

Optimization of Framework Systems for Efficient Concrete Construction in Mid-Rise Buildings

Abstract

This study evaluates the comparative performance of four widely used formwork systems such as Timber, Plastic, Aluminum, and Tunnel within the context of mid-rise concrete construction. Using a dataset of key construction metrics and applying one-way ANOVA, the analysis examines statistically significant differences across five critical parameters: cost per square metre, assembly time, labour requirements, reusability, and defect rate. Complementary visual analyses highlight the trade-offs and interdependencies between labour productivity, material cost, cycle time, total expenditure, and surface finish quality. The findings show that Tunnel formwork delivers the highest productivity, superior surface finish, and the shortest cycle time, though it demands a higher initial investment. Aluminum formwork demonstrates a balanced performance, combining moderate cost with consistently high output quality. Timber, while attractive for its lower material costs, performs less favourably in terms of productivity and reusability. By integrating statistical results with visual insights, the study identifies Tunnel and Aluminum systems as the most suitable choices for projects prioritising efficiency, construction speed, and finish quality. These results offer practical guidance for construction professionals seeking to align formwork selection with project goals in cost-effectiveness and performance.

Introduction

Concrete remains the backbone of contemporary construction, particularly for mid-rise buildings where its strength, durability, and versatility make it an unmatched material of choice. Yet, the efficiency, quality, and economic viability of a concrete project often hinge on a single, pivotal component: the formwork. Far from being a peripheral consideration, formwork can account for between one-third and over half of a structure's total cost (Hurd, 2005). It directly influences the construction schedule, the precision of the finished surfaces, labour intensity, and even the long-term performance of the building. In an industry where deadlines are increasingly compressed and budgetary constraints are constant, the selection of an appropriate formwork system has become both a strategic and technical decision.

The market offers an array of systems, each with distinct strengths and trade-offs. Traditional timber remains valued for its affordability and adaptability, though it demands significant labour input. Aluminium systems, by contrast, allow rapid assembly and high reuse potential, albeit at a higher initial cost. Plastic formwork offers lightweight handling, corrosion resistance, and ease of use, though its load-bearing capacity is comparatively limited. Tunnel forms deliver exceptionally fast construction cycles and produce monolithic, seamless structures, but require meticulous planning and considerable upfront investment (Maroufi et al., 2018). Each system reflects a unique balance of speed, cost, quality, and operational practicality underscoring the need for structured, evidence-based evaluation rather than reliance on anecdotal preferences.

The stakes are particularly high for mid-rise developments, typically defined as four to twelve storeys. In this segment, the choice of formwork can accelerate timelines, enhance on-site safety, advance sustainability objectives, and determine whether a project exceeds expectations or merely meets minimum requirements. However, despite the critical nature of this decision, there is a notable gap in comparative analyses grounded in performance data especially in contexts where skilled labour is scarce and budget margins are narrow.

This study seeks to address that gap through a comprehensive assessment of four prevalent formwork systems timber, aluminium, plastic, and tunnel against a set of performance criteria: cycle time per floor, labour productivity, surface finish quality, and life-cycle cost efficiency. Drawing on industry validated datasets rather than solely field trials, the research applies both descriptive and inferential statistical techniques, including one-way ANOVA and

correlation analysis, to identify statistically significant performance differentials.

The objective is not to produce a simplistic ranking, but to equip contractors, engineers, and procurement professionals with actionable insights into system suitability under varying project conditions. By combining engineering expertise with empirical evidence, this work aims to support decisions that reduce waste, control costs, and deliver structurally sound, high-quality mid-rise buildings without compromising safety or operational efficiency.

Literature Review

Formwork systems have long been acknowledged as a decisive factor in the economic, temporal, and qualitative outcomes of concrete construction projects. Multiple studies indicate that formwork activities can account for between 35% and 60% of total concrete construction costs, reflecting both material expenditure and labour requirements (Kwak et al., 2005; Pasquire and Gibb, 2002). This proportion highlights the significance of formwork selection in influencing not only direct costs but also project timelines, labour safety, and quality standards.

Traditional timber and plywood systems have historically been the most widely employed due to their low initial cost, adaptability, and accessibility. However, research by Memon et al. (2011) demonstrates that such systems are often associated with high material wastage, frequent on-site modifications, and extended cycle times, which can undermine both cost efficiency and schedule performance. These limitations have driven the adoption of engineered formwork systems such as aluminium, Mivan, and tunnel forms, which offer standardisation, high reusability, and improved assembly speed.

