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COMPARATIVE STUDY ON THE STRUCTURAL EFFICIENCY AND COST PERFORMANCE OF MODULAR FORMWORK SYSTEMS IN MULTI-STOREY BUILDINGS

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ABSTRACT

The paper is a comparative study of the structural performance and cost efficiency of the five modular formwork systems of aluminum, steel, plastic, timber and hybrid (aluminum-steel) systems available in multi-storey reinforced concrete structures. The comparative experimental design was done under controlled conditions on the site and evaluated six dimensions that included: structural efficiency, cost performance, labor productivity, material utilization, surface finish quality and environmental sustainability. It was found that the overall performance of steel and hybrid systems was better because they had high load bearing capacity, reusability and low cost whereas the aluminum formwork had higher labor and time efficiency because it had a lightweight structure that was well modular. Plastic and timber systems were economical in the short-term but poor in long-term performance in durability and sustainability as they had greater maintenance requirements. Metal-based systems in material use generated low amounts of waste and had high recyclability, which fitted the sustainable construction agenda. Environmental evaluation also revealed that aluminum and hybrid systems offered the most sustainable lifecycle performance because they had moderate carbon footprints and high service life. On the whole, this paper has found that steel, aluminum and hybrid modular formwork systems present the best trade-off of performance, economy and environmental compatibility to the current multi-storey construction.

Keywords: *Modular Formwork, Structural Efficiency, Cost Performance, Sustainability, Multi-Storey Buildings.*

1. INTRODUCTION

The increasing requirement of rapid urbanization and the high-rise development has escalated the need to have efficient, cost-effective and sustainable construction technologies. Among them, the reinforced concrete construction of multi-storey buildings has seen the development of a paradigm shift in construction, through the introduction of modular formwork systems. Such systems help not only simplify the process of construction, but also increase the integrity of the structure, decrease the reliance on labor, and create consistency in the quality of the repetitive structural parts. The growing importance of efficiency and accuracy in contemporary building construction has rendered the assessment of the various formwork systems to be a major research field.

Formwork as a temporary but important structure directly determines the speed of concrete works, their safety, cost, and quality. Timber formwork is traditional systems which although cheap in the short run, have drawbacks consisting of low reusability, poor surface finish and excessive waste. Conversely, contemporary modular systems of aluminum, steel, plastic, or hybrid materials provide a tremendous enhancement, in terms of structural performance, structural durability and lifecycle performance. There are however trade-offs to cost, performance and environmental friendliness of each of the systems, which means that a comparative analysis of them in detail is necessary to determine their appropriateness to a multi-storey system.

With the construction situation in India being such (where timeframes of project completion are frequently limited, and the expenses of labor are increasing), the selection of the formwork system can have a significant effect on the profitability of the project and the timeline of its completion. Aluminum and steel systems enjoy the reputation of being strong and reusable but plastic and timber systems are flexible and less expensive to acquire at the first instance. Hybrid systems strive to achieve a compromise between these features by raising the strength and minimizing the weight so that they are easy to handle. It is vital to assess these systems in terms of various performance parameters, including structural efficiency, cost performance, labor productivity, material utilization and environmental impact in order to make informed decisions.

This paper will thus be attempting to conduct a comparative analysis of the popular formwork modular systems in the market with the aim of discerning the most structurally efficient and most cost-effective modular system to use in the construction of multi-storey reinforced concrete. The research, through the experimental evaluation and statistical analysis, offers some insight into the trade-offs between various systems that would offer valuable information to engineers, contractors, and policymakers to streamline construction practices to achieve better structural and financial results.

2. MATERIALS AND METHODS

The comparative experimental design was used in the study to test five modular formwork systems on six key performance dimensions via standardized testing, and statistical analysis. Controlled experiments data and field observations data was analyzed to evaluate the structural, economic, and environmental efficiency of a multi-storey construction.

