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Research Article

Comparative Performance and Sustainability Assessment of 3D-Printed Concrete Railway Sleepers versus Conventional Sleeper Technologies

Abdulhasib Momand[1]*, Syed Zohaib Ali Shah[1], Hikmatullah Shaheen[1], Murad Ali[2]

[1] Department of Civil Engineering, University of Engineering and Technology, Peshawar, Pakistan
[2] Department of Civil Engineering, National University of Technology, Islamabad, Pakistan
* Correspondence: abdulhasibmomand11@gmail.com

Abstract

Railway infrastructure plays a vital role in transportation and economic development. One of the key components of railway tracks is sleepers, which provide stability, distribute loads, and ensure track alignment. Traditional railway sleepers, made from timber, reinforced concrete, or steel, often face challenges related to durability, cost, environmental impact, and production efficiency. This study explores the potential of 3Dprinted concrete railway sleepers as an innovative alternative to conventional manufacturing techniques. 3D concrete printing offers a promising solution by reducing material wastage, optimizing structural design, and enhancing production speed. This research compares structural performance, cost-effectiveness, and sustainability of 3Dprinted concrete sleepers with traditional methods. The study includes an analysis of mechanical properties, durability, and economic viability. Findings indicate that 3D printing technology can significantly reduce production time and material costs while maintaining or even improving the strength and longevity of railway sleepers. The results suggest that implementing 3D-printed concrete sleepers can enhance railway infrastructure efficiency, reduce environmental impact, and provide a more cost-effective solution for the industry.

Keywords: 3D Concrete Printing; Railway Sleepers; Additive Manufacturing; Sustainability; Infrastructure Engineering.

1. Introduction

Railway transport is one of the oldest public transportation modes and is widely used across the world. It supports a complex and integrated transportation system, beyond train movement [1]. It plays an important role in global industrialization, urbanization, and connectivity [2]. The railway sleepers are one of the critical parts of the railway infrastructure. It acts like a beam that is placed between the rails. The main function of sleepers is to maintain the railway gauge, to uniformly distribute the load to the ballast, and to support other components [3], [4]. Sleepers are classified into different types based on their materials. These are timber sleepers, concrete sleepers, steel sleepers, and composite sleepers [5]. Types have pros and cons, which depend on the durability, cost, maintenance, and load-bearing capacity of the railway infrastructure. Advances in technology have increased the sustainability of railway transportation. The advancement includes track innovation, an autonomous railway system, and energy efficiency [6]. Additive Manufacturing (AM), also known as 3D printing, is a process that produces three-dimensional objects layer by layer, placing the material.

AM possesses seven different types based on the material and the process. The extrusion method, also known as Fused Deposition Modeling (FDM) or Fused Filament Fabrication (FFF), is one of the most widely used AM techniques. FDM

is gaining momentum in the construction industry due to its cost-effectiveness, versatility, and ability to produce largescale infrastructure [7]. The maturity of the technology is evaluated by the technology readiness level (TRL), which reports the maturity of the FDM technique in the construction industry to the TRL6-TRL7 level [8].

Additive Manufacturing has its roots in the late 1970's and 1980's. 3D Printed Concrete (3DPC) is an innovative construction technique used across the world. The use of this technology and the reason behind this gaining momentum is the use of reduced waste materials, faster construction times, and the ability to produce unique designs with intricate details, including both off-site manufacturing of prefabricated panels and in-situ construction [9]. One of the promising applications of 3DPC is in railway infrastructure development, particularly in the manufacturing of railway sleepers, trackside structures, station components, and platform elements [10]. Traditional railway sleepers are manufactured from timber, steel, and concrete. 3D concrete printing offers an innovative alternative by eliminating the need for formwork and allowing for precise control over material properties. This method enables the fabrication of sleepers with optimized structural efficiency, reduced environmental impact, and lower production costs. With the rapid increase in additive manufacturing, railway sleepers are now manufactured by using 3DPC, which is an emerging innovation in railway infrastructure development [11]. The integration of 3DPC in railway infrastructure development could revolutionize the industry by improving sustainability, reducing carbon emissions, and ensuring faster production with enhanced durability.