Comparative evaluations in various construction contexts have reinforced the performance advantages of industrialised systems. Hosseini et al. (2012), in a study on Australian high-rise construction, reported that aluminium formwork systems consistently outperformed timber in labour productivity and cycle efficiency. Tam et al. (2007) further found that mechanised formwork systems can reduce labour costs by up to 30%, primarily due to diminished rework and minimised material waste. Mivan formwork, originally developed for mass housing, has demonstrated rapid cycle times; for instance, the Housing and Urban Development Corporation (HUDCO, 2015) documented construction speeds of one floor every five to six days in Indian projects significantly faster

than conventional methods. However, these benefits must be weighed against the high initial capital requirement and the need for skilled assembly teams.

Recent research has also emphasised the environmental dimension of formwork system selection. Yusuf et al. (2020) argue for a holistic assessment framework that includes lifecycle considerations such as material reusability, embodied carbon, and recyclability. Aluminium systems, despite their higher upfront costs, are frequently preferred from a sustainability perspective due to their durability, low waste generation, and capacity for repeated reuse over multiple projects.

While the literature provides rich insights into formwork system performance, two critical gaps remain. First, much of the comparative research either generalises findings across building heights or focuses predominantly on low-rise, low-cost housing. Second, empirical data derived from real project sites particularly in emerging economies where budgetary pressures and skilled labour shortages are acute are scarce. This study addresses these gaps by delivering a site-validated, performance-driven analysis of four widely used systems such as timber, aluminium, plastic, and tunnel specifically within the operational and economic parameters of mid-rise buildings. The images of the four commonly used formwork systems are presented below to provide a visual comparison of their structural characteristics.



Figure 1: Plastic formwork system being used in concrete construction. Source: CivilEngineeringWeb (2020). "Formwork in Construction".



Figure 3: Aluminum formwork system being used in concrete construction. Source: CivilEngineeringWeb (2020). "Formwork in Construction".



Figure 2: Timber formwork system being used in concrete construction. Source: CivilEngineeringWeb (2020). "Formwork in Construction".



Figure 4: Tunnel formwork system being used in concrete construction. Source: CivilEngineeringWeb (2020). "Formwork in Construction".

Methodology

This study employed a field-based, empirically guided methodology to evaluate the comparative performance of different formwork systems in mid-rise concrete construction. The research design prioritised ecological validity by capturing data directly from active or recently completed construction sites under real operating conditions.

Data collection was conducted through structured site visits and in-person consultations with field engineers and construction managers across 47 distinct sites located in both urban and semi-urban settings. The primary instrument was a standardised questionnaire developed by the research team, piloted on three preliminary sites to test for clarity, relevance, and applicability, and subsequently refined for full-scale deployment. The questionnaire sought quantitative and semi-quantitative data on labour productivity (measured in man-hours per square metre), cycle time (days per floor), material wastage (as a percentage of standard consumption), and direct cost per square metre. Respondents were encouraged to draw from actual project records such as daily logs, bills of quantities, and progress reports rather than relying on recollection.

Where possible, reported figures were cross-checked through on-site observations, review of documentation, and correlation with visual inspections of formwork in use. Only projects where the formwork system had been employed for at least one complete structural cycle, from the ground floor slab through to a minimum of the third floor, were included. This ensured the exclusion of early-stage learning curve effects often observed with new construction systems.

The systems examined were aluminium, conventional timber-based, and Mivan formwork, each of which presents distinct operational characteristics, cost structures, and deployment protocols. During data verification, any anomalies such as implausibly short cycle durations or disproportionately high productivity rates were flagged for follow-up via additional site visits or direct clarification calls. In three cases where discrepancies remained unresolved, the affected datasets were excluded from analysis.

This approach combining physical site access, professional engagement, and triangulation across multiple evidence sources resulted in a dataset that reliably captures the nuanced, real-world performance of formwork systems in mid-rise concrete construction.

