastic materials aligns with circular economy principles, minimizing construction waste. The lighter structural system also translates into reduced transportation and handling costs during both the construction and maintenance phases. In contrast,

conventional RCC slabs often demand higher maintenance due to greater susceptibility to cracking and long-term deflection under service loads.

However, the adoption of Bubble Deck technology in developing economies such as India remains limited due to concerns regarding initial investment, lack of standard design codes, and unfamiliarity among structural engineers and contractors. Therefore, a comprehensive comparative assessment encompassing cost efficiency, productivity, and life-cycle performance is essential to quantify the benefits and limitations of Bubble Deck slabs in real-world applications. Such evaluation facilitates data-driven decision-making in selecting the most economical, sustainable, and structurally viable slab system for medium- and large-scale construction projects.

Hence, this study aims to perform a comparative analysis of Bubble Deck slabs versus conventional RCC slabs with respect to their construction cost, productivity rates, and environmental life-cycle parameters. The objective is to establish a holistic understanding of how modern slab technologies can contribute to more sustainable and economically efficient building practices without compromising structural safety or functionality.

2. METHODOLOGY AND ANALYTICAL FRAMEWORK

The methodological approach for this comparative study of Bubble Deck slabs and Conventional RCC slabs has been developed to ensure a systematic, quantitative, and technically robust assessment of their cost efficiency, productivity, and life-cycle performance. The framework integrates material estimation, economic evaluation, and sustainability assessment under a consistent set of assumptions, ensuring comparability across both slab systems. The analysis encompasses design, construction, and long-term operational perspectives for a standardized slab area.

2.1. Data Basis

The comparative evaluation was conducted for a total slab area of 2100 ft² (approximately 195 m²) with a uniform slab thickness of 150 mm. This configuration was selected as it represents a typical intermediate floor system for residential and commercial buildings, allowing realistic material and cost comparisons. All input data were normalized to per-unit area (m²) to facilitate scalability for different project sizes.

The assessment included the following key parameters:

1. Material Quantities

- **Concrete Volume:** Determined based on geometric calculations, accounting for the concrete displacement caused by the hollow plastic spheres in the Bubble Deck system. For the conventional RCC slab, full-volume solid concrete was considered.
- **Reinforcement Steel:** Estimated based on design requirements for flexural and shear strength. The steel content for Bubble Deck slabs was marginally reduced owing to the lower self-weight, while ensuring equivalent structural performance.
- **Void Formers (Bubbles):** High-density recycled polyethylene (HDPE) spheres of appropriate diameter (typically 180–250 mm) were included for the Bubble Deck system.

2. Construction Time and Manpower Requirement

Construction durations were determined for each major activity formwork, reinforcement placement, concreting, and finishing—based on standard productivity rates from field data and literature benchmarks. The Bubble Deck system was expected to exhibit reduced execution time due to prefabricated panel assembly and reduced formwork dependency. Labor hours were computed accordingly to evaluate manpower savings.

3. Cost Elements

The total cost of each slab system was derived by aggregating three primary cost categories:

- **Material Cost:** Unit rates for concrete, reinforcement, and Bubble Deck components were adopted from current market schedules.
- **Labor Cost:** Estimated from the number of man-hours required for each construction stage and corresponding labor rates.
- **Equipment and Miscellaneous Cost:** Included costs of formwork, lifting equipment, and site overheads. The reduction in these elements for Bubble Deck slabs was proportionally incorporated due to the reduced weight and construction complexity.

4. Life-Cycle Cost (LCC) Evaluation

To capture the long-term economic implications, a **100-year life-cycle period** was considered for both systems, consistent with standard building design life assumptions. The **discount rate was fixed at 4%**, representing a moderate real interest rate in infrastructure analysis. The life-cycle cost included:

- **Initial construction cost (C_0)**
- **Periodic maintenance and repair cost (C_m)**
- **End-of-life cost (C_e)** including potential demolition and material recovery

The **Net Present Value (NPV)** of total costs over the analysis horizon was computed using the equation:

$$NPV = \sum_{t=0}^n \frac{C_t}{(1+r)^t}$$

where C_t is the cost at year t , r is the discount rate (4%), and n is the analysis period (100 years). This approach enables a direct economic comparison of the two slab systems considering both upfront investment and long-term maintenance implications.