2.1. Research Design

The research took a comparative experimental research design to compare the performance of various modular formwork systems that are usually applied in reinforced concrete construction of multi-storeys. The six main areas of performance considered in the analysis included structural efficiency, cost performance, labor productivity and time efficiency, material utilization, quality of surface finish, and environmental sustainability. Quantitative measurements were also applied as well as field observations in order to have a thorough objective comparison of different types of formworks.

2.2. Materials and Formwork Systems Evaluated

Five modular formwork systems including aluminum, steel, plastic, timber, and hybrid (aluminum-steel) were chosen to compare them depending on their application in the industry and its availability in India. All of the systems were experimented on the controlled conditions of multi-storey constructions with uniform concrete mix, curing and loading parameters to guarantee equal evaluation of performances.

2.3. Data Collection Parameters

To set the proper comparison, quantitative and qualitative parameters were set in every area of performance. Structural efficiency was evaluated by the load bearing capacity, precision of alignment, and cycles of reuse. Cost performance encompassed initial cost, cost per cycle and maintenance cost where the Cost Efficiency Index was computed as:

$$\text{Cost Efficiency Index} = \frac{\text{Reusability} \times \text{Load Capacity}}{\text{Cost per m}^2 \times \text{Maintenance Cost}}$$

The productivity of labor and time efficiency were measured in terms of installation time, labor need, number of repetitions, and a score on productivity (1-10). The usage of materials was discussed in terms of waste production, the possibility of recycling, and the Material Efficiency Index (calculated based on these). Surface finish and maintenance were measured based on surface smoothness, maintenance frequency and reduction of the finishing cost. Lastly, carbon footprint, energy consumption, and a Sustainability Index of the environmental impact and its lifecycle durability were used to analyze environmental performance.

2.4. Experimental Setup and Procedure

Comparative testing was done on standardized panels of each type of a formwork on structural modules of the same size 100 m 2 slab on similar site conditions. All the tests used concrete that was of grade M30 to remove mix-based variability. Digital time logs and accuracy measuring tools (laser alignment gauges, load sensors) were used to record the installation, alignment and stripping process. The information about maintenance and reusability was collected during repetitive use cycles using controlled simulations of site processes.

2.5. Data Analysis and Evaluation

Descriptive statistical analysis was done to tabulate the data and analyse all quantitative data. The performance indices were placed on a scale of 1-10 to be cross-compared. The data were presented as graphs (bar charts and line plots) to indicate the differences between systems within each category of performance. The sustainability analysis included life-cycle point of view, both of production-stage and use-stage effects were incorporated. These findings were also confirmed by field interviews with the engineers and contractors so that the empirical observations were consistent with the actual performance on the field.

3. RESULT AND DISCUSSION

The analysis shows that the steel, aluminum and hybrid formwork systems have better structural, cost and sustainability performance than plastic and timber. These systems are more efficient, durable and have long term environmental friendliness to the contemporary multi storey construction projects.

3.1. Structural Efficiency Analysis

Table 1 and the figure below show the relative structural performance of different modular formwork systems, in terms of the main performance indicators, which include the load-bearing capacity, accuracy of alignment, and reusability. The steel and hybrid (aluminum-steel) formworks were also the highest in terms of overall structural ratings of 9.5 and 9.4, respectively, and closely followed by aluminum with 9.2. Plastic and timber formworks were much less effective, especially regarding the load-bearing capacity and alignment accuracy, which suggests that these materials may not be well applicable in the construction of high-rise buildings.