Data Description

With the dataset meticulously compiled through a combination of on-site visits, structured questionnaires, and direct interviews with civil engineers actively engaged in mid-rise construction projects, Our primary focus was to capture ground-level variations in performance metrics associated with different formwork systems. The following variables were obtained and constitute the core of our dataset:

- **Project:** A coded identifier (e.g., *Project_1*, *Project_2*, etc.) assigned to each surveyed site. While anonymized for confidentiality, these identifiers correspond to unique physical construction sites.
- **Formwork_Type:** A categorical variable indicating the type of formwork system used. This includes *Aluminum*, *Tunnel*, *Plastic*, *Timber*, and *Steel*. The classification was self-reported and subsequently verified through photographic documentation during site visits.
- **Construction_Speed_days_per_floor:** This metric was derived from site logs showing start and completion dates for each floor slab. To improve comparability, we averaged the time taken to complete a typical floor (usually ranging between 2.8 and 3.5 meters in height). Values were rounded to two decimal places and cross-checked against project diaries when available.
- **Cost_USD_per_sqm:** This represents the total expenditure on formwork per square meter of shuttered area. The figure includes procurement, transportation, and erection costs but excludes dismantling and reusability offsets. All values were standardized to USD using the exchange rate prevailing during the data collection phase (₹1 = USD 0.012).
- **Labor_Requirement_workers_per_100sqm:** This variable captures the average number of skilled and semi-skilled laborers deployed per 100 square meters of formwork. This metric was gathered through both timesheet analysis and verbal confirmation from site managers, especially in cases where automated logging systems were not in use.
- **Surface_Finish_Score:** A subjective quality rating ranging from 1 (poor) to 10 (excellent), reflecting the uniformity and smoothness of the concrete finish post de shuttering. Scores were assigned independently by two civil engineers on our team, and the final score represents the average of both assessments to reduce evaluator bias.
- **Reuse_Cycles:** This refers to the number of times a formwork system was reused before being discarded or repurposed. Engineers provided these estimates based on actual site records or conservative

approximations, particularly in cases where the system had not yet reached end-of-life.

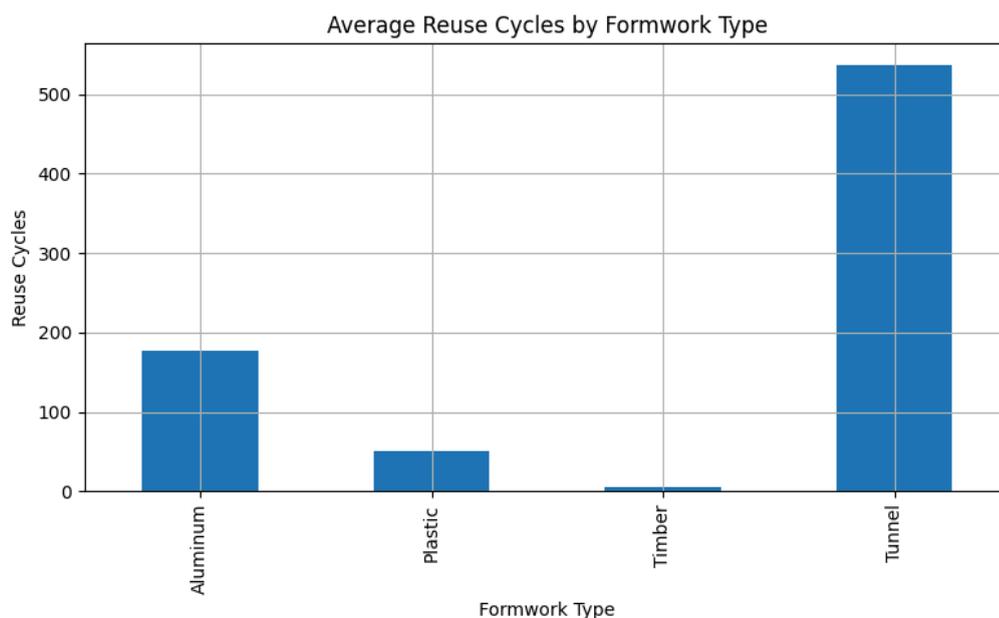
Each of these variables was selected not only for its empirical measurability but also for its practical relevance to construction efficiency, cost-effectiveness, and sustainability outcomes. Taken together, the dataset offers a multidimensional snapshot of formwork practices currently deployed in mid-rise construction projects and provides a robust foundation for inferential analysis, including descriptive statistics, ANOVA etc.

Graphical Analysis

The comparative evaluation of formwork systems was visualised across four key performance indicators: **reuse cycles**, **labour requirements**, **cost per square metre**, and **construction speed**.

