Comprehensive Evaluation of Geopolymer Concrete for Enhanced Railway Sleeper Performance

Moulya H V[1*], A Chandrashekhar[2], Ananthayya M B[3]

[1*]Assistant Professor, Department of Civil Engineering, Nitte Meenakshi Institute of Technology, Visvesvaraya Technological University, Bengaluru, Karnataka, India, moulyahv123@gmail.com

[2]Professor and Head, Department of Civil Engineering, KVG College of Engineering, Sullia, Dakshina Kannada, Karnataka, India

[3]Professor and Head, Department of Civil Engineering, Sai Vidya Institute of Technology, Rajankunte, Bengaluru, Karnataka, India

ABSTRACT

The current research explores the load-bearing performance of geopolymer concrete sleepers as a sustainable alternative to conventional cement-based sleepers in railway infrastructure. Through rigorous comparative analysis, the study demonstrates that geopolymer sleepers exhibit comparable or superior strength characteristics under various loading conditions. The Key mechanical properties, including compressive strength, flexural strength, split tensile strength, and durability, are systematically assessed to evaluate the performance of geopolymer concrete thoroughly. The study investigates constant ratios of Ground Granulated Blast Furnace Slag (GGBS) to fly ash (60:40) and different ratios recycled coarse aggregate to natural coarse aggregate (100:0, 0:100, 70:30) to determine the optimal mix proportions. The experimental methodology employs a mix ratio of 1:1.28:3 and an 8 M alkaline solution with a NaOH to Na_2SiO_3 ratio of 1:2.5, alongside an alkaline solution to binder ratio of 0.43. Additionally, the static bending strength of the sleepers is analyzed, providing deeper insights into their structural performance. This research significantly advances the knowledge and application of geopolymer concrete in railway infrastructure, highlighting its potential for enhanced sustainability and durability.

KEYWORDS: Geopolymer Concrete; Railway Sleepers; Compressive Strength; Sustainability; Durability

1. INTRODUCTION

Railway sleepers are a critical component of railway infrastructure, providing stability and support to the rail tracks. Traditionally, sleepers have been constructed from materials such as wood, steel, and concrete, each with its own set of advantages and limitations [1-3]. However, with increasing environmental concerns and the need for more sustainable construction practices, there has been a growing interest in finding alternatives to traditional materials [4-5]. One such promising alternative is geopolymer concrete, which is derived from industrial by-products like fly ash and slag [6]. This study aims to conduct a comprehensive evaluation of the load performance of geopolymer concrete sleepers compared to conventional cement-based sleepers, focusing on mechanical properties, durability, and environmental impact. Geopolymer concrete offers several benefits over conventional Portland cement-based concrete, including higher compressive strength, lower environmental impact, and reduced carbon emissions [7-10]. By utilizing industrial by-products as the primary binder, geopolymer concrete not only reduces the consumption of natural resources but also mitigates the disposal of waste materials [11-12]. This research explores the feasibility of geopolymer concrete as a sustainable solution for railway sleepers, providing a detailed analysis of its mechanical properties such as compressive strength, flexural strength, and split tensile strength. Additionally, the study evaluates the durability and long-term performance of geopolymer concrete sleepers under various loading conditions, offering insights into their potential for large-scale application in railway infrastructure [13-15].

The experimentation involves using different ratios of Ground Granulated Blast Furnace Slag (GGBS) to fly ash (60:40) and recycled coarse aggregate to natural coarse aggregate (100:0, 0:100, 70:30) to determine the optimal mix proportions for geopolymer concrete. A mix ratio of 1:1.28:3 and an 8 M alkaline solution with a NaOH to Na_2SiO_3 ratio of 1:2.5 is employed, along with an alkaline solution to binder ratio of 0.43. The study also examines the static bending strength of the sleepers, enhancing the depth of the findings and providing a comprehensive understanding of the material's performance. This detailed investigation aims to establish the practicality of geopolymer concrete sleepers in railway applications, highlighting their potential to improve sustainability and durability in the sector. Geopolymer concrete represents a significant advancement in sustainable construction practices. By reducing carbon emissions and environmental impact, it offers a viable alternative to conventional concrete, contributing to sustainable resource management and reduced reliance on virgin materials [16]. The use of industrial by-products like fly ash and GGBS not only enhances the mechanical properties and durability of the concrete but also promotes the recycling of waste materials, aligning with the principles of a circular economy [17-18]. This research aims to encourage the use of geopolymer concrete in construction, providing valuable information to engineers, builders, and stakeholders interested in sustainable construction practices. The successful adoption of geopolymer concrete sleepers could lead to more resilient and eco-friendly railway infrastructure, supporting global efforts towards sustainability and environmental preservation.

2. LITERATURE REVIEW

A study investigated the flexural behavior of geopolymer concrete beams made from fly ash, exposed to temperatures between 200°C and 800°C, finding significant deviations in deformation and reduced ductility at elevated temperatures, along with an equation for predicting crack width after exposure [19]. Research compared M40 grade Geopolymer Concrete (GPC) beams to conventional cement concrete beams, noting higher compressive strength and similar load-deflection responses, with GPC beams showing higher curvature and ultimate load capacity [20]. Another study examined sodium hydroxide molarity's impact on geopolymer concrete properties, concluding that higher molarity improves compressive strength, slump, and split tensile strength, with GGBS-based geopolymer concrete performing best at 15M concentration [21]. Research on the flexural behavior of GGBS-based geopolymer concrete beams found them stronger and with better load-deflection behavior than conventional M40 grade concrete beams [22-23]. A comparison of RGPC to RPCC beams highlighted that GRAC beams had lower elastic modulus but greater deflection and improved strength with optimized alkali content [24].