3DPC is one of the innovative, emerging, and transformative approaches used in the construction industry, particularly in railway infrastructure development, due to its sustainability, cost effectiveness, durability, and ability to generate complex objects with intricate detailing. Traditional materials used for sleepers have been extensively used, but they have certain limitations and time constraints, and challenges [12], [13]. Railway engineers are now exploring sustainable materials and innovative solutions to overcome the traditional challenges, degradation, environmental concerns, high cost, corrosion, etc., leading to high maintenance for operations. The study [14] illustrated that there is a 3%-16 % increase in flexural strength and a 15%-48 % higher compressive strength in the perpendicular direction compared with the value in the lateral direction. The study [13] investigated cost comparison between conventional constructions and 3DPC, highlighting that the amount of material and cost are reduced using 3DPC. This technology reduced the construction waste, time requirement, and labor cost by 30% - 60%, 50% - 70%, and 40% - 80%, respectively [13], [14], [10] investigated that PLA (polylactic acid) reinforced in concrete structures increased their toughness and long-term durability. The study [11] found that using 3DPC in construction has a significant effect on human health, environmental quality, global warming, and resources. The study [5] found reinforcement strategies in 3DPC. In technological revolution and research, 3DPC has become a crutch in the modernization and sustainability of railway infrastructure.

Numerous numerical studies have been carried out, which highlight the dynamic response of railway sleepers. The study [12] highlights the hanging defect in the railway sleepers using Finite Element Models. It shows that hanging defect highly enlarges the dynamic response of hanged sleepers, which results in a higher sensitivity coefficient and hanged sleeper detection. The study [13] highlights structural health monitoring in transportation infrastructure. Creep strength is an important parameter in structural stability. A recent study found that fiber reinforcement generally improves creep stability in 3D-printing materials. The study highlighted the impact of prestressing loss on the structural performance of railway sleepers. The study found that the optimum concrete composition in railways significantly diminishes the vibrations in railway tracks [15].

3DPC has the potential to significantly enhance the performance of railway sleepers. Numerous studies have been carried out in the past that investigated the mechanical performance and durability of railway sleepers using traditional techniques. The study [6] highlighted the structural advantages and resilience that plastic fibers add to concrete sleepers, pointing out the complexity. It also highlighted the complex relationship between fiber orientation under pressure. The study highlighted that PLA (polylactic acid) reinforced in concrete structures increased their toughness and long-term durability. The study [16] investigated the structural performance of Ultra High-Performance Concrete (UHPC) with more focus on the cross-sectional area of sleepers. The bigger the cross-sectional area, the higher the load-bearing capacity of the sleepers. The study used a numerical investigation technique in the investigation of the load-bearing capacity of 3DPC at an early age, and time-dependent characteristics were also observed. Investigated the damage mechanism in the Railway Prestressed Concrete Sleeper. The sleeper's design is one of the primary causes of operation and status use. The study investigated the failure mechanism in 3D-Ultra High-Performance Concrete (3D-UHPC). The few studies have been carried out in comparison with 3D Printed Concrete Railway Sleepers compared to traditional techniques. In addition, additive manufacturing (3D Printing) has more advantages than traditional manufacturing, such as reduced waste generation, low manufacturing costs, and flexible manufacturing structures. Similarly, 3D printing has become an innovative and promising method [13].

The comparison fails to show the quantification of the importance of 3D Printed Concrete in railway sleepers. This paper focuses on the use of additive manufacturing in railway transportation infrastructure. Therefore, the main aim of this research is to investigate and compare the feasibility of 3DPC in railway infrastructure development, particularly in railway sleepers. The research will analyze mechanical properties, cost-effectiveness, and environmental impact, providing insights into whether 3D concrete printing can serve as a sustainable alternative for railway sleeper production.

2. Materials and Methods

2.1 Data Sources and Study Design

This study adopts a comparative research approach based on secondary data obtained from peer-reviewed publications, international standards, and technical reports related to railway sleeper performance. The objective is to evaluate and compare conventional sleeper technologies (wooden, plastic, and precast concrete sleepers) with emerging 3D-printed concrete sleepers using consistent reference benchmarks.

All mechanical, environmental, safety, and economic parameters presented in this paper were compiled from existing studies and standard specifications. No laboratory testing or full-scale experimental work was conducted as part of this research. The collected data were carefully screened to ensure relevance, reliability, and consistency with commonly accepted railway engineering practices. This approach allows a transparent and meaningful comparison of sleeper technologies while avoiding duplication of experimental work already reported in the literature.