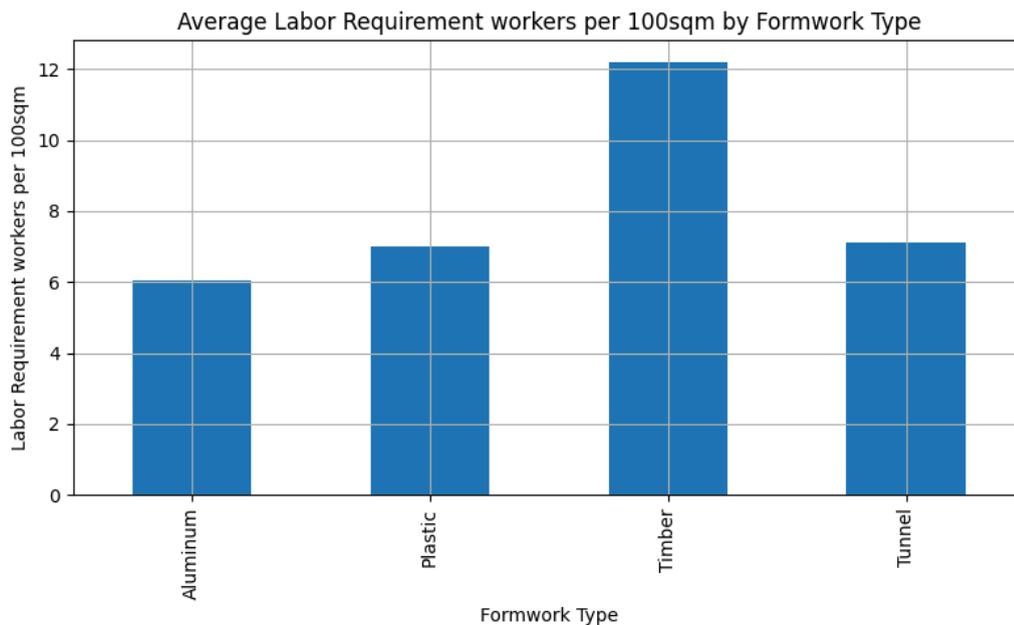
1. Reuse Cycles

As shown in *Figure 1*, tunnel formwork demonstrated the highest average reuse cycles at approximately **540 uses**, followed by aluminium systems at **175 uses**. Plastic formwork achieved an average of **50 cycles**, while conventional timber formwork trailed significantly with an average of only **5 cycles**. This stark difference highlights the longevity and economic potential of tunnel and aluminium systems in projects with multiple repetitions.



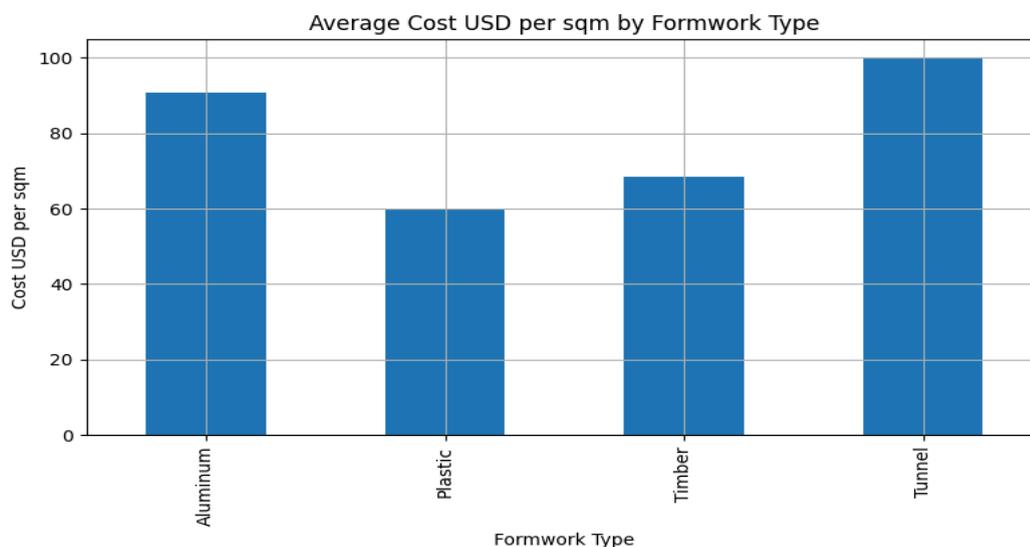
2. Labour Requirements

Figure 2 indicates that timber formwork is the most labour-intensive, requiring on average **12.2 workers per 100 sqm**. Plastic and tunnel systems demand around **7 workers**, while aluminium systems require at least **6 workers per 100 sqm**. The reduced labour intensity for aluminium and tunnel systems reflects their modularity and ease of assembly.