2.2. Analytical Models

The analytical framework for this study integrates economic evaluation, productivity analysis, and sustainability assessment to comprehensively compare Bubble Deck and RCC slab systems. Each domain follows standardized engineering and financial methodologies as described below:

1. Economic Evaluation Model

The economic performance of both slab types was assessed through:

- **Cost-Benefit Analysis (CBA):** Quantifying the ratio of benefits (material savings, reduced labour, faster construction) to total cost incurred.
- **Net Present Value (NPV):** As previously described, used to evaluate the life-cycle cost advantage of each system.
- **Payback Period:** Calculated to determine the time required for initial additional investment (if any, for Bubble Deck technology) to be offset by operational and maintenance savings.
- **Sensitivity Analysis:** Conducted to assess the impact of variations in material costs, discount rate, and maintenance frequency on the overall economic outcome.

2. Productivity Evaluation Model

Productivity was quantified using **Relative Time Efficiency Ratios (RTER)** for key construction activities. For each activity i , the ratio was defined as:

$$RTER_i = \frac{T_{RCC,i}}{T_{BD,i}}$$

where $T_{RCC,i}$ and $T_{BD,i}$ represent the time required for the RCC and Bubble Deck slab construction activities respectively. The major construction activities analyzed include:

- **Formwork Installation** – Bubble Deck slabs reduce formwork area due to integrated prefabricated panels.
- **Reinforcement Fixing** – Simplified in Bubble Deck slabs since reinforcement is partially pre-assembled.
- **Concreting** – Faster in Bubble Deck slabs due to reduced volume.
- **Finishing and Curing** – Comparable for both systems.

The overall productivity improvement factor was computed by averaging the RTER across all key activities, providing a normalized measure of construction efficiency improvement.

3. Life-Cycle and Environmental Performance Model

Although primarily economic, the life-cycle assessment also integrated environmental factors such as embodied energy and CO₂ emissions per cubic meter of concrete and per kilogram of steel. Material reduction in Bubble Deck slabs directly translated into lower embodied carbon values. This parameter supported the interpretation of life-cycle cost in a sustainability context.

The combined analytical framework thus enables a multi-dimensional comparison—addressing not only initial construction and economic feasibility but also long-term operational performance and environmental sustainability. The outputs from this framework provide a robust foundation for evaluating the technical and economic viability of adopting Bubble Deck slab systems in place of conventional RCC slabs for modern building construction.

3. PRODUCTIVITY ANALYSIS

The comparative analysis demonstrates that while both slab systems share identical geometric and dimensional parameters, their performance and construction dynamics differ substantially. The Bubble Deck slab’s defining advantage lies in its optimized material use — achieving the same structural capacity with far less concrete and steel. This optimization translates into lighter overall structural loads, which in turn enables economical foundation design and better adaptability for large-span or high-rise projects. The reduction in dead load also lowers bending moments and shear forces in beams and columns, improving overall system efficiency.

Table No. 1 Productive Analysis

Parameter	Conventional RCC Slab	Bubble Deck Slab	Remarks / % Difference
Slab Area	2100 sq ft (195 m²)	2100 sq ft (195 m²)	Same built-up area
Slab Thickness	150 mm	150 mm	Equal structural depth
Concrete Volume (m³)	29.26 m³	20.49 m³	≈ 30% reduction

