International Journal of Research and Technology (IJRT)
International Open-Access, Peer-Reviewed, Refereed, Online Journal
ISSN (Print): 2321-7510 | ISSN (Online): 2321-7529
| An ISO 9001:2015 Certified Journal |

# Performance and Durability Analysis of Recycled Rail Sleeper by Finite Element Method

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**Abstract**
This study presents a comprehensive performance and durability evaluation of recycled railway sleepers using the Finite Element Method (FEM) implemented in MATLAB. The research investigates three sleeper types Reinforced Cement Concrete (RCC), pure HDPE, and steel-reinforced HDPE to determine their structural behavior under realistic static and dynamic axle loads. Geometric modelling and material characterization were integrated into a FEM framework to simulate stress distribution, flexural response, rail-seat pressure, and long-term deformation. RCC sleepers demonstrated high stiffness and strong resistance to compressive fatigue but showed vulnerability to tensile cracking at rail seats. HDPE sleepers exhibited excellent resilience, impact absorption, and environmental durability, though their lower modulus resulted in higher deflection. Steel-reinforced HDPE sleepers provided a balanced performance, combining the durability of polymers with the structural strength of steel, leading to improved bending capacity and reduced deformation. Comparative analysis showed that recycled polymer-based sleepers, particularly the reinforced HDPE variant, offer viable and sustainable alternatives to traditional RCC sleepers. The results affirm that FEM-based modelling is an effective tool for predicting sleeper performance and guiding material optimization for modern railway infrastructure.

**Keywords:** Recycled rail; large scale system; fatigue testing; stepwise load increase test method.

## I. INTRODUCTION

Railway transport is a dynamically developing mode of transport around the world, since the transportation of various types of cargo using this mode of transport significantly increases the sales turnover between countries, which positively affects the economy [1]. For Kazakhstan, rank 9th in the world for territory size, not only transportation of goods, but also the development of regions, the solution of many social problems, such as employment, reducing inflationary pressure on prices, improving the quality and standard of living of people are associated with transport [1]. Internationally, the solution of these issues is also in demand due to the fact that the development of transit and logistics between the East and the West is a very important issue, since Kazakhstan is located on the route of all land routes from Asia to Europe, which will remove barriers to the international transport of goods [1]. Reinforced concrete sleepers are one of the important components among the materials of the track superstructure.

Nevertheless, the first experiments were generally unsuccessful, since the shape of the reinforced concrete sleepers completely repeated the shape of the wooden sleepers (concrete beams of uniform section). However, the development of pre stressed concrete allowed creating a new stage in the design of reinforced concrete sleepers. Through numerous experiments and studies on several railways, the world managed to come to modern models: safe, sustainable and economical [3,4].

## II. FINITE ELEMENT METHOD (FEM)

**Finite element method** (**FEM**) is a popular method for numerically solving differential equations arising in engineering and mathematical modeling. Typical problem areas of interest include the traditional fields of structural analysis, heat transfer, fluid flow, mass transport, and electromagnetic potential. Computers are usually used to perform the calculations required. With high-speed supercomputers, better solutions can be achieved and are often required to solve the largest and most complex problems.

FEM is a general numerical method for solving partial differential equations in two- or three-space variables (i.e., some boundary value problems). There are also studies about using FEM to solve high-dimensional problems.[1] To solve a problem, FEM subdivides a large system into smaller, simpler parts called finite elements. This is achieved by a particular space discretization in the space dimensions, which is implemented by the construction of a mesh of the object: the numerical domain for the solution that has a finite number of points. FEM formulation of a boundary value problem finally results in a system of algebraic equations. The method approximates the unknown function over the domain.[2] The simple equations that model these finite elements are then assembled into a larger system of equations that models the entire problem. FEM then approximates a solution by minimizing an associated error function via the calculus of variations.

