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FLEXURAL BEHAVIOR OF RAILWAY PRE-STRESSED GEOPOLYMER COMPOSITE SLEEPERS

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ABSTRACT

This experimental investigation evaluates the flexural behavior of prestressed geopolymer sleepers in comparison to conventional prestressed concrete (PSC) sleepers, adhering to RDSO and IRS T-39 standards. Four sleeper specimens were analyzed: M-60 (control mix), M-60+GF (M-60 with glass fiber), GPC-16M (16 Molarity geopolymer concrete), and GPC-16M+GF (GPC-16M with glass fiber). Key parameters studied included static load at the center top, moment of resistance at the rail seat bottom, and full-scale static bending tests. Results indicated that GPC-16M+GF outperformed the other specimens, exhibiting a 25.47% increase in 28-day compressive strength and a 65.8% increase in flexural strength compared to M-60. Static bending tests revealed a 63.71% increase in center top load and an 8.24% increase in moment of resistance for GPC-16M+GF. Additionally, this specimen demonstrated superior ductility and toughness, with a 47.46% enhancement in energy absorption capacity. The findings suggest that the integration of glass fiber and geopolymer concrete significantly improves the mechanical properties and durability of PSC railway sleepers, enhancing their performance under static loads and extending track life.

Keywords: Geopolymer Concrete (GPC), High-Performance Concrete (HPC), Glass Fibers (GF), Molarity, Prestressed Composite Sleepers.

I. INTRODUCTION

Indian Railways serves as a vital component of the nation's transport infrastructure, facilitating connectivity and promoting national integration across diverse regions. Despite the expansion of road networks, railways remain a primary mode of transportation, operating over 13,000 trains daily on a vast 68,988-kilometer network. However, much of this infrastructure is over a century old and is increasingly challenged by rising rail traffic, heavier axle loads, and the need for modernization. Prestressed Concrete (PSC) railway sleepers are essential for maintaining track stability and alignment, yet the growing demand for transportation has led to the deterioration of existing track systems.

To address these challenges, the exploration of High-Performance Concrete (HPC) and Geopolymer Concrete (GPC) presents promising alternatives. HPC is engineered to enhance durability and structural capacity, while GPC, derived from industrial by-products, offers significant environmental benefits, including reduced carbon emissions. This research focuses on the static behavior of prestressed geopolymer composite sleepers, aiming to evaluate their mechanical properties and performance compared to conventional PSC sleepers. By investigating the potential of advanced materials like Ground Granulated Blast Furnace Slag (GGBS) and fly ash, this study seeks to enhance the strength and durability of railway sleepers, ultimately contributing to the sustainability and efficiency of railway infrastructure.

Geopolymer are component of the existing sustainable Cementitious binder systems, that can be synthesized from an extensive range of precursors rich in alumina and silica, with diverse accessibility, reactivity, and of course, cost-effectiveness across the planet. Quite recently, they have aroused as a most modern binder with ecological sustainability attributes. Their ceramic-like characteristics established them as thermal and fire-resistant materials. The production process i.e., geopolymerization interestingly displays low carbon footprints and lower energy ingesting which is roughly 60% lesser than the present OPC-production, as well as the reaction kinetics requires low-temperature conditions at just atmospheric pressure. Not only have that, nine times less CO_2 emissions helps to relief the great dilemma of global warming as compared to existing OPC producing clinker's emissions.

II. EXPERIMENTAL PROGRAM

The present experimental program was designed to investigate the flexural behavior Railway Pre-Stressed Geopolymer Composite Sleepers as per IRS T-39. PSC sleepers were reinforced with Glass fibers. The concrete mix ingredients consist of Cement, fly ash, GGBS and Glass fibers on four different mixes with the following PSC railway sleeper test specimens. The experimental setup was carried out in accordance with IRS T-39.

III. MATERIALS

Different types of materials are used to produce geopolymer concrete, a combination of Cement, Class-F fly ash and ground granulated blast furnace slag (GGBS) were used, both sourced from the Ultratech RMC Plant in Bangalore. These materials were selected as primary binders due to their high silica and alumina content, which are essential for the geopolymerization process. Locally available crushed sand (M-Sand) served as the fine aggregate, passing through a 4.75 mm sieve and retained entirely on a 150-micron sieve, ensuring an optimal particle size distribution. Coarse aggregates of 20 mm downsize were incorporated to achieve the required strength and workability. Portable water was added to adjust the mixture consistency and enable proper handling during casting. An alkaline activator solution was employed, mixed at a ratio of 0.25 with sodium silicate (Na_2SiO_3) and sodium hydroxide (NaOH) in a defined ratio to enhance the polymerization reaction and increase the concrete's mechanical properties. To ensure the feasibility and quality of the materials, physical tests on the fine and coarse aggregates were performed in accordance with IS 383-2016 and IS 2386 (Parts 1-4, reaffirmed in 2002)

IV. METHODOLOGY

The experimental program aims to evaluate the ductility, bending strength, fracture strength, and resistance to fracture of prestressed concrete (PSC) railway sleepers. The bending test is crucial for determining the material's performance under pressure, especially for ductile materials subjected to bending forces.