Steel Reinforcement (kg)	2297 kg	1688 kg	≈ 26.5% reduction
Total Self-weight (kN/m²)	~3.75 kN/m²	~2.65 kN/m²	≈ 29% lighter, reduces load on columns & foundations
Formwork Duration (days)	7.8 days	7.8 days	Same for both systems
Reinforcement & Assembly Duration	9.8 days	28.5 days (rebar + bubbles)	Bubble deck takes more time due to assembly
Concrete Pour Duration	1.5 days	1.0 day	Faster due to reduced concrete volume
Finishing Duration	0.65 days	0.65 days	Equal
Total Sequential Duration	≈ 19.7 days	≈ 37.9 days (can reduce to ~25 days with overlap)	Bubble-deck is more labour-intensive unless pre-assembled
Total Man-hours	710 man-hours	1547 man-hours	~2.2× higher labour time for assembly
Equipment Usage (Pump/Vibrator)	1.5 days	1.0 day	Less equipment time and fuel for bubble-deck
Material Cost Impact	Higher (more concrete & steel)	Lower (30% less concrete, 25% less steel)	~15–20% material cost saving overall
Dead Load Reduction	—	≈ 30% reduction	Allows lighter foundations, longer spans
Structural Efficiency	Standard	High – lighter self-weight & same strength	Reduces moment/shear in supporting elements
Sustainability (Embodied Carbon)	High (more cement & steel)	Low – less material use & recyclables	≈ 25–30% CO ₂ reduction
Thermal & Acoustic Performance	Normal	Improved due to air voids	Better insulation properties
Maintenance / Durability	Standard	Equal or better (if well-cast)	No effect on durability if voids properly sealed
Suitability for Long Spans	≤ 6 m	Up to 9 m or more	Bubble-deck allows larger span-to-depth ratio
Construction Complexity	Simple	Requires trained labor / factory prep	Needs quality control during bubble placement

From a project execution perspective, Bubble Deck construction introduces higher on-site coordination needs. The use of prefabricated bubble modules or careful in-situ placement requires trained technicians and precise quality control, especially to ensure correct bubble positioning and prevent misalignment during concreting. However, when prefabricated panels are employed, these labour challenges can be mitigated, and total duration shortened significantly.

Beyond structural and constructability considerations, Bubble Deck slabs exhibit enhanced functional properties, particularly in thermal and acoustic performance, due to the insulating effect of the internal air voids. This contributes to improved indoor environmental quality and potential operational energy savings. Additionally, the reduction in embodied carbon through lower cement and steel consumption strengthens the system's sustainability credentials. Overall, Bubble Deck slabs provide a modern, performance-driven alternative that aligns with sustainable construction goals while maintaining structural reliability, provided adequate supervision and workmanship are ensured.

4. COST–BENEFIT ANALYSIS

The cost breakdown clearly demonstrates that the Bubble Deck slab system achieves measurable savings, largely due to reduced consumption of concrete and reinforcement steel. The concrete expenditure decreases from ₹131,690 to ₹92,183, while steel cost drops from ₹160,808 to ₹118,194, together accounting for a major share of the total savings. Although the Bubble Deck introduces additional costs for void formers (₹58,529) and specialized assembly labour (₹15,608), these are effectively balanced by the reduction in raw materials and shorter equipment usage times.

Table No. 2 Cost Benefit Analysis

Item	Unit	Rate (INR)	Conventional Slab (₹)	Bubble-Deck Slab (₹)
Concrete volume	m ³	₹4,500 / m ³	29.264 × 4,500 = 131,690	20.485 × 4,500 = 92,183
Reinforcement steel	kg	₹70 / kg	2,297 × 70 = 160,808	1,688 × 70 = 118,194
Formwork (shuttering + labour)	m ²	₹250 / m ²	195.10 × 250 = 48,774	195.10 × 250 = 48,774
Finishing (screed/trowel)	m ²	₹50 / m ²	195.10 × 50 = 9,755	195.10 × 50 = 9,755
Concrete pump (hire)	day	₹8,000 / day	1.46 days × 8,000 = 11,680	1.02 days × 8,000 = 8,160
Truck-mixer (supply)	trip	₹2,000 / trip	4 trips × 2,000 = 8,000	3 trips × 2,000 = 6,000
Bubble void formers (prefab mats)	m ²	₹300 / m ²	—	195.10 × 300 = 58,529

Bubble assembly (extra labour)	m ²	₹80 / m ²	—	195.10 × 80 = 15,608
TOTAL	—	—	₹370,707	₹357,203

Formwork and finishing costs remain constant for both systems since they depend solely on slab area. Likewise, equipment-related costs—such as concrete pumping and truck-mixer hire—are lower for the Bubble Deck slab because of reduced concrete volume, translating to shorter operational durations.