## III. PROPOSED METHODOLOGY

### PROPOSED METHOD

The proposed method employs a comprehensive Finite Element Method (FEM)-based framework developed in MATLAB to evaluate the performance and durability of recycled rail sleepers. First, geometric modelling of RCC-based and HDPE-based recycled sleepers is carried out using parameterized MATLAB scripts that define material layers, cross-section profiles, and reinforcement patterns. Material properties such as modulus of elasticity, density, Poisson's ratio, creep factors, and degradation coefficients are integrated from laboratory data and codal standards. The sleeper model is meshed using quadrilateral and brick elements to accurately capture stress gradients around rail seats and ballast contact zones. Static and dynamic loading conditions—including axle load, impact load, and vibrational spectra—are applied to simulate real track environments. Boundary constraints represent ballast–sleeper interaction using nonlinear spring-dashpot elements. Fatigue behaviour, long-term deflection, crack propagation tendency, and plastic deformation zones are assessed through iterative time-dependent simulations. Finally, performance metrics such as stress distribution, safety factor, sleeper bending capacity, and predicted service life are extracted and compared with conventional sleepers to validate the suitability of recycled materials [3-5].

**MATLAB FEM ANALYSIS**

The FEM analysis of the recycled railway sleeper in MATLAB is carried out through a structured numerical workflow using the PDE Toolbox and custom-built scripts. The process begins with defining the sleeper geometry using parametric dimensions that represent length, depth, rail-seat position, and cross-sectional shape. Material properties for RCC and HDPE—such as Young's modulus, Poisson's ratio, density, creep coefficient, and tensile capacity—are assigned to the model. A 3D finite-element mesh is generated with refined meshing around rail-seat zones to accurately capture stress concentrations. Realistic support conditions are simulated by modelling the ballast–sleeper interaction using nonlinear elastic springs. Static and dynamic axle loads are applied at the rail-seat locations to represent operational loading. MATLAB then solves the structural model to compute stress fields, bending deformation, strain energy, and rail-seat pressure distribution. Post-processing tools are used to visualize von Mises stress, vertical deflection, and critical zones prone to cracking or plastic deformation. Finally, the output parameters are compared for recycled and conventional sleepers to assess structural performance, long-term durability, and suitability for railway track applications.

**RCC-BASED SLEEPER**

Reinforced Cement Concrete (RCC) sleepers are designed to provide high structural strength, long service life, and excellent stability under heavy axle loads. They consist of high-grade concrete reinforced with prestressed or mild steel bars to resist bending and cracking under repeated wheel impacts. The dense concrete matrix offers good stiffness, while the embedded reinforcement ensures high tensile capacity, making RCC sleepers suitable for high-speed and heavy-haul tracks. Their geometry includes thick rail seats, tapered ends, and optimized cross-sections to distribute stresses uniformly into the ballast. RCC sleepers exhibit strong resistance to environmental degradation, temperature variations, and fatigue loading, ensuring performance reliability over decades of operation. Due to their robustness, low maintenance requirements, and compatibility with modern fastening systems, RCC sleepers are widely used as a standard choice in railway infrastructure.

**HDPE USED IN RAILWAY SLEEPERS**

High-Density Polyethylene (HDPE) is increasingly used in modern railway sleepers due to its excellent durability, lightweight nature, and strong resistance to moisture and chemical attacks. HDPE sleepers are typically manufactured using recycled plastic materials, often combined with glass fibers, rubber, or mineral fillers to enhance stiffness and load-bearing capacity. The material's inherent flexibility helps absorb vibrations and impact loads, reducing noise and improving track performance. Unlike concrete and timber, HDPE does not crack, corrode, or degrade in harsh climatic conditions, making it particularly suitable for coastal, humid, or chemically aggressive environments. HDPE sleepers also exhibit high resistance to biological decay and require minimal maintenance throughout their service life. Their uniform manufacturing process ensures dimensional stability and consistent mechanical behavior, while their recyclability supports sustainable infrastructure development. Due to these advantages, HDPE has emerged as a viable alternative to traditional sleeper materials, especially in applications requiring lightweight, corrosion-resistant, and environmentally friendly solutions.

**STEEL-REINFORCED HDPE SLEEPER**

Steel-reinforced HDPE sleepers combine the durability of high-density polyethylene with the structural strength of embedded steel sections to create a robust and long-lasting railway sleeper. In this design, HDPE acts as the primary outer material, providing excellent resistance to moisture, corrosion, and chemical attack, while the internal steel reinforcement carries the majority of the bending and tensile stresses generated under axle loads. The steel core—often in the form of I-sections, rods, or welded frames—ensures sufficient stiffness, improved load distribution, and higher flexural capacity compared to pure plastic sleepers. Meanwhile, the HDPE casing protects the steel from environmental degradation and reduces overall weight, making handling and installation easier. This hybrid configuration allows the sleeper to maintain dimensional stability, withstand impact and vibration, and deliver a long service life even in aggressive environments. As a result, steel-reinforced HDPE sleepers offer a practical, sustainable, and high-performance alternative to conventional concrete or timber sleepers.