A study focused on the environmental benefits of low calcium fly ash as an alternative to OPC, finding GPC beams exhibited higher flexural strength and similar load-deflection characteristics to control beams [25-26]. Research on geopolymer concrete mix designs for specific strengths tested hybrid composite beams, confirming their suitability for civil infrastructure and railway sleepers [27]. An emphasis on the environmental advantages of GPC noted its higher compressive strength and durability compared to OPC, positioning it as a sustainable construction material [28]. An exploration of GPC for railway sleepers found higher ultimate load capacity and increased deflection compared to conventional sleepers, highlighting its viability for sustainable railway infrastructure [29]. An investigation into alternative materials for railway sleepers proposed pultruded FRP composites and fly ash-based geopolymer concrete as effective substitutes with satisfactory performance under four-point bending tests [30]. Research developed geopolymer concrete for railway sleepers, achieving high compressive strengths with ambient curing and demonstrating suitability for railway applications with significant energy savings [31]. A review of the durability and performance of advanced materials for railway sleepers noted GPC and fiber-reinforced concrete's effectiveness in enhancing durability and performance compared to traditional materials [32]. An evaluation of the flexural behavior of GPC beams suggested they exhibit higher load capacities and deflections compared to OPCC beams, emphasizing the need for refined design parameters for accurate predictions [33]. A study highlighted the superiority of GFRP reinforcement over steel in concrete structures, proposing its use in bridge decks to enhance durability and reduce corrosion [34]. An examination of the failure modes of traditional railway sleepers recommended protective strategies and explored emerging materials like geopolymer concrete for improved longevity [35]. Research discussed the benefits of alkali-activated fly ash in concrete sleeper production, emphasizing rapid strength development and long-term durability [36]. A study explored high-performance geopolymer concrete for railway sleepers, finding superior load-bearing capacity and cost-effectiveness compared to traditional concrete [37]. Research integrated advanced materials like CNTs, CF, and PF into high-performance concrete for PSC railway sleepers, enhancing load-deflection characteristics and reducing sleeper size for improved handling and performance [38].

The literature review reveals that geopolymer concrete (GPC), particularly with fly ash and GGBS, exhibits superior compressive and flexural strengths, higher ultimate load capacity, and enhanced durability compared to conventional cement concrete. Sodium hydroxide molarity significantly influences GPC properties, with optimal performance at higher concentrations. GPC demonstrates environmental benefits, offering a sustainable alternative to OPC with reduced CO_2 emissions. Its application in railway sleepers shows promise, with enhanced load-bearing capacity, deflection characteristics, and energy savings. Advanced materials like CNTs, CF, and PF further improve concrete performance, underscoring the potential of GPC and other innovative materials to drive sustainable construction practices and infrastructure development.

3. MATERIALS AND METHODOLOGY

The current research work explores the feasibility and advantages of integrating geopolymer concrete into railway sleeper construction. Geopolymer concrete offers significant benefits over traditional cement-based alternatives, including increased strength, durability, and environmental sustainability. The study focuses on optimizing mix designs specifically for railway sleepers and examines advanced manufacturing techniques. It includes a detailed assessment of structural performance through static bending strength analysis. This research aims to enhance the understanding and application of geopolymer concrete in railway infrastructure. By investigating the properties and manufacturing processes of geopolymer concrete, the project seeks to unlock its potential to revolutionize railway sleeper construction. Ultimately, this effort aims to contribute to a more sustainable and resilient railway infrastructure system, promoting environmental stewardship and structural integrity simultaneously.

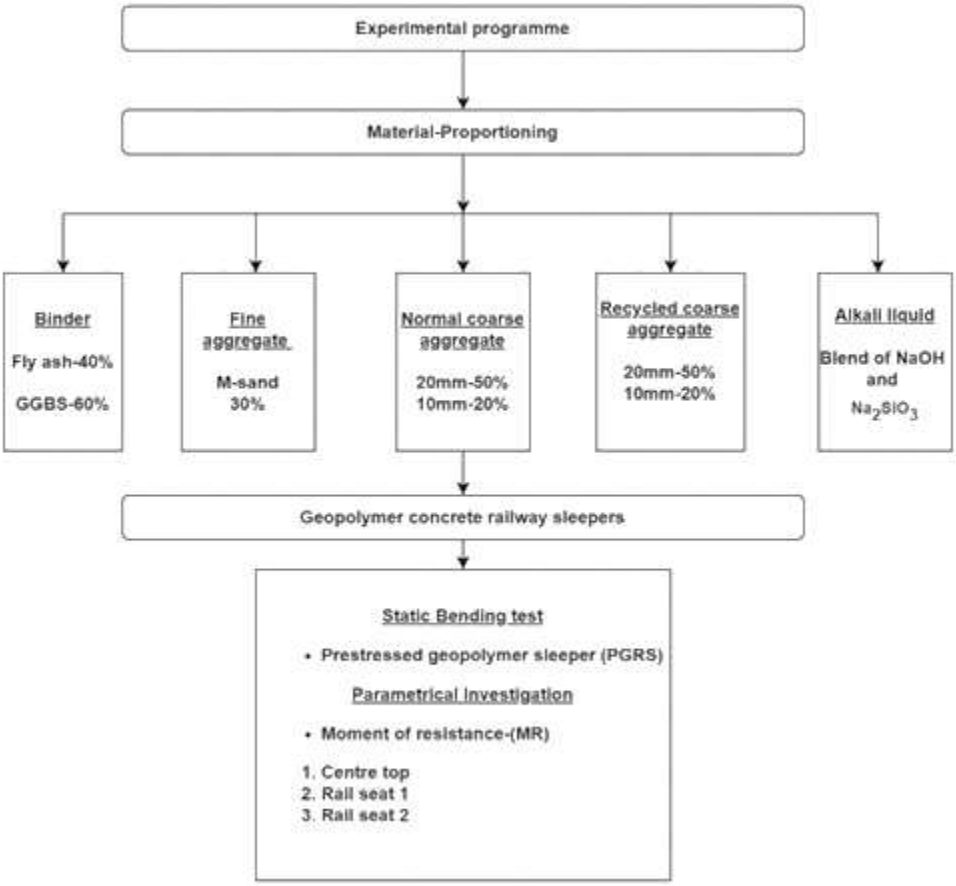

Fig 2: Methodology of Current Research Work

3. Investigative process

3.1 Investigational parameter

Different combinations of fly ash and GGBS are being considered to prepare geopolymer concrete. These combinations include: F100 G0 (100% fly ash and 0% GGBS), F80 G20 (80% fly ash and 20% GGBS), F60 G40 (60% fly ash and 40% GGBS), F40 G60 (40% fly ash and 60% GGBS), F20 G80 (20% fly ash and 80% GGBS), and F0 G100 (0% fly ash and 100% GGBS). The molarity of the NaOH solution is maintained at 8 M. Additionally, the Na_2SiO_3 and NaOH solutions are mixed in a ratio of 2.5:1, while the alkaline liquid to fly ash ratio is 0.43:1.