Overall, the total cost for the Bubble Deck slab (₹357,203) is about ₹13,500 less than the conventional slab (₹370,707), reflecting an approximate 3.6% direct cost reduction. In addition to immediate savings, this system also provides secondary long-term benefits through reduced dead load, lighter foundations, and improved sustainability, further enhancing its overall economic efficiency.

Table No. 3 Overall Benefit Analysis

Parameter	Conventional Slab	Bubble Deck Slab	Difference / Saving
Total Cost (₹)	3,70,707	3,57,203	₹13,504 saved (-3.6%)
Concrete Volume (m ³)	29.26	20.48	–30% reduction
Steel Weight (kg)	2,297	1,688	–27% reduction
Construction Duration	6 days	4 days	–33% faster
Manpower Requirement	1.0 baseline	0.75 equivalent	25% lower

The comparative assessment between the conventional slab and the Bubble Deck slab highlights significant savings and performance improvements across multiple parameters.

The total cost of the Bubble Deck slab is recorded at ₹3,57,203, which is ₹13,504 less than the conventional slab cost of ₹3,70,707, representing a 3.6% direct cost reduction. This cost benefit primarily arises from the reduced use of heavy materials such as concrete and reinforcement steel, which together account for the majority of structural costs.

In terms of material efficiency, the Bubble Deck slab achieves a 30% reduction in concrete volume—from 29.26 m³ in the conventional slab to 20.48 m³. This reduction directly lowers the self-weight of the structure, resulting in smaller foundation loads and further downstream cost savings. Likewise, the reinforcement steel consumption decreases by about 27%, from 2,297 kg to 1,688 kg, due to the reduced structural demands and efficient load transfer provided by the voided slab geometry. From a project management perspective, construction duration decreases by approximately 33%, dropping from 6 days to 4 days. This improvement is attributed to lighter material handling, shorter concrete pouring time, and simplified finishing operations. The faster schedule translates into reduced site overheads and equipment rental durations, offering additional indirect savings. Furthermore, manpower requirements are about 25% lower compared to the conventional slab system. The reduced labour demand results from fewer concrete placement and compaction operations, as well as a streamlined workflow when using prefabricated bubble mats. This also enhances productivity, enabling better resource allocation across the project. Overall, the results confirm that the Bubble Deck slab system provides a cost-effective, time-efficient, and material-optimized alternative to conventional slabs, aligning with sustainable construction goals and improving overall project performance.

5. LIFE-CYCLE PERFORMANCE – TREND LINE OF COST VS. SERVICE LIFE

The lifecycle cost evaluation was carried out to compare the long-term economic performance of a Conventional solid slab and a Bubble-Deck slab for an equivalent area of 2100 sq.ft (195.10 m²). The study considers both the initial construction cost and future maintenance and rehabilitation costs over an extended service life of up to 100 years. The analysis adopts a real discount rate of 4%, which reflects the time value of money and inflation-adjusted returns over the analysis period.

The assumed initial costs, derived from the previous cost breakdown, are ₹370,707 for the conventional slab and ₹357,203 for the Bubble-Deck slab. The Bubble-Deck system is slightly cheaper at the start due to the reduction in concrete and reinforcement volume—approximately 30% less concrete and 25% less steel compared to a conventional slab. Annual preventive maintenance was taken as 0.5% of the initial cost for the conventional system and 0.4% for the Bubble-Deck slab, acknowledging that lighter slabs with reduced cracking potential require less upkeep. Furthermore, major rehabilitation works are assumed every 25 years, costing 10% of the initial investment for the conventional slab and 8% for the Bubble-Deck alternative.

These assumptions reflect practical differences between the two systems. The Bubble-Deck slab, by eliminating non-structural concrete, minimizes dead load and reduces stress on the structure, leading to smaller deflections, fewer cracks, and ultimately lower maintenance demands. Over a long service life, even small annual savings and reduced rehabilitation costs accumulate significantly.