4.1 Mechanical Properties of Concrete

4.1.1 Compression Strength Test

Concrete quality is assessed by measuring compressive strength, defined as the load causing failure divided by the cross-sectional area.

Standard cube moulds (150 mm x 150 mm x 150 mm) are used as per IS:516-1959.

Testing is conducted using a 300 T capacity compressive testing machine, applying load uniformly at a rate of 35 to 40 kN per minute until failure.

Compressive strength is calculated using the formula:

$f = P/A$ (N/mm^2)

4.1.2 Flexural Strength Test

Flexural strength is evaluated using bending tests on beam specimens (100 mm x 100 mm x 500 mm).

The modulus of rupture is calculated based on the location of fracture:

If the fracture occurs within the middle third of the span, a>133 mm,

$fb = PL/bd^2$ (N/mm^2)

If the fracture occurs outside the middle third but deviating by not more than 5 percent of the span length, 110 < a < 133mm

$fb = 3Pa/bd^2$ (N/mm^2)

If fracture occurs by more than 5 percent outside the middle third, a < 110mm, then the results of the test should be rejected

4.2 Static Bending Test

The static bending test for railway sleepers is a critical evaluation used to assess the flexural strength and durability of sleepers under load. This test is particularly important for materials like concrete, wood, or composite sleepers, which support railway tracks and bear the repetitive, high-stress loads from passing trains. Understanding the bending behavior and load-bearing capacity of sleepers helps ensure the reliability and longevity of railway infrastructure, where sleeper failure could lead to significant operational and safety issues.

The static bending strength test of PSC geopolymer railway sleeper specimens under monotonic loading until ultimate stage was conducted to investigate:

- Moment of resistance (MR) test (Rail seat bottom, center top)
- Moment of failure (MF) test (Rail seat bottom)

The Moment of Resistance test at Rail seat bottom and Center Top and Moment of Failure test at Rail seat bottom were conducted on the specimens for four different mixes.

4.3 Full-Scale Static Bending Test

The full-scale static bending test on railway sleepers is conducted to evaluate the flexural strength, load-bearing capacity, and deformation characteristics of sleepers under static loading conditions. This methodology replicates the actual service loads that sleepers experience in railway installations, allowing for an accurate assessment of their performance and durability.

The Full-Scale Static Bending Test of the prestressed concrete railway sleeper test specimens under monotonic loading condition was conducted. The experimental Load deflection values comprising of First Crack Load and Ultimate Load, Ductility index, Toughness index, Energy absorption and Crack pattern were obtained for different concrete matrices of prestressed concrete railway sleeper test specimens.

4.4 Mixes

Different mixes are prepared for testing:

M-60 (HPC): Control mix.

M-60+GF: M-60 with glass fiber.

GPC-16M: Geopolymer concrete with 16 molarity.

GPC-16M+GF: Geopolymer concrete with 16 molarity and glass fiber.

The materials required for each mix are specified in terms of weight for cement, aggregates, water, and additives.

This methodology outlines the systematic approach taken to evaluate the performance of PSC railway sleepers under various mechanical tests and conditions.

V. RESULTS AND DISCUSSION

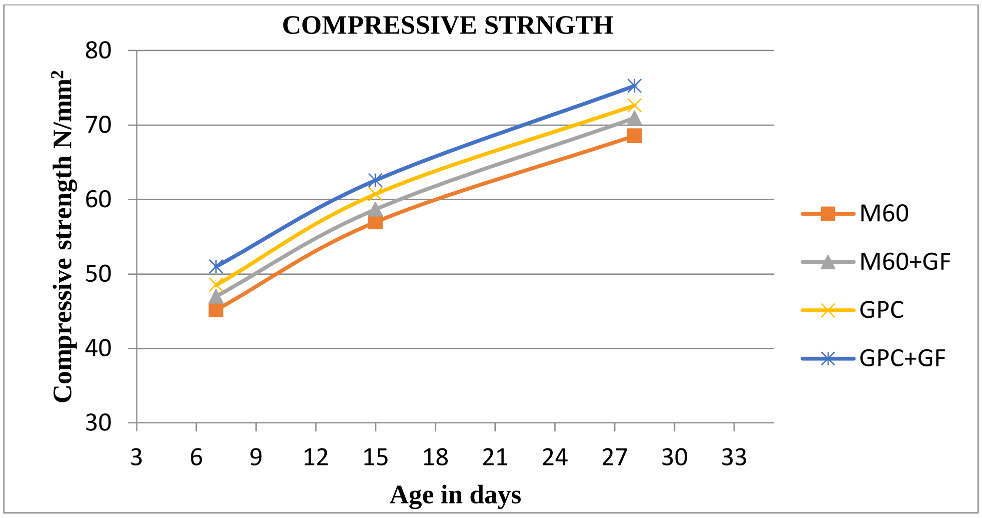
The investigation into the performance of prestressed concrete (PSC) railway sleepers using various concrete matrices revealed significant findings regarding compressive strength, flexural strength, static and Full-static bending tests and overall structural behavior.