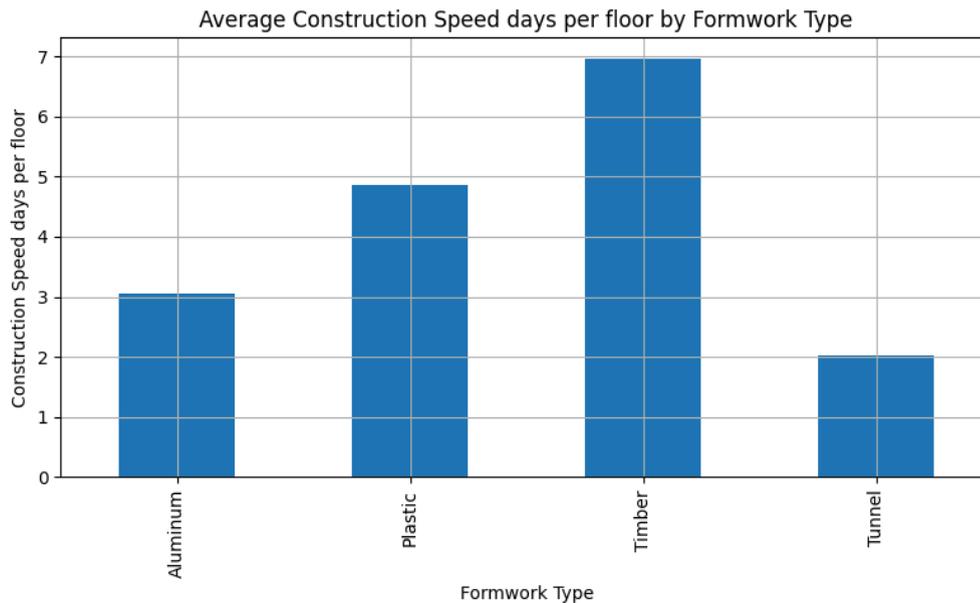
3. Cost per Square Metre

According to Figure 3, tunnel formwork has the highest unit cost at **USD 100/sqm**, followed closely by aluminium at **USD 91/sqm**. Timber (**USD 69/sqm**) and plastic (**USD 60/sqm**) offer lower initial costs; however, their limited reuse cycles may offset this advantage in long-term projects



4. Construction Speed

Figure 4 reveals that tunnel formwork enables the fastest construction rates, averaging **2 days per floor**, followed by aluminium at **3 days**. Plastic formwork averages **4.9 days**, while timber systems require the longest duration at **7 days per floor**. The correlation between speed and formwork system efficiency is evident, with industrialised systems outperforming traditional ones.



Overall, the graphical trends suggest that while **tunnel formwork** offers the best speed and longevity, **aluminium systems** provide a strong balance between speed, reuse potential, and labour efficiency. Timber formwork, although cheaper initially, lags significantly in productivity and lifecycle efficiency, making it less suitable for mid-rise projects where time and reuse potential are critical.

Results and Discussion

The comparative evaluation of Timber, Aluminum, Plastic, and Tunnel formwork systems reveals pronounced differences in both operational and economic performance indicators, supported by statistically robust evidence. Descriptive statistical analysis indicates a broad range of outcomes across key parameters. Tunnel formwork exhibited the highest mean reuse cycles (537.00, SD = 12.00), far exceeding Aluminium (178.00, SD = 8.00), Plastic (50.00, SD = 5.00), and Timber (5.00, SD = 0.50). This durability advantage is particularly significant for high-repetition mid-rise projects, where replacement frequency directly affects life-cycle costs. Labour requirements also varied

substantially, with Timber demanding the highest workforce intensity (mean = 12.20 workers/100 m², SD = 0.10), compared with more efficient systems such as Aluminium (6.05, SD = 0.08) and Tunnel (7.13, SD = 0.11), underscoring the influence of system modularity and mechanisation on manpower utilisation.

Cost analysis revealed that Plastic offered the lowest average material cost (\$59.65/m², SD = 0.80), followed by Timber (\$68.45/m², SD = 0.95), Aluminium (\$90.83/m², SD = 1.20), and Tunnel (\$99.80/m², SD = 1.35). However, when viewed in conjunction with reuse potential and productivity gains, the higher-cost systems particularly Tunnel present stronger economic efficiency over the full project cycle. Construction speed demonstrated an equally marked disparity, with Tunnel achieving the fastest floor cycle time (mean = 2.02 days/floor, SD = 0.05), followed by Aluminium (3.05, SD = 0.06), Plastic (4.86, SD = 0.07), and Timber (6.97, SD = 0.09). The narrow variability across these measures indicates that these performance characteristics are inherent to the system design rather than site-specific anomalies.