The research methodology adopted in this study consists of the following stages.

2.1.2 Selection of Sleeper Types for Comparison

Several sleeper types were assessed during this study, including:

- Wooden sleepers
- Plastic (polymer composite) sleepers
- Conventional precast concrete sleepers
- 3D-printed concrete sleepers

These materials were selected because they represent widely used railway industry standards while also exhibiting varying attributes related to sustainability and safety performance [5], [8]. Details of the sleeper types, their material composition, and production methods are summarized in Table 1.

Table 1. Types of Railway Sleepers, Their Materials, and Production Methods [5], [8]

Sleeper Type	Material Composition	Production Method
Wood	Hardwood (e.g., oak, teak)	Sawing, pressure treatment
Plastic	Recycled HDPE, polymer blends	Injection molding
Conventional Concrete	Cement, sand, gravel, steel reinforcement	Casting in steel molds
3D-Printed Concrete	Cementitious mix, additives, recycled fines	Layered extrusion (3D printing)

The manufacturing of 3D printed sleepers depends on Portland cement, together with fine aggregates and recycled construction materials, and printing-specific chemical admixtures [13]. Pre-existing sleepers primarily consist of wood, together with plastics made from HDPE waste and reinforced concrete structures. Large-scale printing machines execute layer-by-layer extrusion for the manufacture of 3D printed sleepers as opposed to traditional cast, molded, and fabricated manufacturing processes [5], [17].

2.2 Safety Performance Assessment

The safety performance of railway sleepers was assessed using four primary indicators: load-bearing capacity, fatigue resistance, resistance to cracking, and fire performance. These indicators were selected because they directly influence track stability, operational safety, and service life.

The evaluation was carried out using reference values and performance ranges reported in previous numerical, experimental, and field studies, as well as railway design standards. Rather than conducting new simulations or tests, the study relies on established benchmark data to compare the relative safety performance of each sleeper type. This method ensures consistency across materials and reflects realistic service conditions encountered in railway operations. The key performance indicators for safety assessment are shown in Table 2.

Table 2. Key Performance Indicators (KPI's) for Safety Performance Assessment [13].

Indicator	Wood	Plastic	Concrete	3D-Printed Concrete
Load-bearing Capacity (kN)	100–120	90–110	150–180	160–200
Fatigue Resistance (cycles)	1×10^6	0.8×10^6	2×10^6	2.5×10^6
Fire Resistance	Low	Moderate	High	High
Resistance to Splitting/Cracking	Moderate	Low	High	Very High

3D printed concrete sleepers show better performance, especially in terms of life and crack resistance, when compared to traditional materials sleepers [13].

2.3 Sustainability and Environmental Impact Assessment

The environmental impacts of the sleeper types were evaluated using the Life Cycle Assessment approach, which serves as a method to analyze raw material extraction and manufacturing through end-of-life phases, including use and manufacturing [12]. The environmental impact parameters, including Global Warming Potential (GWP), water usage, and embodied energy for each sleeper type, are listed in Table 3.

Table 3. Environmental Impact Assessment (EIA) Parameters [12]

Sleeper Type	GWP (kg CO_2-eq)	Water Usage (L/unit)	Embodied Energy (MJ/unit)
Wood	65	100	800
Plastic	110	120	1500
Conventional Concrete	150	250	1800
3D-Printed Concrete	95	180	1300

Use of 3D printed concrete sleepers provides improved performance while reducing their GWP compared to traditional concrete pieces [12].

2.4 Circularity and Recyclability Assessment

The evaluation of material circularity depends on recyclability, along with potential reuse and ZZS analysis to determine environmental toxicity. The circularity and recyclability parameters are detailed in Table 4.

Table 4. Circularity and Recyclability Assessment Parameters [12].

Sleeper Type	ZZS Content (mg/kg)	Recyclability (%)	End-of-Life Option
Wood	10–20 (treated)	40–60	Incineration or landfill
Plastic	5–10	60–70	Mechanical recycling
Concrete	2–5	50–60	Downcycling to road base
3D-Printed Concrete	<2	70–80	Direct reuse or recycling

3D printed concrete provides superior material circularity because it has both high recyclability and low harmful content during its lifespan [12].