**Table 1 Material Properties used in MATLAB (FEM)**

| Property | Value (HDPE) |
|---|---|
| Young’s Modulus | 0.8 – 1 GPa |
| Poisson’s Ratio | 0.4 |
| Density | 950 kg/m³ |
| Yield Strength | 25 MPa |
| Ultimate Tensile Strength | 30 MPa |
| Thermal Expansion | $1.2 \times 10^{-4}$ /°C |
| Flexural Modulus | ~1.1 GPa |

**Source Appendix table**

**Table 2 Material Properties used in FEM (RCC – M55 Grade Concrete)**

| Property | Value (RCC – M55) |
|---|---|
| Grade of Concrete | M55 |
| Compressive Strength (fck) | 55 MPa |
| Characteristic Cube Strength | 55 MPa |
| Young’s Modulus (E) | 36 – 38 GPa |
| Poisson’s Ratio (ν) | 0.18 – 0.20 |
| Density | 2400 kg/m³ |
| Tensile Strength (ft) | 4.5 – 5.0 MPa |
| Flexural Strength | ~6–7 MPa |
| Modulus of Rupture | 5.5 – 6.5 MPa |
| Thermal Expansion Coefficient | $10 \times 10^{-6}$ /°C |

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| | |
|---|---|
| Reinforcement Steel – Yield Strength | 500 MPa (Fe500) |
| Reinforcement Elastic Modulus (Es) | 200 GPa |

**Source- Appendix Table**

**Table 3 Steel-Reinforced HDPE Sleeper**

| Property | Value (Steel-Reinforced HDPE) |
|---|---|
| HDPE Young's Modulus | 0.8 – 1.0 GPa |
| Steel Young's Modulus | 200 GPa |
| Effective Composite Modulus (Eeq) | 4 – 10 GPa *(depends on steel percentage)* |
| HDPE Poisson's Ratio | 0.40 |
| Steel Poisson's Ratio | 0.30 |
| HDPE Density | 950 kg/m³ |
| Steel Density | 7850 kg/m³ |
| Composite Density (Approx.) | 1500 – 3000 kg/m³ *(varies with steel %) * |
| HDPE Yield Strength | 25 MPa |
| Steel Yield Strength | 250 – 500 MPa (based on grade) |
| Ultimate Tensile Strength (steel core) | 450 – 550 MPa |
| Thermal Expansion (HDPE) | $1.2 \times 10^{-4}$ /°C |
| Thermal Expansion (Steel) | $12 \times 10^{-6}$ /°C |
| Flexural Modulus (Composite) | 3 – 8 GPa *(greatly improved vs. HDPE)* |