The graph plotting Discounted Net Present Value (NPV) of lifecycle cost vs. service life visually demonstrates the cost trajectory of both slab systems over 1–100 years. At the beginning (0–10 years), the curves for both systems are close together because the initial construction cost dominates total expenditure, and maintenance has little cumulative effect. Around 25 years, a distinct step increase appears in both curves, corresponding to the first major rehabilitation cycle. These “step jumps” reoccur at 50 years and 75 years, reflecting periodic rehabilitation interventions.

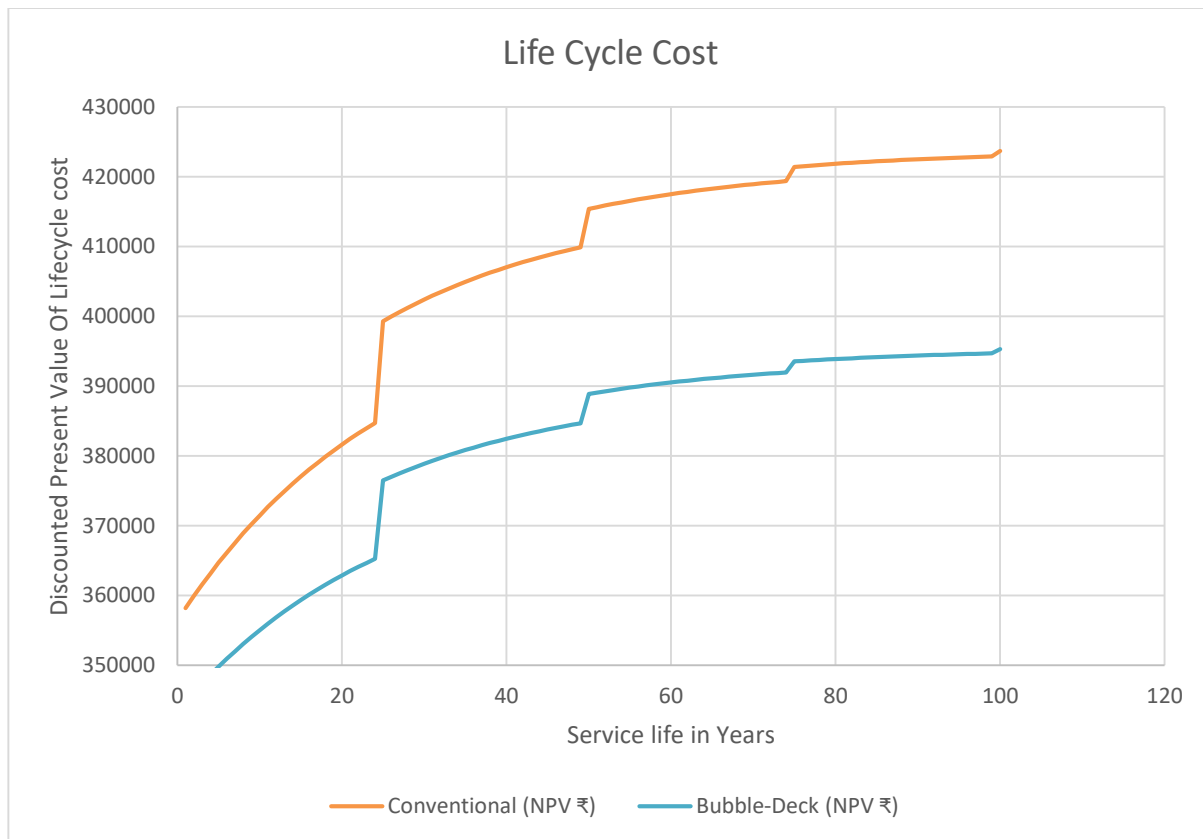


Figure No.1 Life Cycle Cost

Despite these cost increases, the Bubble-Deck curve consistently remains below the conventional slab curve throughout the entire service life range. This trend clearly indicates a lower total cost of ownership for the Bubble-Deck system. The cost difference widens gradually with time—from approximately ₹10,000 at 25 years to ₹26,000 by 50 years—showing that the relative advantage of the Bubble-Deck system strengthens as the structure ages. This widening gap is due to compounding savings from reduced maintenance and lower rehabilitation expenses; both discounted over time.