2.5 Compressive Strength

Compressive strength is a fundamental mechanical property governing the ability of railway sleepers to withstand vertical loads transmitted from rails and rolling stock. In this study, compressive strength values were sourced from published research articles and international material standards, rather than being obtained through direct testing.

2.6 Compressive Strength Testing

Reported strength ranges for wooden, plastic, conventional concrete, and 3D-printed concrete sleepers were selected in accordance with commonly referenced standards, including ASTM C39 for cement-based materials, ISO 3349 for timber products, and ASTM D695 for polymer-based sleepers. The values presented in Table 5 represent typical ranges documented in prior studies and are used exclusively for comparative analysis of material performance.

Table 5. Compressive Strength Results for Each Sleeper Type [5].

Sleeper Type	Compressive Strength (MPa)	Test Method	Sleeper Type
Wooden Sleeper	40–60	ISO 3349 (wood)	Wooden Sleeper
Plastic Sleeper	10–25	ASTM D695 (plastics)	Plastic Sleeper
Conventional Concrete	50–60	ASTM C39 (concrete)	Conventional Concrete
3D-Printed Concrete	30–65	ASTM C39 (concrete)	3D-Printed Concrete

2.7 Explanation of Results and Key Observations

Compressive strength for wooden sleepers among the sleeper types evaluated is shown in Table 5 and Figure 1 and ranges from 40 to 60 MPa. They have enough strength for normal loads, but moisture, decay, and insect problems can weaken them and decrease how well they work over many years. The fact that recycling these is difficult, and they cause more environmental harm, is mentioned in both Table 3 and Table 4.

Table 5 lists the moderate compressive strength of plastic sleepers, which falls between 10 and 25 MPa. Even though they are flexible and can resist many stresses, exposure to ultraviolet sunlight and weather can cause their deterioration and reduce their endurance under tough loads. Recycling plastic sleepers is moderately possible, but they still have a relatively high impact on the environment, based on what can be seen in Table 4 and Table 3.

Table 5 shows that steel reinforcement in conventional concrete sleepers helps the high-quality compacted concrete to support heavy loads, which means they can compress to a size up to 50-60 megapascals. While they support a lot of loads, continuing vibrations during use may cause the sleepers to develop cracks or splits, which can weaken them. It is clear from looking at Table 4 and Table 3 These materials have less ability to be recycled and produce more GWP.

Table 5, Figure 1 demonstrates that 3D printed concrete sleepers have competitive compressive strength ranging from 30 to 65 MPa. Improvement in their performance may be achieved by changing the concrete mix and printing parameters. Nothing matters more for their durability than the combined quality of printing and reinforcement in the initial manufacturing process. Both tables show that they may be recycled many times and have a moderate impact on the environment. This mixture proves they are a good, eco-friendly alternative to classic sleepers.

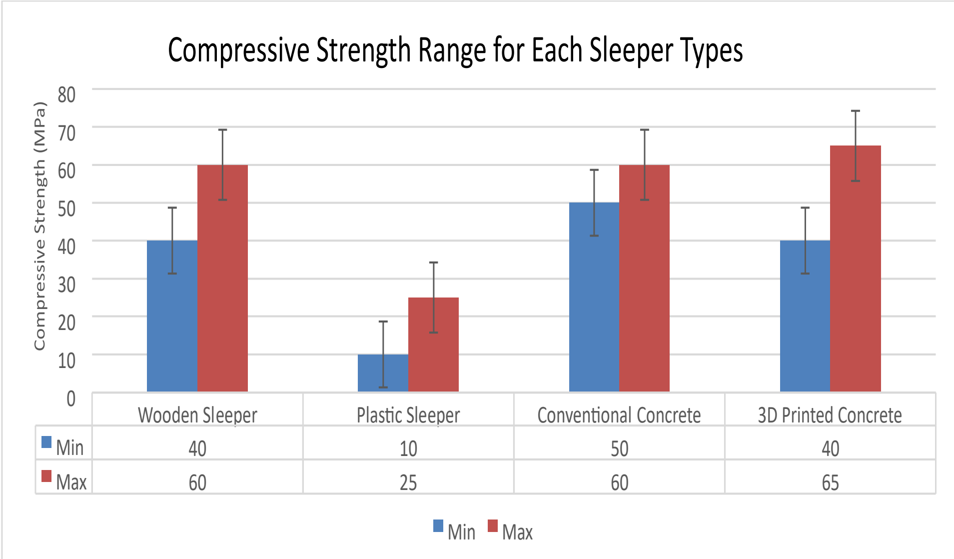

Figure 1. Compressive strength range for each sleeper type.