3.2 Constituents employed.

The synthesis of geopolymer concrete involves several materials: fly ash, GGBS, alkaline activators, aggregate and water. In the current experiment, Class F dry fly ash that meets IS 3812:2003 standards were utilized, and it is collected from Cashutech Nirmitha Kendra, Shakthi Nagar, Raichur- 584102. Fly Ash is a fine, grey, amorphous powder primarily consisting of silica, alumina, and calcium, physical and chemical properties are shown in table 1 for both Fly Ash and GGBS. The GGBS, a by-product of pig iron manufacturing from blast furnaces, was obtained in granulated form and ground to a fineness like Portland cement. The GGBS powder, sourced from Shrusti innovations, Peenya industrial area Bengaluru 560058, has spherical particles and appears white. The chemical composition of GGBS, tested according to IS 12089:1987 requirements, is summarized in Table 2.

Table 1. Physicochemical Properties of Fly Ash and GGBS

Parameters	Materials	
	Fly Ash	GGBS
Physical properties		
Specific gravity	2.53	2.86
Bulk Density	1.226g/cm^3	1.280g/cm^3
Color	Grey	off-white
Chemical properties		
pH	8.5	10.03
Silica SiO_2	55.57	35.27
Aluminum Oxide (Al_2O_3)	32.97	21.20
Oxide of Iron (Fe_2O_3)	1.50	1.65
Magnesium Oxide (MgO)	0.92	8.46
Oxide of Calcium (CaO)	2.84	31.25

In this study, the fine aggregate, commonly referred to as manufactured sand (MS), was sourced locally and its physical properties were assessed in accordance with BIS 2386-1963 (reaffirmed in 2002). The specific gravity of MS was determined to be 2.64 kg/m³, with a bulk density of 1860 kg/m³. The coarse aggregates, sourced from local granite in crushed form with a maximum size of 20 mm and minimum is 10mm, and Recycled Coarse Aggregate (RCA) obtained from an IL&FS Delhi waste recycling operation, were also analyzed. Their specific gravity values were found to be 2.81 and 2.32 respectively, determined using the density bottle method. The bulk densities of the aggregates were recorded as 1670 kg/m³ and 1550 kg/m³. The Los Angeles Abrasion test, conducted according to IS: 2386 (Part IV), yielded abrasion values of 19% and 16% respectively, both falling below the maximum specified value of 30%. Furthermore, the impact value tests, carried out in accordance with IS: 2386 (Part IV), revealed values of 13.24% and 14.2%, significantly lower than the prescribed limit of 30% for wearing surfaces. In the context of this research, alkaline activators consist of a combination of Na_2SiO_3 and NaOH solutions, designed to initiate reactions with the SiO_2 and Al_2O_3 components found in fly ash and GGBS. A specific ratio of 2.5 between Na_2SiO_3 and NaOH was employed, drawing on insights from prior studies.

Table 2. Tests Conducted on Fine Aggregate

Test Conducted	Result Obtained	Required Value as per IS
Specific Gravity	2.66	IS 2386 Part-3 (1963) 2.65-2.67
Bulk Density (Loosely Packed)	1435.49 kg/m³	1200-1750 kg/m³

Table 3. Physical Properties of Coarse Aggregate

Test Conducted	Result Obtained		Required Value as per IS
	NCA	RCA	
Specific Gravity	2.81	2.32	IS 2386(Part 3):1963 2.5 to 3.0
Bulk Density	1670 kg/m³	1550 kg/m³	1200-1750 kg/m³
Crushing Value	24.19%	32.30	IS 2386 Part-3 (1963) ≤ 45%
Abrasion Value	16%	19%	IS 2386 Part-3 (1963) ≤ 30%
Impact Value	13.24%	14.2%,	IS 2386 Part-3 (1963) ≤ 45%

3.2.1 Sodium Silicate

Sodium silicate, a binder and adhesive, is used in construction for concrete sealing and densification [43]. It reacts with calcium hydroxide to form calcium silicate hydrate (CSH) gel, which improves concrete's durability and resistance.

3.2.2 Sodium Hydroxide

Sodium hydroxide, or caustic soda, is a highly soluble alkali used in various industrial processes, including chemical manufacturing, paper production, and petroleum refining [44]. It is essential for making soaps, detergents, and for refining processes. Proper safety protocols are necessary due to its corrosive nature. The materials used are illustrated as follows: Class F fly ash as shown in Figure 1(a), Ground Granulated Blast Slag in Figure 1(b), Fine Aggregate (M-Sand) in Figure 1(c), Coarse Aggregate in Figure 1(d), Sodium Silicate Solution in Figure 1(e), and Sodium Hydroxide in Figure 1(f).

1 (a) Class F Fly ash **1 (b) GGBS** **1 (c) Fine Aggregate**

1 (d) Coarse Aggregate **1 (e) Sodium Silicate** **1 (f) Sodium Hydroxide**

Fig 1: Materials Utilized in the Preparation of Geopolymer Concrete

3.3 Synthesis of geopolymer concrete mix designs

The total aggregate content, including both coarse and fine aggregates, makes up about 70% to 80% of the concrete mix by mass. For our composition, we assume that the aggregates constitute 75% of the mix, with fine aggregate representing 30% of the total aggregate content. Within the coarse aggregate portion, 70% is Coarse Aggregate - I (20mm), and the remaining 30% is Coarse Aggregate - II (10mm). Research indicates that the density of geopolymer concrete is similar to conventional concrete, approximately 2400 kg/m³. By knowing the aggregate volume and concrete density, we can calculate the mass proportions of the alkaline liquids and source binder materials, with an alkaline liquid to cementitious material ratio of 0.43. The required amounts of NaOH and Na2SiO3 solutions per cubic meter of concrete are determined from the Na2SiO3 to NaOH ratio. This study presents two trial mixes, detailed in Table 2, comparing normal concrete and geopolymer concrete for an M60 grade. Table 5 outlines the mix design parameters for M60 grade geopolymer concrete railway sleepers, with a mix ratio of 1:1.22:3.51 and a density of 2450 kg/m³. The aggregate content constitutes 77% of the concrete volume, and the binder and solution together total 565 kg/m³, with fly ash and Ground Granulated Blast Furnace Slag (GGBS) at 158 kg/m³ and 237 kg/m³, respectively. Sodium hydroxide and sodium silicate are added at 68 kg and 102 kg, maintaining an alkaline liquid ratio of 1:2.5.