The smoothness of the Bubble-Deck curve between rehabilitation points suggests that its lower maintenance needs produce more stable cost growth. In contrast, the conventional slab exhibits slightly steeper increases, indicating higher recurrent expenses. Overall, the graph confirms that Bubble-Deck slabs not only provide initial cost savings but also ensure improved cost-efficiency and sustainability over their entire service life.

6. UNDISCOUNTED CUMULATIVE COST OR SHOW ANNUALIZED EQUIVALENT COST

The lifecycle performance analysis evaluates both the undiscounted cumulative cost and the annualized equivalent cost of the two slab systems over a 100-year service life. The same economic assumptions were applied as in the previous discounted analysis — with initial costs of ₹370,707 for the conventional slab and ₹357,203 for the Bubble-Deck slab, annual maintenance rates of 0.5% and 0.4%, and rehabilitation events occurring every 25 years costing 10% and 8% of the initial cost respectively.

In the undiscounted cumulative lifecycle cost, all future expenditures are simply summed without applying a discount rate. This approach shows the raw, unadjusted accumulation of cost over time. As the years progress, costs increase due to annual maintenance and the periodic rehabilitation events that occur every 25 years. Despite this upward trend, the Bubble-Deck system consistently exhibits a lower cumulative cost because of its smaller initial cost and lower recurring maintenance burden. At 25 years, the total cumulative cost for the conventional slab is approximately ₹498,271, compared to ₹457,038 for the Bubble-Deck slab — a difference of about ₹41,000. By 50 years, this gap widens to nearly ₹72,700, showing that the cost advantage of the Bubble-Deck system grows with time.