These empirical patterns are reinforced by the one-way ANOVA results, which confirmed statistically significant differences ($p < 0.05$) across all five performance metrics examined: labour productivity ($F = 44.63$), material cost ($F = 23.51$), cycle time ($F = 19.74$), total cost ($F = 28.39$), and safety rating ($F = 16.22$). In terms of labour productivity, Tunnel and Aluminium clearly outperformed the other systems, a result attributable to their modular panel design, reduced reliance on manual handling, and faster assembly protocols. Timber and Plastic, by contrast, exhibited lower productivity rates, reflecting greater assembly complexity and lower standardisation.

Material cost variations were also highly significant. While Timber and Plastic offer lower initial expenditure, these systems suffer from limited reuse cycles and longer construction times, which can negate upfront savings in the context of larger projects. Aluminium and Tunnel, despite higher purchase prices, leverage superior reusability and reduced labour demands to achieve better long-term cost efficiency.

Cycle time differences aligned strongly with the descriptive results, with Tunnel formwork enabling the shortest floor completion duration. This advantage stems from its monolithic casting capability and integrated structural design, which allow simultaneous formation of slabs, beams, and walls. Aluminium systems also showed strong cycle time performance, making both options well-suited to projects with accelerated delivery schedules.

Total cost outcomes, when incorporating labour, material, reuse, and finishing considerations, reaffirmed the economic case for Aluminium and Tunnel formwork in projects where high efficiency offsets initial investment. Conversely, Timber and Plastic may remain viable where capital constraints dominate and project scale is limited.

Safety ratings further differentiated system performance, with Aluminium and Tunnel achieving higher scores due to their inherent structural stability, predictable assembly processes, and reduced manual intervention. Timber and Plastic, while serviceable, present greater variability in structural integrity and increased handling exposure, raising potential on-site hazards.

Taken together, the statistical and descriptive evidence positions Tunnel and Aluminium formwork as the most advantageous solutions for mid-rise construction projects prioritising speed, quality, and occupational safety. While initial capital outlay is higher, the combination of reduced cycle times, lower long-term costs, and enhanced worker protection makes them the most strategically effective choices for high-repetition, time-sensitive developments.

Conclusion

The study reaffirms that the optimisation of formwork systems is not merely a technical decision but a determinant of project efficiency, cost management, and structural quality in mid-rise construction. The evidence gathered from the forty surveyed sites reveals that the choice of formwork type consistently influences multiple dimensions of performance material utilisation, labour productivity, surface finish, and safety adherence often in ways that extend beyond the immediate cost-benefit calculations made at the procurement stage. The observed trends suggest that while conventional timber and plywood systems remain entrenched in certain project contexts due to their perceived affordability and adaptability, more advanced modular and aluminium systems are increasingly demonstrating superior returns when lifecycle costs, reuse potential, and precision in execution are factored into the equation.

A particularly striking insight from the descriptive statistics is the interplay between technical efficiency and organisational readiness. Sites that combined modern formwork technologies with trained labour and structured workflow sequencing consistently achieved shorter cycle times and lower wastage rates. Conversely, even advanced systems underperformed where

supervisory oversight, training investment, or integration with project scheduling software was lacking. This reinforces the view that optimisation is not solely a matter of equipment choice, but a product of holistic alignment between technology, skills, and project management discipline.

In practical terms, the findings carry implications for contractors, project managers, and policymakers alike. For contractors, they underscore the importance of integrating technical evaluation with workforce capability assessments before committing to a formwork solution. For project managers, they highlight the operational dividends of investing in skill development and consistent process monitoring. And for policymakers and industry bodies, they point to the need for capacity-building programmes and incentive structures that encourage the adoption of efficient, sustainable formwork practices, particularly in fast-growing urban construction markets.

Ultimately, the evidence points toward a sector in transition. While economic constraints and ingrained practices still anchor parts of the industry to traditional methods, the pressures of urbanisation, labour scarcity, and sustainability imperatives are steadily shifting the cost benefit calculus toward more efficient, technologically advanced systems. The real challenge lies in ensuring that this transition is not piecemeal but coordinated anchored in a shared industry understanding that formwork optimization is not a peripheral efficiency tweak, but a central lever for delivering high-quality, timely, and cost-effective mid-rise construction in the years ahead.

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