Table 4. Composition ratios for trial mixes per cubic meter.

Mix ID	Cement	Fly ash	GGBS	MS	RCA		NaOH	Na_2SiO_3	Water	Admixture /Superplasticizer
					CA – I (20mm)	CA – II (10mm)				
NCS	450			483	981	420			130	2.25
GPCS	-	170	236	483	981	420	68	102		

Table 5: Mix Design for Geopolymer Concrete Railway Sleepers

Parameter	Value	Parameter	Value
Grade	M 60	Binder + solution	564 g/m^3
Ratio of sleeper	1:1.22:3.51	Mass of binder	(564/1+0.43) = 394 g/m^3
Density	2450 kg/m^3	Fly ash (40%)	158 g/m^3
Consider aggregate present in concrete	1886kg (≈77%)	GGBS (60%)	236 g/m^3
Coarse aggregate – I (20mm) (70%)	981 g/m^3	A/B (liquid)	170 g/m^3
Coarse aggregate – II (10mm) (30%)	420 g/m^3	Ratio for liquid (NaOH: Na_2SiO_3)	1:2.5
Fine aggregate – M – sand	483 g/m^3	Sodium Hydroxide	68 g/m^3
Alkaline liquid	0.43 (assumed)	Sodium Silicate	102 g/m^3

Table 6 Mix Design Ratios provides the proportions of various components used in the geopolymer concrete mix. Fly ash constitutes 40% of the binder, while GGBS makes up 60%. The fine aggregate (M-sand) is included at a ratio of 1.22, and coarse aggregates are divided into two sizes: Coarse Aggregate – I (20mm) at 2.48 and Coarse Aggregate – II (10mm) at 1.06. The final mix ratio used for the concrete is 1:1.22:3.54.

Table 6: Mix Design Ratios

Component	Ratio
Fly Ash	0.4
GGBS	0.6
Fine Aggregate (M-Sand)	1.22
Coarse Aggregate – I (20mm)	2.48
Coarse Aggregate – II (10mm)	1.06
Final Mix Ratio	1:1.22:3.54

The calculation for the quantity of materials required to produce one railway sleeper details the specific amounts needed. The sleeper measures 2.75 meters in length, 0.2 meters in width, and 0.2 meters in depth, with a slope of 1:20, resulting in a volume of 0.11 m³. Including an additional 50% to account for excess, the total volume is 0.165 m³. The total material required is 396 kg, which includes 27.72 kg of fly ash, 41.58 kg of GGBS, 89.1 kg of fine aggregate (M-sand), 145.53 kg of coarse aggregate – I (20mm), and 62.37 kg of coarse aggregate – II (10mm). Additionally, 11.88 liters of sodium hydroxide and 17.82 liters of sodium silicate are used. Table 7 presents various trial mix ratios to assess the performance of the geopolymer concrete. These trials vary in the proportions of fly ash to GGBS and the ratio of recycled coarse aggregate (RCA) to natural coarse aggregate (NCA). Trial 1 uses 40% fly ash and 60% GGBS with an RCA ratio of 100:0, Trial 2 maintains the same fly ash and GGBS proportions but with a 0:100 RCA ratio, and Trial 3 employs a 70:30 RCA ratio.

Table 7: Trial Mix Ratios

Trial	Fly Ash	GGBS	RCA Ratio
1	40%	60%	100:0
2	40%	60%	0:100
3	40%	60%	70:30

Table 8: Preparation of Alkaline Solution

Step	Details
Calculate Amounts	Determine quantities of sodium hydroxide and sodium silicate (1:2.5 ratio).
Dissolve Sodium Hydroxide	Add 360 grams of sodium hydroxide pellets to 500 ml of water and stir until dissolved.
Dilute Solution	Dilute the dissolved solution to 1000 ml with additional water.
Scale Up	Adjust quantities as needed for the number of sleepers.
Safety Precautions	Use gloves during preparation due to the exothermic reaction of sodium hydroxide with water.

4. MANUFACTURING PROCESS OF SLEEPERS

The manufacturing process of geopolymer concrete railway sleepers involves several critical steps, ensuring precision and quality throughout.

Selection of Raw Materials: The process begins with the selection of raw materials, including fly ash, GGBS, M-sand, and coarse aggregates, which are combined with an alkaline activator solution and steel reinforcements.

Preparation of Alkaline Solution: The alkaline solution is prepared by mixing sodium hydroxide and sodium silicate in a 1:2.5 ratio. This mixture reacts with the raw materials to form a geopolymer paste that binds the components together. The preparation is carried out carefully to ensure the consistency of the solution, as illustrated in **Fig 2**, where sodium hydroxide is being dissolved and mixed.

Fig 2: Placement of Reinforcement

Preparation of Molds: The molds for the railway sleepers are fabricated to specific dimensions and are mounted on a steel bench designed to hold multiple molds in alignment, as shown in **Fig 3**. This setup is essential for maintaining uniformity during the molding process.

Fig 3: Batching process

Molding: The geopolymer concrete mixture is poured into the prepared molds, where steel inserts or frames are positioned to provide additional support. The casting process is visualized in **Fig 4**, which highlights the pouring of concrete into molds. Steel reinforcements, consisting of 16 high-tensile steel wires with a diameter of 3 mm and a length of 2.75 meters, are incorporated into the molds to enhance the structural strength of the sleepers.

Fig 4: Casting Process of Sleeper

Curing: After molding, the sleepers undergo a curing process to allow the geopolymer concrete to achieve its final strength. Curing can be conducted at ambient temperatures or through controlled heating, depending on the mix's requirements. This step is illustrated in **Fig 5**, showing the curing process.

Fig 5: Finishing of Sleeper Process

Demolding: Once curing is complete and the sleepers have attained the desired strength, they are carefully demolded. This step is depicted in **Fig 6**, which shows the accuracy checks and removal of the sleepers from the molds.