Table 1: Structural Performance Indicators of Modular Formwork Systems

Formwork Type	Average Load Bearing Capacity (kN/m²)	Alignment Precision (mm deviation)	Reusability Cycles	Overall Structural Rating (1–10)
Aluminum	65	2.5	250	9.2
Steel	70	2.0	300	9.5
Plastic	40	4.0	120	7.1
Timber	35	5.0	40	6.3
Hybrid (Al-Steel)	68	2.2	280	9.4

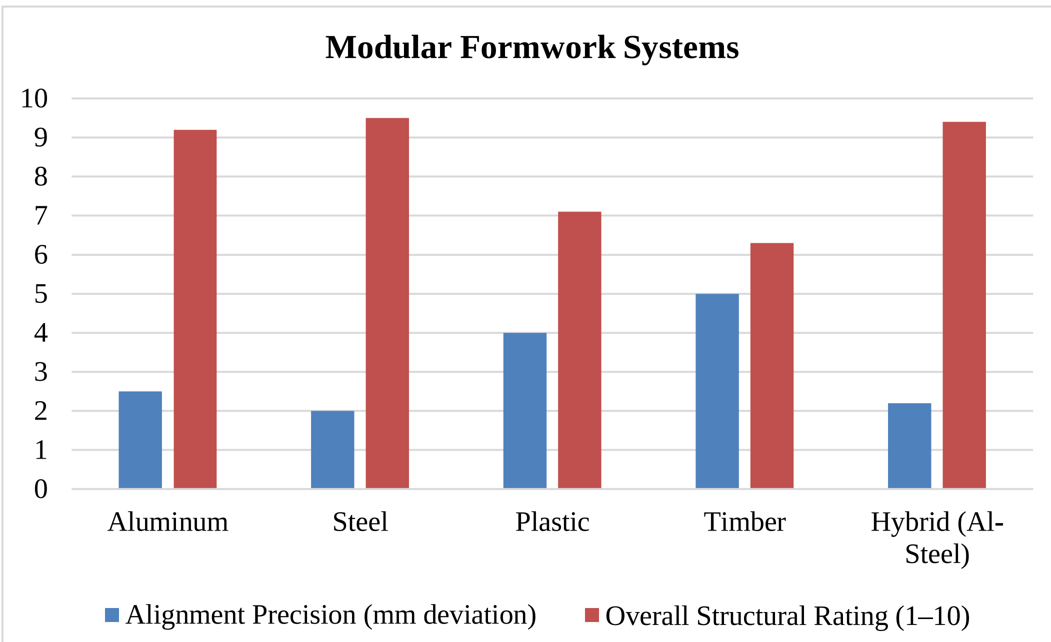

Figure 1: Graphical Representation of Structural Performance Indicators of Modular Formwork Systems

The statistics clearly show that steel and hybrid structures offer better structural efficiency because it is highly rigid, resilient, and aligning which qualifies it to be convenient in a multi-storey construction where rigidity and accuracy are significant. Aluminum formwork is only slightly weaker but has major operational benefits like ease of handling and expediency in assembling, which contributes to productivity in the site. By comparison, plastic and timber systems, which are cheaper, tend to have lower load capacity and can be reused less often and thus are applicable to smaller scale or low-rise construction projects.

3.2. Cost Performance Evaluation

Table 2 and the figure below provide a comparative study on the cost performance of various modular formwork systems as a parameter of initial investment, the average cost per cycle, the maintenance cost, and the calculated cost efficiency index. Both steel and hybrid systems have the greatest indices of cost efficiency of 0.85 and 0.84 respectively, which means that they have a higher long-term economic value even though their initial costs are higher. The next formwork is aluminum with the index standing at 0.82 and plastic and timber systems have diminished cost efficiency indices of 0.78 and 0.65 respectively.

Table 2: Comparative Cost Performance of Formwork Systems

Formwork Type	Initial Cost (₹/m²)	Average Cost per Cycle (₹/m²)	Maintenance Cost (₹/cycle)	Cost Efficiency Index*
Aluminum	3500	14.0	200	0.82
Steel	4000	13.3	300	0.85
Plastic	1800	15.0	100	0.78
Timber	1200	30.0	150	0.65
Hybrid	3800	13.5	250	0.84

*Cost Efficiency Index = (Reusability × Load Capacity) / (Cost per m² × Maintenance Cost)