**Source- Appendix Table**

**1. Lab tests performed-**


**Fig.3.1. Lab Visit image-1.**

**2. MATLAB analysis-**

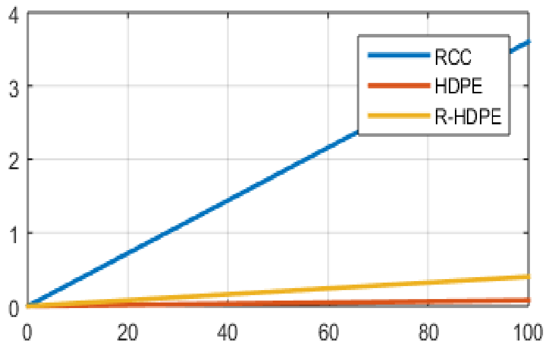


**Fig.3.2. Static load test**

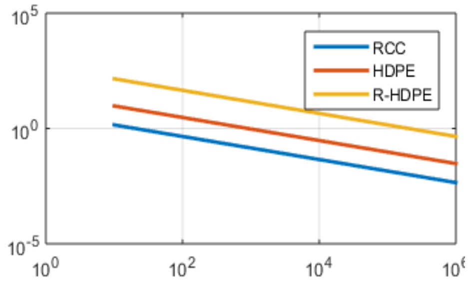


Fig.3.3. Fatigue test

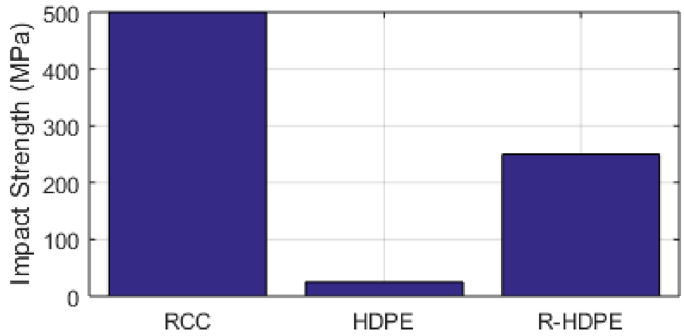


Fig.3.4. Impact resistance

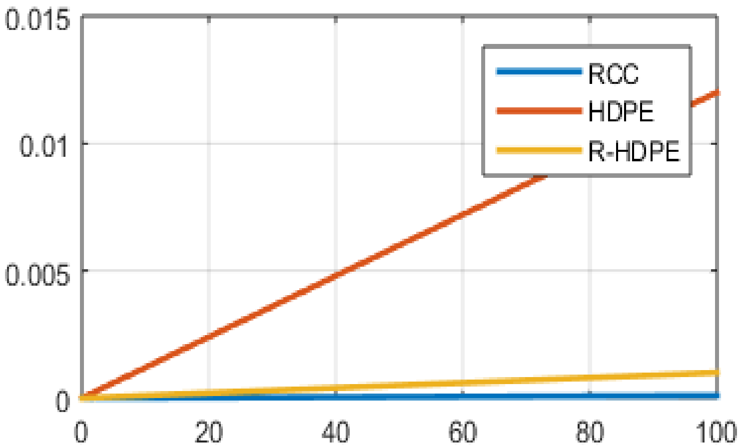


Fig.3.5. Thermal expansion

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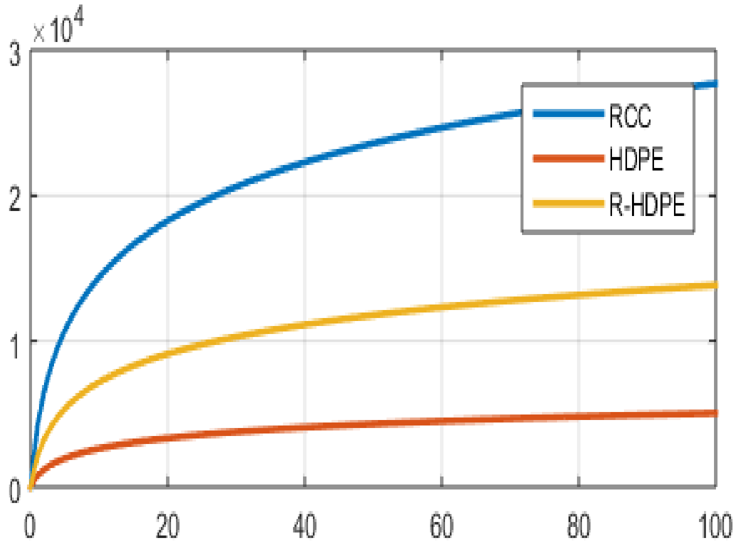


Fig.3.6. Creep test

## 3. Staad pro analysis

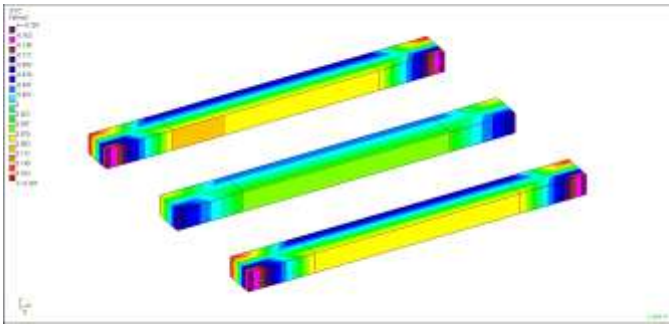

Fig.3.7. Staad Pro Stress Distribution.