Fig 6: Checking the Accuracy Process

5. RESULTS AND DISCUSSIONS

Compression Test (IS 456:2000 and IS 516:1959)

The Table 10 presents the results of the compressive strength tests conducted on 150 mm × 150 mm × 150 mm cubes of different mixes, evaluated at curing periods of 7, 14, and 28 days. The average compressive strength values are recorded for each curing period, and the data is represented graphically in Fig 7.

Table 10: Compression test result in N/mm²

Mix Designation	7 Days	14 Days	28 Days
M 1	42.42	49.53	56.68
M 2	57.16	64.29	67.89
M 3	56.67	62.33	66.24

The Mix 2, featuring 100% Normal Coarse Aggregate (NCA), exhibits compressive strengths of 57.16 N/mm², 64.29 N/mm², and 67.89 N/mm² at 7, 14, and 28 days of curing, respectively. This mix shows superior strength performance compared to the other mixes. The difference in compressive strength between Mix 2 (100% NCA) and Mix 3 (70% Recycled Coarse Aggregate (RCA) and 30% NCA) is marginal, at approximately 2.46%, demonstrating minimal impact of RCA on compressive strength.

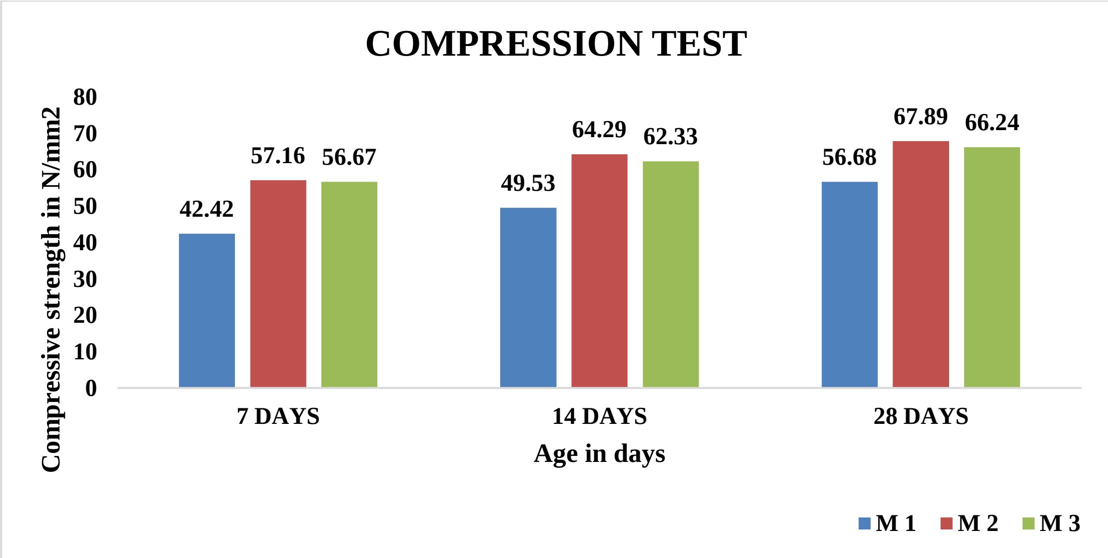

Fig 7: Compressive Strength of Trail Mixes

Flexural Test (IS 516:1959)

Table 11 shows the results of the flexural strength tests performed on beams of dimensions 500 mm × 100 mm × 100 mm, assessed at curing periods of 7, 14, and 28 days. The average flexural strength values are detailed for each curing period and illustrated in Fig 8.

Table 11: Flexural test result for Trail mixes

Mix Designation	7 Days	14 Days	28 Days
M 1	3.88	4.42	5.21
M 2	4.02	4.74	5.49
M 3	3.97	4.53	5.36

The Mix 2, containing 100% NCA, exhibits flexural strengths of 4.02 N/mm², 4.74 N/mm², and 5.49 N/mm² at 7, 14, and 28 days, respectively. This mix demonstrates superior flexural strength compared to other mixes. The strength discrepancy between Mix 2 (100% NCA) and Mix 3 (70% RCA and 30% NCA) is approximately 5.233%, indicating a relatively minor effect of RCA on flexural strength.

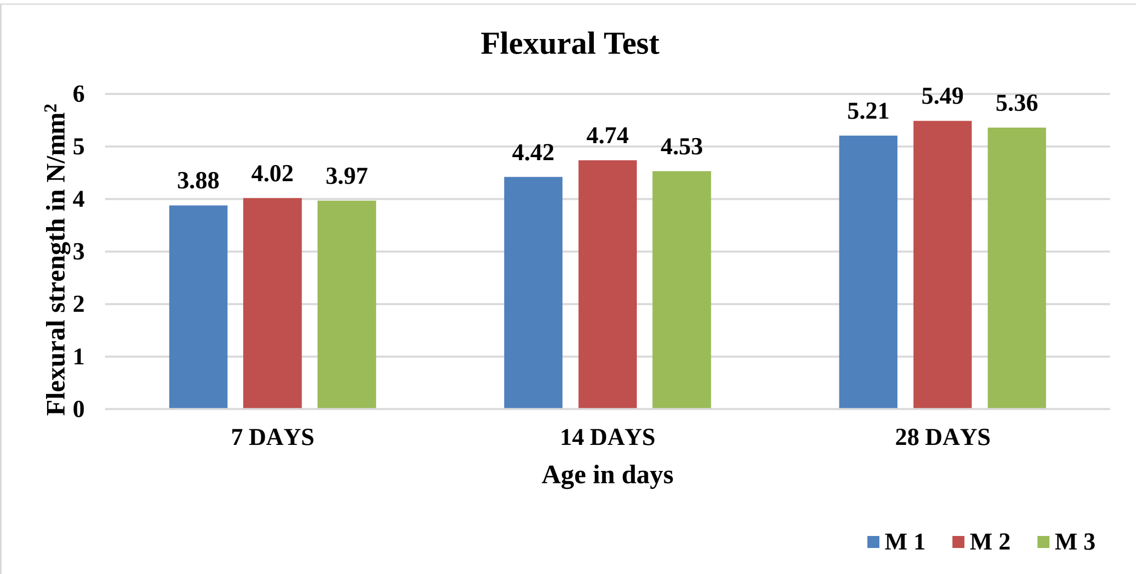

Fig 8: Flexural Test Strength for Trail Mixes

Split Tensile Test (IS 456:2000 and IS 5816:1999)

The Table 12 presents the results of the split tensile strength tests performed on cylinders with dimensions 200 mm × 100 mm, assessed at 7, 14, and 28 days of curing. The average split tensile strength values are documented for each curing period and depicted in Fig 9.