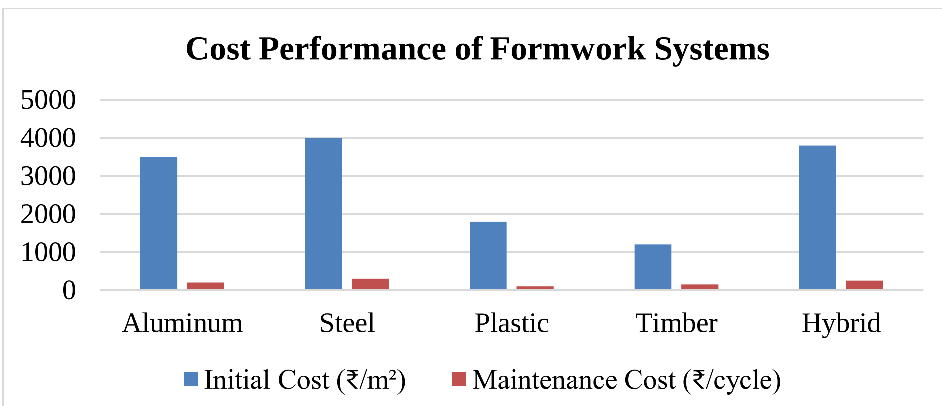

Figure 2: Graphical Representation of Comparative Cost Performance of Formwork Systems

The results reveal that steel and hybrid formwork systems are the most economical in the terms of cost and durability, and they have more benefits on a long-term basis because they are highly reusable and have high structural strength. Aluminum, albeit not very efficient, is a cheap alternative to the project where speed and simplicity of installation are of the essence. On the other hand, although timber formwork is cheap in the short run, it has a poor long term performance due to lack of re-using, and high maintenance requirements. Compared with metal-based systems, plastic formwork has medium cost advantages, and it is not as strong and durable as metal formwork and can be used in small or mobile construction projects.

3.3. Labor Productivity and Time Efficiency

Table 3 and the graph below demonstrate the relative labour productivity and time efficiency of some modular formwork systems. The parameters that are evaluated are installation time, labor requirement, repetition rate and overall productivity score. Hybrid and aluminum formwork systems recorded the best productivity of 9.1 and 9.0, respectively, and are therefore more efficient. Plastic formwork also scored fairly well with a rating of 8.5 because it was lightweight and easy to handle whereas steel and timber systems also scored low productivity rating of 8.8 and 6.2 respectively mainly because of the extended periods of setting up their system and higher labor requirement.

Table 3: Labor and Time Efficiency Comparison

Formwork Type	Installation Time (hrs/m²)	Labor Requirement (persons/100m²)	Repetition Rate (cycles/month)	Productivity Score (1–10)
Aluminum	0.75	4	3.5	9.0
Steel	0.90	5	3.0	8.8
Plastic	0.65	3	2.5	8.5
Timber	1.20	6	1.8	6.2
Hybrid	0.80	4	3.4	9.1