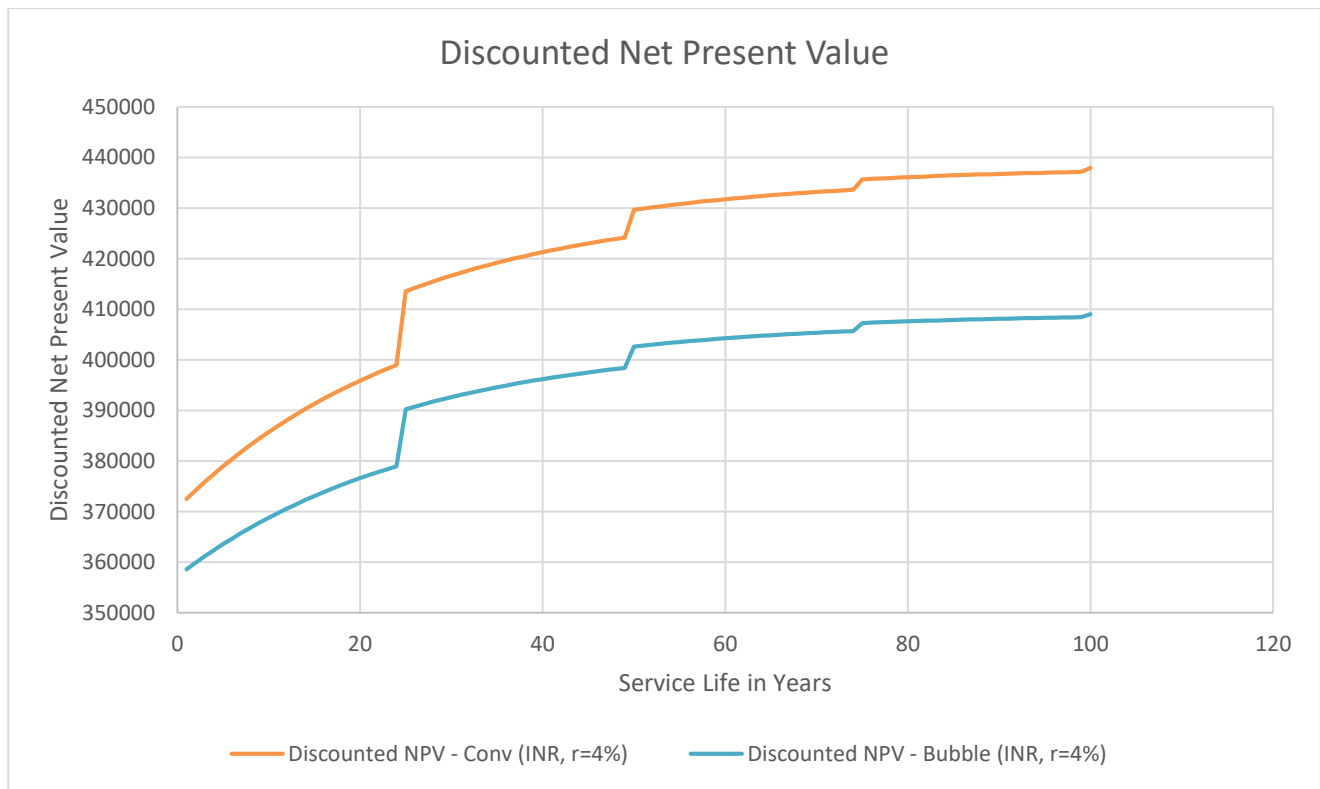


Figure No.2 Discounted Net Present Value

The annualized equivalent lifecycle cost analysis, on the other hand, expresses the total cost of ownership as a uniform annual expense — equivalent to the average cost per year over the structure's lifespan. This measure allows a fair comparison between alternatives that might have different service lives or cost patterns. In this case, the annualized cost for the conventional slab starts higher and declines gradually over time as the total costs spread over more years. The Bubble-Deck slab maintains a slightly lower annualized cost throughout. For example, at 25 years, the annualized cost is ₹19,953 per year for the conventional system and ₹19,037 per year for the Bubble-Deck slab; by 50 years, these values drop to ₹19,055/yr and ₹17,931/yr, respectively.