Table 12: Split Tensile test result for Trail mixes

Mix Designation	7 Days	14 Days	28 Days
M 1	3.42	3.88	4.42
M 2	5.13	5.58	5.76
M 3	4.79	5.06	5.38

The Mix 2, comprising 100% NCA, shows split tensile strengths of 5.13 N/mm², 5.58 N/mm², and 5.76 N/mm² at 7, 14, and 28 days, respectively. This indicates that Mix 2, constructed entirely with NCA, exhibits superior split tensile strength. The strength variation between Mix 2 (100% NCA) and Mix 3 (70% RCA and 30% NCA) is minimal, at around 6.823%, demonstrating a minor impact of RCA on split tensile strength.

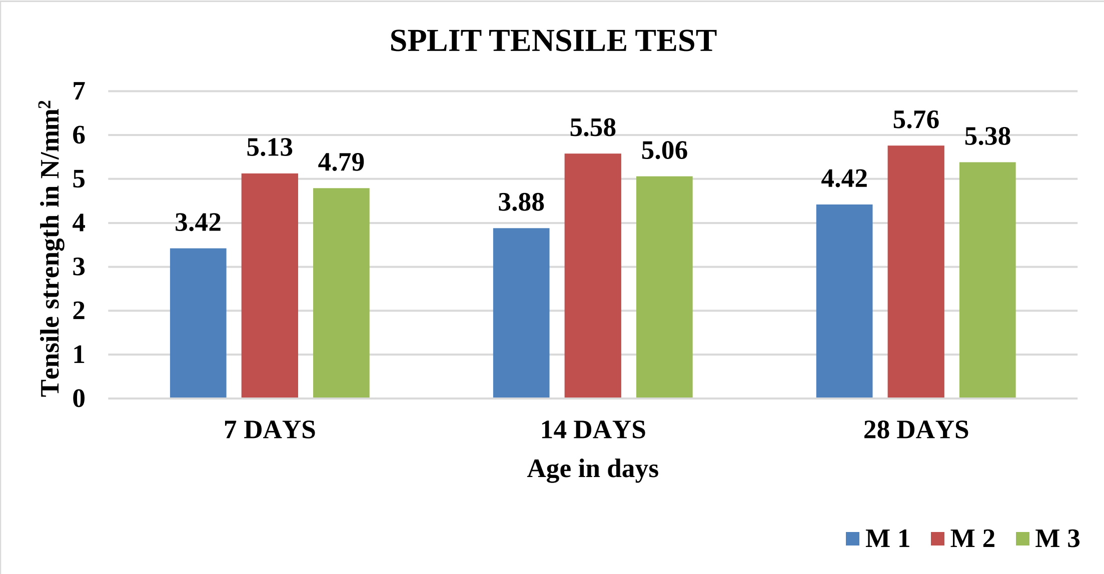

Fig 9: Split Tensile strength for Trail Mixes

Static Bending Test: The static bending test is a critical evaluation procedure used to determine the bending strength and rigidity of concrete railway sleepers or other structural elements. This test assesses how well a sleeper can withstand bending loads, which is crucial for ensuring its performance under real-world conditions. The static bending test is vital for ensuring that railway sleepers are designed and manufactured to withstand the operational stresses they will encounter, ensuring safety and longevity in railway infrastructure. The Fig 10 illustrates the testing arrangements for the static bending test, which is designed to assess the bending strength of the sleepers. The Fig 11 shows the cross-section of the sleeper used in the test, providing a detailed view of its dimensions and internal structure.

Fig 10: Testing arrangements for Static Bending Test

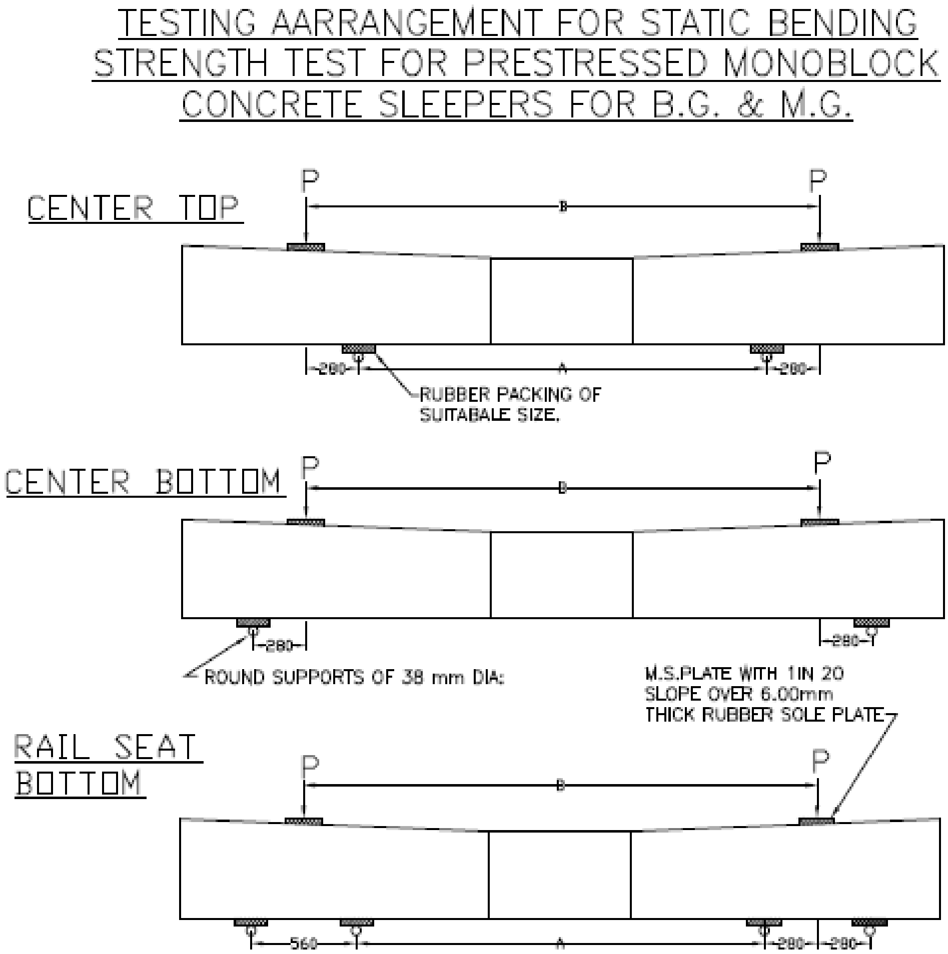

Fig 11: Cross Section of Sleeper

The Fig 12 depict the Centre Top Method employed in the static bending test. In this procedure, a load is applied at the top center of the sleeper, perpendicular to its longitudinal axis, at a rate of 15 kN/min. This method evaluates the sleeper's ability to withstand loads applied directly at the center of its top surface.