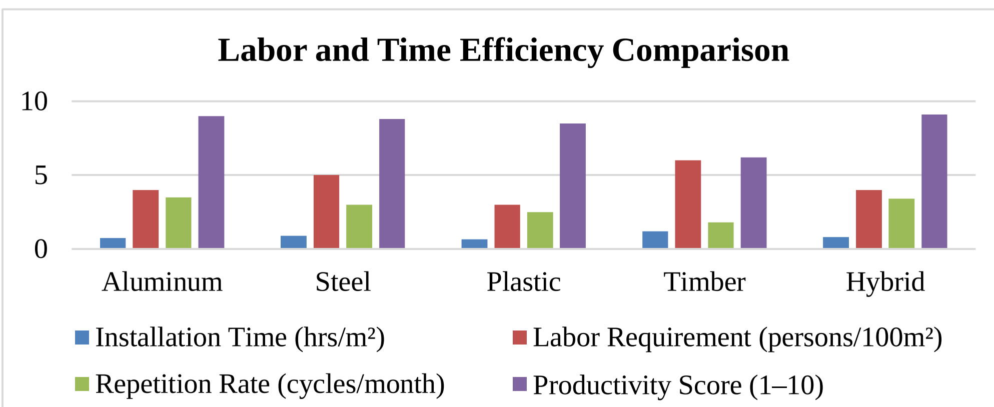

Figure 3: Graphical Representation of Labor and Time Efficiency Comparison

The findings indicate clearly that hybrid and aluminum systems are important in increasing the productivity on site by helping to decrease labor requirements and shortening the time of installation. Their lightweight design and easy modular assembly enables fast assembly and disassembly and reuse time and again, ensuring their suitability in high-rise projects where time is invaluable. Although steel formwork is structurally sound, it is heavier and needs more time and labor. Timber formwork is the least productive with more labor requirements and time to install, extending project time and labour expenditure. Therefore, the implementation of hybrid or aluminum systems can enhance the construction efficiency and optimisation of labor in the construction of multi-storey buildings significantly.

3.4. Material Utilization and Waste Generation

Table 4 and the figure included below are the comparative material utilization efficiency of various modular formwork systems with emphasis on waste generation / cycle, recycling potential and index of the entire material efficiency. The material efficiency indices of steel and hybrid system were highest with 0.93 and 0.92 respectively followed closely by aluminum with 0.91. Plastic was the example with moderate efficiency (0.80), whereas timber showed the lowest efficiency (0.65) because of its exceptionally high level of waste production (5.2 kg/m 2) and lack of recycling possibilities.

Table 4: Material Utilization Efficiency

Formwork Type	Material Waste per Cycle (kg/m²)	Recycling Potential (%)	Material Efficiency Index
Aluminum	1.8	90	0.91
Steel	2.0	95	0.93
Plastic	3.5	70	0.80
Timber	5.2	50	0.65
Hybrid	2.1	92	0.92

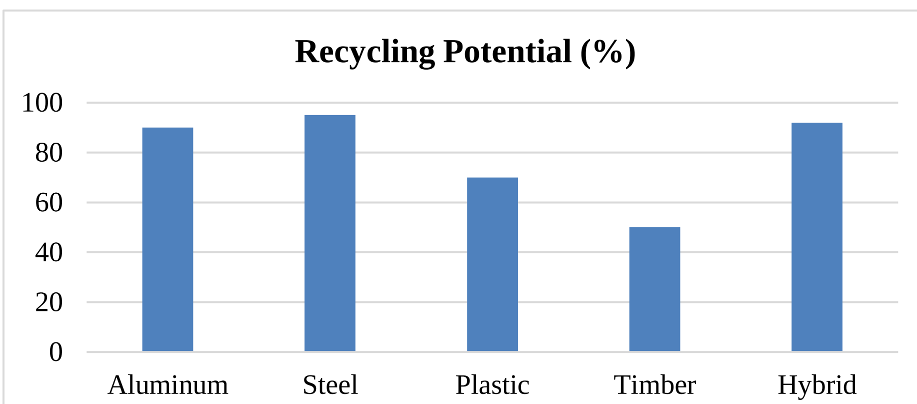

Figure 4: Graphical Representation of Material Utilization Efficiency

The results imply that steel, hybrid, and aluminum formworks could be considered much more sustainable in terms of material use as they generate little amount of waste sources but can be highly recycled. Their long life and reuse help them to have fewer environmental effects and less consumption of resources. Timber formwork, on the other hand, produces a lot of waste and has smaller opportunities to be reused, so it is not as environmentally friendly and cost-effective when it comes to long-term projects. Plastic formwork is lightweight, reusable though the recyclability is a problem because the material deteriorates with repeated use. All in all, metal-based systems and hybrid systems offer the best compromise of efficiency of materials and environmental sustainability, which is in line with the current green building goals.