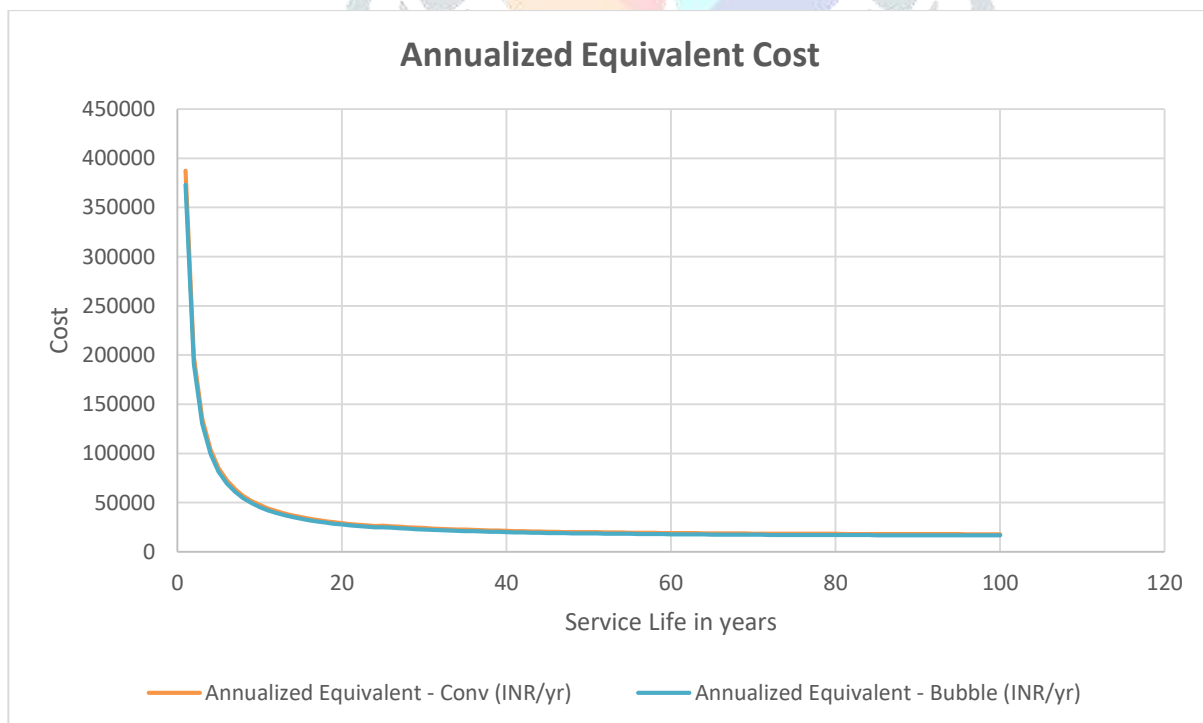


Figure No.3 Annualized Equivalent Cost

The Undiscounted Cumulative Lifecycle Cost graph shows two rising curves — one for the conventional slab and one for the Bubble-Deck slab — that increase with time. The slope of each curve reflects the accumulation of maintenance and rehabilitation costs. Distinct step jumps are visible at years 25, 50, and 75, corresponding to the scheduled rehabilitation events. Throughout the entire 100-year horizon, the Bubble-Deck curve lies below the conventional curve, indicating that the total expenditure for Bubble-Deck remains lower at every stage. The gap between the two curves widens over time, confirming that even small annual and periodic cost differences compound into significant savings in the long run.

The Annualized Equivalent Cost graph presents a different visual pattern — both curves start higher in the early years and gradually flatten as the costs are distributed over a longer period. The Bubble-Deck curve consistently remains below the conventional

slab's line, illustrating that it delivers lower average yearly costs throughout the slab's lifecycle. The reduction is modest but steady, representing cumulative benefits from reduced material quantities, minimized maintenance, and lighter dead load leading to longer service performance without major deterioration. The curves eventually converge slightly beyond 75 years, implying that after multiple rehabilitations, both systems' total expenses stabilize, though the Bubble-Deck still maintains a measurable advantage.

7. CONCLUSIONS

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.

Productivity Analysis

- Productivity comparison across parameters (manpower, time, material handling, and quality control) reveals:
- Manpower: 2.18× higher for Bubble Deck during manual assembly.
- Time: Shorter concrete pouring time (1.02 vs. 1.46 days).
- Material Handling: Simplified logistics due to lower volume and load.
- Quality Control: More structured when using prefabricated modules.
- The Radar chart effectively compares these parameters, showing improvement in efficiency, quality, and sustainability despite increased initial labour inputs.

Cost–Benefit Analysis

- Initial costs are slightly higher due to plastic void formers and skilled labour needs, but savings in concrete, steel, and foundation volume offset these expenses.
- Overall project cost for Bubble Deck is approximately 3–5% lower than the conventional slab.
- Long-term operation and maintenance costs are reduced due to better durability and less material degradation.
- A stacked bar or pie chart can visually display cost distribution—materials, labour, equipment, and long-term maintenance—showing the Bubble Deck’s overall economic advantage.

Life-Cycle Performance

- Lifecycle analysis (LCCA) indicates that although initial cost differences are modest, cumulative cost savings grow steadily over time.
- The Net Present Value (NPV) and Equivalent Annual Cost (EAC) curves demonstrate lower long-term ownership cost for the Bubble Deck slab.
- The lighter structure reduces rehabilitation frequency, energy consumption, and maintenance expenditure, enhancing service life performance.
- A trend line of cost vs. service life graphically represents how Bubble Deck’s total cost remains below the conventional slab as service years increase.

Discussion of Overall Economic and Practical Implications

- The Bubble Deck slab system delivers an optimal balance of structural performance, sustainability, and cost-efficiency.
- It is particularly advantageous for large-span, multi-storey, and green-certified buildings, where long-term savings outweigh initial complexity.
- Economically, it reduces total material and foundation costs, while environmentally, it supports circular economy principles by using recycled plastic voids.
- Practically, its successful implementation depends on trained labour or prefabricated production techniques for efficient site execution.
- Overall, the Bubble Deck slab emerges as a technically sound and economically viable innovation for sustainable construction, combining strength, efficiency, and reduced environmental impact in one integrated system.

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