Fig 12: Centre Top Method in Static Bending Test

The Fig 13 illustrates the Rail Seat Method, where the load is applied to the sleeper at specific points (RS1 and RS2) to simulate the conditions experienced by the sleeper in real railway track scenarios. The load is also maintained at a rate of 15 kN/min. This method replicates the forces exerted by railway rails and train traffic, providing a realistic assessment of the sleeper's performance under operational conditions.

Fig 13: Rail Seat Method

Conventional vs Geopolymer Concrete Railway Sleepers

Railway sleepers, also referred to as railroad ties or crossties, are critical components of railway infrastructure. These horizontal beams, typically constructed from wood, concrete, or steel, are positioned beneath the railway rails to provide essential support and stability. The primary functions of sleepers include distributing the load of the train and its cargo across the ballast, maintaining the rail gauge, and ensuring smooth and safe rail operations. Over time, railway sleepers experience wear and tear due to the constant dynamic loads from trains and environmental exposure. As a result, regular maintenance and replacement are necessary to uphold the safety and efficiency of railway operations. Modern trends favor the use of more durable materials such as concrete and steel, which offer extended service lives and reduced maintenance compared to traditional wooden sleepers. The table 13 provides the acceptance cracking and failure load values for concrete sleepers under different loading configurations. It includes the minimum required loads for various test conditions, such as center top and rail seat bottom loading.

Table 13: Load Acceptance for Concrete Sleepers Broad Guage Test load for acceptance (P in kN) (IRS T-39-85 Fifth Revision - Feb 2016)

Sleeper	Center Top (kN)	Center Bottom (kN)	Rail Seat Bottom	
			Cracking (kN)	Failure (kN)
BG	60	52.5	230	370
MG	25	40	150	250

Table 14 shows the detailed test results of the cracking load values for normal concrete sleepers. It compares the measured cracking loads with the reference values to evaluate the performance of the sleeper mix.

Table 14: Testing Results of Conventional Concrete Sleepers

Sleeper No	MR Test (Load in kN)		Rail Seat Bottom		
	Center Top (CT)	Center Bottom (CB)	Cracking Load (kN)		MF Test (Load in kN)
			1st Rail Seat	1st Rail Seat	
1	79	69	287	289	438

The table 15 details the cracking load values for different Geopolymer concrete sleeper types. It compares the measured cracking loads against reference values to assess the performance of each sleeper mix.

Table 15: Cracking Load Values for Concrete Sleepers

Sleeper Type	Center Top (CT) Cracking Load (kN)	Average CT Load (kN)	Reference CT Cracking Load (kN)	Center Bottom (CB) Cracking Load (kN)	Average CB Load (kN)	Reference CB Cracking Load (kN)
M2A	84	82.5	≥68	68	68.5	≥60
M2B	81	-		69	-	
M3A	77	76.5		66	66.0	
M3B	76	-		66	-	

The table 16 summarizes the cracking load values for different sleeper mixes tested at the rail seat. It shows how each mix performs in terms of load-bearing capacity and provides average cracking loads compared to reference values.

Table 16: Rail Seat Positive Bending Moment at Cracking Limits

Sleeper Type	Cracking Load (kN)		Reference Cracking Load (kN)	MF Test (Load in kN)
	1st Rail Seat	2nd Rail Seat		
M2A	302	305	≥270	531
M2B	297	300		523
M3A	284	287		521
M3B	283	285		517

The experimental results of compressive strength, flexural strength, and split tensile strength indicate the performance characteristics of different mixes of geopolymer concrete railway sleepers. M1 mix was rejected as the compressive strength is not fitted to cast the sleeper. For compressive strength, mixes M2 and M3, with 100% Normal Coarse Aggregate (NCA) and a blend of 70% Recycled Coarse Aggregate (RCA) and 30% NCA respectively, exhibit promising results, satisfying the compressive strength requirement of ≥60 N/mm² as per IRS specifications. These mixes were further evaluated through static bending tests, where they withstood the specified loads for Moment of Resistance (MR) and Moment of Failure (MF). The tested sleepers exhibited satisfactory performance under various loading conditions, indicating their suitability for railway infrastructure. The geopolymer concrete mixes M2 and M3 demonstrated adequate compressive, flexural, and tensile strengths, meeting the required standards for railway sleepers. The static bending tests confirmed that these sleepers, whether composed of NCA or a combination with RCA, can perform effectively under simulated railway conditions. This reinforces the feasibility of using geopolymer concrete with recycled aggregates as a viable alternative to traditional concrete sleepers.

Cracking behaviours

The cracking behaviors and failure modes of all tested sleepers under impact loads are illustrated in Figures 14 and 16. For all tested sleepers, both flexural and shear cracks were induced by the drop hammer impact, regardless of the potential energy level, aligning with the findings of Kaewunruen and Remennikov [46]. However, the cracking patterns under impact load differed from their failure modes under static load [47]. Most sleepers exhibited a flexural-tension failure mode without forming shear cracks under static loading. In this study, severe diagonal cracks initiated at the impact point and propagated to the bottom surface at an angle of approximately 45°. The test results indicated that under drop hammer impact, severe diagonal cracks forming shear-plugs of RC beams were observed, even though the beams displayed ductile flexural failure modes under static loads. Minor flexural and shear cracks were observed in the geopolymer concrete sleeper, with small amounts of concrete chipping out under the load in the mix with a 30% replacement of natural coarse aggregate.