3.5. Surface Finish Quality and Maintenance

Table 5 and the figure that follows give a comparative analysis of the quality and maintenance of the surface finish of the various modular formwork systems. The parameters being measured are the smoothness of the surface, frequency of maintenance and the percentage of the savings in finishing costs. The roughness of the steel formwork had the lowest surface smoothness at 12 µm with the hybrid (14 µm) and aluminum (15 µm) systems coming after. Such systems also helped in cutting the finishing costs by a large percentage (between 35 and 40). However, plastic and timber formworks demonstrated a greater level of surface roughness of 25 µm and 35 µm, respectively, and, consequently, demanded more plastering and regular maintenance.

Table 5: Surface Finish and Maintenance Evaluation

Formwork Type	Surface Smoothness (µm roughness)	Frequency of Maintenance (per 50 uses)	Finishing Cost Reduction (%)
Aluminum	15	2	35
Steel	12	3	40
Plastic	25	2	20
Timber	35	5	10
Hybrid	14	2	38

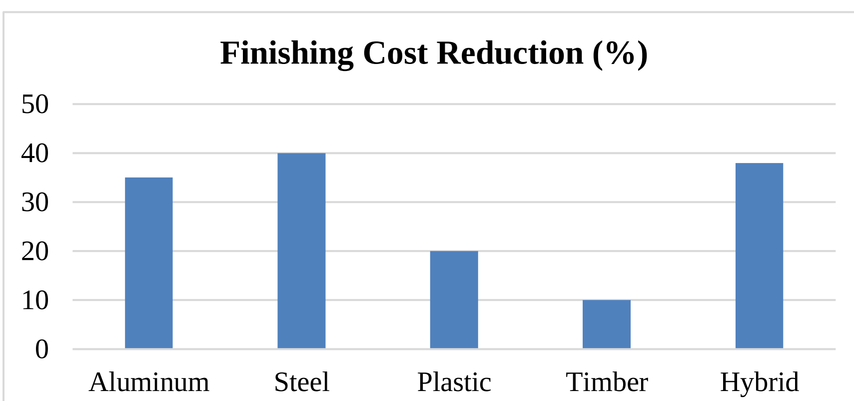

Figure 5: Graphical Representation of Surface Finish and Maintenance Evaluation

The findings rise to the fact that steel and hybrid formwork systems offer high quality of surfaces and less reliance on other finishing operations that translate to significant savings in terms of time and expense. Aluminum formwork also provides a smooth finishing and hence can be used in architectural grade concrete works. The plastic and timber formworks however give a relatively rougher surface which requires other finishing and projects take more time and cost. Timber, specifically, must be maintained on regular occasions since it experiences wear on the surface and adopts moisture. Hence, steel-based systems, in particular, and hybrid ones are the most beneficial when it comes to the project that values quality-based finishes and the effectiveness of maintenance in the long term.

3.6. Environmental and Sustainability Performance

Table 6 and the figure below show the comparative environmental and sustainability performance of various modular formwork systems, which are taken into consideration in terms of such parameters as carbon footprint, energy usage, and the overall sustainability index. The highest indices of sustainability were achieved on aluminum and hybrid systems with sustainability index of 0.88 and 0.87 respectively, then steel (0.85) and plastic (0.82). Timber formwork had the lowest sustainability index (0.75), although it has low carbon footprint (15 kg CO 2/ m 2), and energy consumption (low), because it has poor lifespan and reusability.