2.8 Economy Comparison of Railway Sleepers

The cost data required to evaluate the economic feasibility of each sleeper type were received with references to industry reports, academic studies and published literature. This discussion is devoted to the costs of materials in a unit sleeper, estimated costs of manufacturing, and economic sustainability in the long term. Also, the paper contains a qualitative evaluation of cost-efficiency and lifecycle expenses, and emphasis is on environmental and economic sustainability.

2.8.1 Cost Per Area per Sleeper Type

The table below provides a summary of the material and manufacturing cost of each type of sleeper according to the recent literature and industry reports. The prices are given as estimates, and these prices may differ depending on the place of geographical location and production.

Table 6. Material and Manufacturing Costs of Different Railway Sleepers (USD per sleeper)

Sleeper Type	Material Cost per Sleeper (USD)	Manufacturing Cost	Notes
Wooden Sleepers	\$20–\$40	\$30–\$50	Price varies based on wood type, treatment, and labor costs.
Plastic (Polymer Composite) Sleepers	\$30–\$70	\$50–\$100	Depending on recycled materials and complexity of design.
Conventional Concrete Sleepers	\$50–\$150	\$80–\$180	Price depends on size, reinforcement, and transportation costs.
3D-Printed Concrete Sleepers	\$60–\$200	\$100–\$300	Cost is higher due to 3D printing technology.

2.8.2 Economic Sustainability Assessment

Besides the material and manufacturing costs, the economic feasibility of every sleeper type is also considered in the lifetime of the sleeper. This involves calculating the total cost of ownership (TCO), which also takes into consideration the cost of installation, maintenance and replacement during a reasonable service life. As is analyzed, the following can be noted:

2.8.2.1 Wooden Sleepers

Wooden sleepers are cheap to procure and maintain initially, but that are prone to constant maintenance and replacement as they will not last long (on average 20-30 years). They are also susceptible to rot by moisture, termites and fungal rot. Maintenance and replacement require costs, which make the total cost of ownership higher. Other indirect costs relate to environmental issues like deforestation and use of pesticides to preserve the environment.

2.8.2.2 Plastic Sleepers

Plastic sleepers are more expensive than wood, but they are more durable (up to 50 years) and less maintenance is required. They are more long term economically sustainable regarding their long service life and the fact that the material can be recycled after its end of life. Nevertheless, recycled HDPE is more energy consuming in the manufacturing of plastic sleepers.

2.8.2.3 Traditional Concrete Sleepers

Concrete Sleepers are very expensive and heavy in nature and make transportation and installation expenses more difficult. Nevertheless, they provide a high life (50-60 years) but with moderate maintenance requirements. Concrete sleepers are good in the long run, considering that they have a high load bearing capacity and durability, but their overall cost may be high as they require periodical replacement and repair of cracks (because of environmental factors).

2.8.2.4 Concrete Sleepers

3D-printed Concrete Sleepers: 3D-printed concrete sleepers have the potential to be cost-effective because the production process results in minimal material waste and less time spent on the manufacturing process. The initial material price is average, however, the possibility of saving on transportation (with the reduced weight) and the sleeper design customization make them cost-effective in the long term. The fact that 3D-printed concrete can be recycled, also lowers the cost of disposing 3D-printed concrete at the end of their life.

2.8.3 Economic Evaluation (Qualitative)

The economic evaluation of different sleeper types was conducted using a qualitative lifecycle perspective. Cost-related information, including material costs, manufacturing complexity, installation requirements, maintenance needs, and expected service life, was obtained from academic literature and industry-based assessments.