Fig 14: Failure moment at Rail seat - shear failure – Normal Concrete Sleeper

Fig 15: Flexural-shear failure – Geopolymer Concrete Sleeper- Mix 2

Fig 16: Flexural-shear cracking with concrete crushing – Geopolymer Concrete Sleeper- Mix 3

Tables 17 and 18 present a detailed cost analysis for normal concrete sleepers and geopolymer concrete sleepers, respectively, highlighting the material expenses associated with each type and allowing for a comparative assessment of their economic viability.

Table 17: Cost Analysis for Normal Concrete Sleepers

Sl. No.	Material	Quantity Required for 1 Sleeper	Rate in Rs	Cost in Rs
1	Cement Grade 53s	59.4 kg	400 Rs/bag	475.2
2	Manufactured Sand	63.76 kg	900 Rs/ton	57.38
3	Natural Coarse Aggregate size 20mm	129.49 kg	600 Rs/ton	77.69
4	Natural Coarse Aggregate size 10mm	55.44 kg	680 Rs/ton	37.69
5	Reinforcement (3mm 3Ply HTS Wire)	7.35 kg	70 Rs/kg	514.36
6	Admixtures (AURACAST 270M)	0.294 kg	95 Rs/kg	27.93
7	Water	17.16 kg	-	-
Total Material Cost				1190.25

Table 18: Cost Analysis for Geopolymer Concrete Sleepers

<table>
<tr><th>Sl. No.</th><th>Material</th><th>Quantity Required for 1 Sleeper</th><th>Rate/Ton in Rs</th><th>Cost in Rs</th></tr>
<tr><td>1</td><td>Fly Ash</td><td>59.4 kg</td><td>Free of Cost</td><td>0</td></tr>
<tr><td>2</td><td>Recycled Coarse Aggregate size 20mm</td><td>129.49 kg</td><td>Free of Cost</td><td>0</td></tr>
<tr><td>3</td><td>Recycled Coarse Aggregate size 10mm</td><td>55.44 kg</td><td>Free of Cost</td><td>0</td></tr>
<tr><td>4</td><td>Manufactured Sand</td><td>63.76 kg</td><td>900 Rs/ton</td><td>57.38</td></tr>
<tr><td>5</td><td>Sodium Silicate</td><td rowspan="2">17.16 kg</td><td>60 Rs/kg Solution</td><td rowspan="2">663.00</td></tr>
<tr><td>6</td><td>Sodium Hydroxide</td><td>17.40 Rs/kg Solution</td></tr>
<tr><td>7</td><td>Reinforcement (3mm 3Ply HTS Wire)</td><td>7.35 kg</td><td>70 Rs/kg</td><td>514.16</td></tr>
<tr><td>8</td><td>Water</td><td>-</td><td>Free of Cost</td><td>0</td></tr>
<tr><td colspan="4">Total Material Cost</td><td>1234.00</td></tr>
</table>

Normal Concrete - The total material cost for one sleeper is 1190.25 Rs. The primary cost contributors are cement, reinforcement, and coarse aggregates. Geopolymer Concrete - The total material cost for one sleeper is 1234.00 Rs. The higher cost is primarily due to the inclusion of sodium silicate, despite some materials being free of cost, such as fly ash and recycled aggregates. Despite its slightly higher material costs, geopolymer concrete offers several advantages over traditional normal concrete. One of its most significant benefits is its reduced environmental impact. Geopolymer concrete uses industrial by-products such as fly ash and slag, which greatly decreases reliance on Portland cement and reduces CO_2 emissions associated with cement production. In the calculation table, the material costs are shown as zero because these waste materials are often freely available or sponsored, and their use prevents environmental harm from disposal. Consequently, transportation or collection charges depend on the material's availability. This practice conserves natural resources and mitigates the environmental impact of construction activities. Geopolymer concrete also demonstrates superior durability compared to normal concrete, showing excellent resistance to high temperatures, acidic conditions, and chemical attacks. This enhances the lifespan of structures and reduces maintenance costs. Although the initial material cost of geopolymer concrete may be higher, its improved durability and lower maintenance needs can result in reduced long-term costs, making it a cost-effective choice over the structure's lifespan.

6. CONCLUSION

The experimental investigations have yielded several critical insights into the performance and sustainability of geopolymer concrete sleepers compared to traditional normal concrete sleepers:

- **Mechanical Performance:** Geopolymer concrete sleepers demonstrate comparable or enhanced structural strength relative to conventional concrete sleepers. Notably, geopolymer sleepers made with 100% natural coarse aggregate exhibit a compressive strength of 67.89 N/mm², while those incorporating 70% recycled aggregate achieve a compressive strength of 66.24 N/mm², indicating only a marginal reduction in strength.

- **Environmental Impact:** Geopolymer concrete significantly reduces environmental impact by substituting Portland cement with industrial by-products such as fly ash and Ground Granulated Blast Furnace Slag (GGBS). Additionally, the incorporation of recycled aggregates further diminishes the ecological footprint, contributing to more sustainable construction practices.
- **Structural Integrity:** The moment resistance of geopolymer concrete sleepers surpasses that of normal concrete sleepers. Specifically, geopolymer sleepers with 100% natural aggregates achieve a moment resistance of 293 kN, whereas those with 70% recycled aggregates record a moment resistance of 285 kN. In comparison, normal concrete sleepers exhibit a moment resistance of 287 kN.
- **Curing and Set Time:** Geopolymer concrete exhibits rapid setting characteristics and can be cured under ambient conditions, which contrasts with the traditional curing methods required for normal concrete, such as steam and water curing. This property enhances the efficiency of construction processes.
- **Carbon Footprint:** The use of geopolymer concrete results in a significantly lower carbon footprint due to reduced reliance on Portland cement, thereby mitigating the greenhouse gas emissions associated with its production.
- **Cost Analysis:** Despite a marginal increase in material costs geopolymer concrete sleepers being priced at 1234.00 Rs compared to 1190.25 Rs for normal concrete sleepers the overall economic benefits, including enhanced durability and environmental advantages, make geopolymer sleepers a cost-effective and superior alternative.

Overall, while geopolymer concrete sleepers incur a slight increase in material costs, their superior environmental performance, comparable or enhanced mechanical properties, reduced carbon footprint, and efficient curing processes render them a highly advantageous choice for modern infrastructure development. The marginal cost difference is offset by their long-term benefits and sustainability, making geopolymer concrete a compelling option in the field of railway sleeper technology.

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