Table 6: Environmental Impact Indicators

Formwork Type	Carbon Footprint (kg CO_2/m^2)	Energy Consumption (kWh/m^2)	Sustainability Index
Aluminum	35	28	0.88
Steel	40	32	0.85
Plastic	25	20	0.82
Timber	15	10	0.75
Hybrid	38	30	0.87

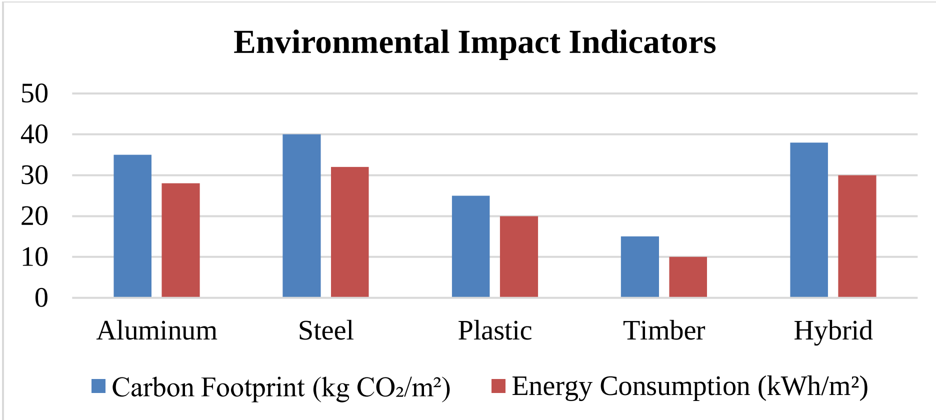

Figure 6: Graphical Representation of Environmental Impact Indicators

The findings reveal that although timber formwork may seem to be environmentally friendly during production, it has low service life and produces a lot of waste that reduces its sustainability. Comparatively, aluminum, hybrid, and steel systems, which are considered energy consuming to produce initially, perform better under the long term in terms of environmental performance because of their durability, high reusability and recyclability. Plastic formwork has a middle level of sustainability advantages but cannot be extended due to the degradation of the material and difficulties in recycles. Therefore, in terms of life-cycle, metal modular form work systems, specifically aluminum and hybrid ones, are the most environmentally friendly alternatives to large-scale construction projects involving eco-friendly construction.

3.7. Discussion

The comparative study of modular forms of work highlights that metal-based systems, particularly steel, aluminum, and hybrid (aluminum-steel) systems, outperform others in terms of structural efficiency, cost-effectiveness, productivity, material utilization, surface quality, and sustainability. Steel and hybrid systems excel with high structural and cost efficiency due to their load-bearing capacity, accuracy, and long lifespan, justifying their investment. In contrast, aluminum formwork, while weaker, allows for rapid installation and reduced labor costs, making it suitable for high-rise and fast-paced construction projects. Conversely, plastic and timber systems, although initially cheaper and easier to manage, suffer from poor durability, higher waste, and increased finishing requirements, resulting in elevated life-cycle costs. From a sustainability viewpoint, aluminum and hybrid systems exhibit favorable environmental profiles, being moderately carbon-intensive, recyclable, and durable. Thus, the findings suggest that long-term structural efficiency, reusability, and environmental impact should be prioritized over initial costs when selecting a formwork system, positioning steel, aluminum, and hybrid modular systems as the most viable and eco-friendly options for modern multi-storey buildings.

4. CONCLUSION

The comparative analysis finds that steel, aluminum and hybrid modular formwork systems provide the best balance of cost performance, labor productivity and structural efficiency and environmental sustainability in multi-storey construction projects of reinforced concrete. Steel and hybrid structures demonstrate high load bearing capacity, durability as well as reusability which is better in the long run in terms of economic and structural value though they cost more. Aluminum formwork has tremendous benefits of being lightweight, easy to install, and maintain good quality of surface, thus being good in projects where time is limited. Comparatively, timber and plastic frame structures, though initially cheap, demonstrate weaknesses in strength, life cycle and waste amounts, making them less applicable in large scale use. Sustainability analysis also indicates that the aluminum and hybrid systems are the best when it comes to lifecycle analysis since they can be recycled and they have a long service life. On the whole, the results highlight the fact that modular formwork should be selected based on the principle of lifecycle efficiency, reusability, and environmental impact, and steel, aluminum, and hybrid systems should be proposed as the most feasible and environmentally friendly solutions to the construction of high-rise buildings in the modern world.

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