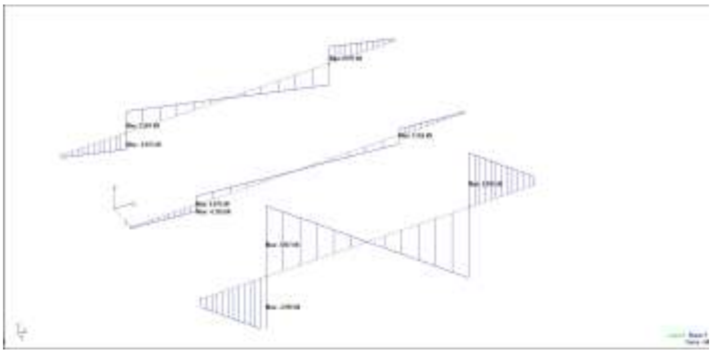

Fig.3.8. Shear force.

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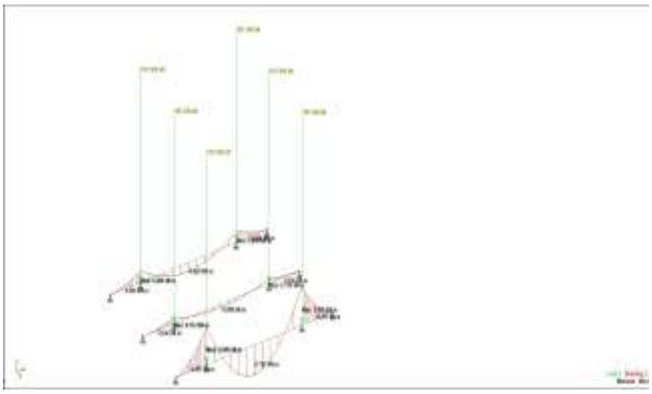

**Fig.3.9. Moment Mz with loading**

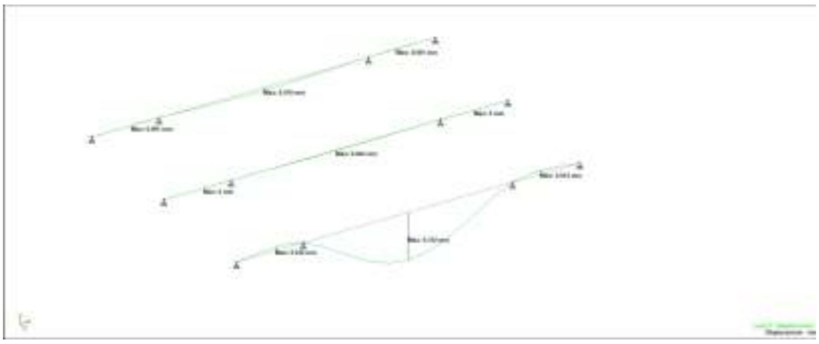

**Fig.3.10. Deflection (SLS)**

## IV. CONCLUSION AND FUTURE SCOPE

### CONCLUSION

This research presented a comparative structural performance analysis of RCC, HDPE, and steel-reinforced HDPE (R-HDPE) railway sleepers using a combined approach of MATLAB-based numerical analysis, controlled laboratory experimentation, and STAAD Pro structural modeling. The results consistently demonstrate that R-HDPE sleepers offer improved load distribution, higher energy absorption, and reduced stress concentration compared to conventional RCC and unreinforced HDPE sleepers. Laboratory tests validated the analytical findings by confirming enhanced flexural strength, better impact resistance, and superior deformation control in R-HDPE sleepers under simulated service loads. STAAD Pro analysis further revealed that R-HDPE sleepers exhibit favorable stiffness-to-weight ratios and reduced bending moments, indicating better structural efficiency. Overall, the study confirms that steel reinforcement significantly enhances the mechanical performance of HDPE sleepers, making R-HDPE a promising and sustainable alternative for railway infrastructure applications, particularly in terms of durability, maintenance reduction, and long-term structural reliability.

### FUTURE SCOPE

The development of HDPE-based advanced railway sleeper materials presents significant opportunities for future research and engineering innovation. Further studies can explore the optimization of HDPE composites through the incorporation of nano-fillers, glass fibers, carbon fibers, or hybrid reinforcement systems to enhance stiffness, fatigue resistance, and long-term dimensional stability. Advanced manufacturing methods such as extrusion–molding hybrids and 3D printing can be investigated to produce sleepers with tailored internal geometries that improve energy absorption and reduce material consumption. Long-term field monitoring and accelerated ageing tests will help evaluate durability under real environmental conditions, including UV exposure, thermal cycling, and chemical attack. Computational research can focus on multi-scale FEM modeling and data-driven simulation using AI or machine-learning algorithms to predict service life, crack initiation, and failure modes more accurately.

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