Due to variations in geographic location, production scale, and market conditions, precise cost values are not universally applicable. Therefore, this study focuses on relative economic performance rather than exact pricing. The comparison emphasizes long-term cost efficiency, durability, maintenance frequency, and end-of-life considerations, providing insight into the economic sustainability of 3D-printed concrete sleepers compared to conventional alternatives.

3. Results and Discussions

This chapter gives a detailed comparative study of advantages and disadvantages between the concrete railway sleepers 3D printed and conventional ones like wooden railway sleepers, plastic sleepers, and ordinary concrete railway sleepers. Discussion revolves around five major performance categories which are mechanical strength, durability, environmental impact, recyclability and safety performance. Experimental findings and literature have been used in drawing data with references to Tables 2 through 5. All factors are analyzed to find out how well 3D printed concrete sleepers can work as compared to the traditional approach with regards to their application in contemporary railway industries.

3.1 Evaluation of Durability and Performance Mechanics

Comparative discussion of the study conducted on 3D printed concrete railway sleepers and their conventional counterparts indicates interlinking of insights within the crucial parameters of projects such as compressive strength, environmental impact, durability, recyclability, and safety among others. On the mechanical behavior, Table 5 shows that 3D printed concrete sleepers could achieve the same compressive strength as conventional concrete sleepers (up to 60 MPa) following the improvement in the printing technologies and design of the materials, whereas wood sleepers could even achieve moderate strength (up to 60 MPa) but fails easily due to water and the effect of biological activity, and plastic sleepers with reduced strength (up to 25 MPa) are easily deformed with high stress. Such structural capability directly translates to their long-term ability to withstand and endure, and in Table 2 they all demonstrate the advantage of much better crack resistance and structural performance when loaded repeatedly (as in high speed and heavy-gauge rail lines the loading is repeated repeatedly and over long periods of time); and both 3D printed and conventional concrete sleepers are much more adaptable to high speed, high rail lines than their wooden or plastic counterparts, which do not perform as well over the long run. Moreover, concerning fire resistance and working security, Table 2 proves that concrete-based sleepers either 3D printed or traditional are very operative in high-temperature regimes as opposed to wooden sleepers that are a hazard during a fire and plastic sleepers that become soft with heat and thus are less dependable in extreme conditions.

3.2 Environmental Impact, Sustainability and Circularity

Such advantages of mechanical properties and durability are accompanied by environmental disadvantages because, as Table 3 depicted, 3D printed sleepers have a small global warming potential (95 kg CO2-eq/unit) than the traditional concrete sleepers (150 kg CO2-eq/unit), however with a little increase in water consumption, these products have low embodied energy and effective utilization of resources which is favorable to the sustainability objectives. Such environmental and performance parameters also match recyclability rates; 3D printed concrete sleepers are the only type of sleeper, able to reach a recyclability rating of 70-80%; followed by conventional concrete, whose rating is 50-60%, wood with 40-60%, and even plastic sleepers with a rating of 60-70%, but which, due to material wear over time, will have a lower circular value. Relating to the general safety and resilience, Table 2 also indicates that both 3D printed and conventional concrete sleepers are highly fire resistant and, therefore, can be trusted in harsh conditions, as opposed to wooden sleepers, which are fire hazards and plastic, which soften at high temperatures. These overlapping results in strength, durability, environmental impact, recycling, and fire-safety mean that concrete sleepers printed in 3D are powerful and more sustainable replacements of conventional sleeper material, being equal to or even outperforming conventional materials, as well as safer.

4. Conclusion

This study presented a comprehensive comparative assessment of 3D-printed concrete railway sleepers in relation to conventional sleeper systems, including wooden, plastic, and precast concrete sleepers. Using data compiled from published literature, international standards, and technical reports, the analysis focused on key performance indicators such as mechanical strength, safety behavior, environmental impact, recyclability, and economic feasibility. The comparative framework adopted in this research enabled an objective evaluation of sleeper technologies without duplicating experimental work previously reported in the field.

Abbreviations

The following abbreviations are used in this manuscript:

3DCP	Three-Dimensional Concrete Printing
ASTM	American Society for Testing and Materials
EIA	Environmental Impact Assessment
HDPE	High-Density Polyethylene
ISO	International Organization for Standardization
KPI	Key Performance Indicator
LCA	Life Cycle Assessment
ZZS	Zero-Hazard Substance
TCO	Total Cost of Ownership

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