5.1 Results of Compressive Strength

The compressive strength tests conducted on the four concrete mixes (M-60, M-60+GF, GPC-16M, and GPC-16M+GF) demonstrated that all mixes exceeded the minimum compressive strength requirement of 60 N/mm^2 as per IRS T-39 specifications. The results indicated that GPC-16M+GF achieved the highest compressive strength of 75.28 N/mm^2 at 28 days, surpassing the minimum requirement by 25.47%. This suggests that the incorporation of geopolymer concrete and glass fibers significantly enhances the compressive strength of railway sleepers, which is crucial for their durability and performance under load.

Table 5.1 Summary of 7, 15 and 28 days Compressive Strength of Test Specimens

Properties	Age (Days)	M-60 (N/mm^2)	M-60+ GF (N/mm^2)	GPC+16M (N/mm^2)	GPC+16M+GF (N/mm^2)
Compressive strength	7	45.18	47.01	48.52	51.01
	15	56.98	58.69	60.74	62.59
	28	68.57	70.95	72.64	75.28



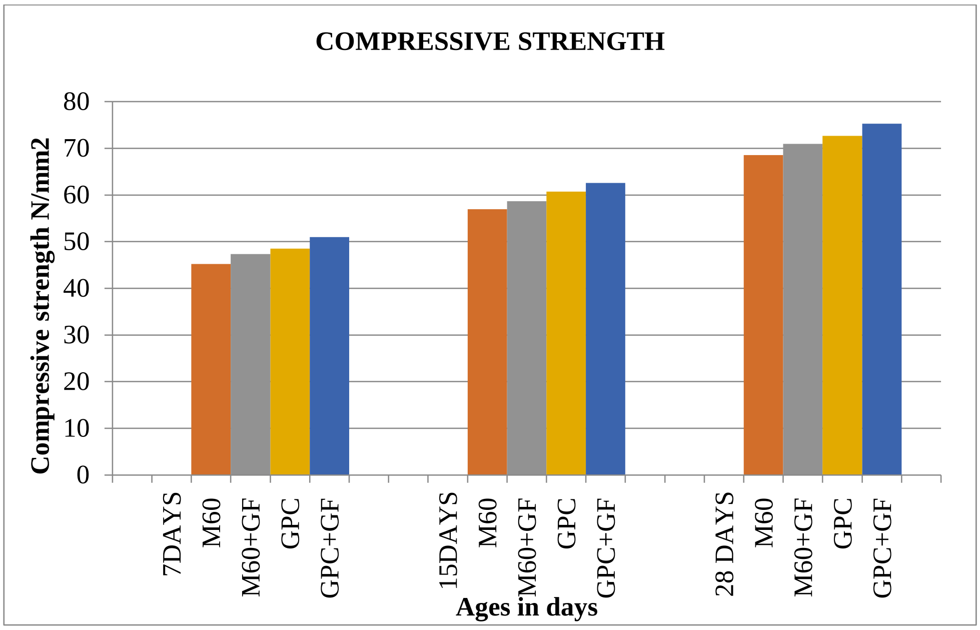


Fig 5.1 Comparison of Compressive Strength with Age of different concrete matrices

5.2 Results of flexural Strength

Similar trends were observed in the flexural strength tests, where all mixes exceeded the minimum requirement of 5 N/mm^2. The GPC-16M+GF mix exhibited the highest flexural strength of 8.29 N/mm^2 at 28 days, which is 65.8% higher than the minimum specified by IRS T-39. This improvement in flexural strength indicates that the addition of glass fibers and the use of geopolymer concrete contribute positively to the structural integrity of the sleepers, enhancing their ability to withstand bending stresses.

Table 5.2 Summary of 7, 15 and 28 days Flexural Strength of Test Specimens

Properties	Age (Days)	M-60 (N/mm^2)	M-60+ GF (N/mm^2)	GPC+16M (N/mm^2)	GPC+16M+GF (N/mm^2)
Flexural strength	7	5.12	5.54	5.91	6.26
	15	5.64	6.05	6.48	6.97
	28	6.96	7.37	7.88	8.29

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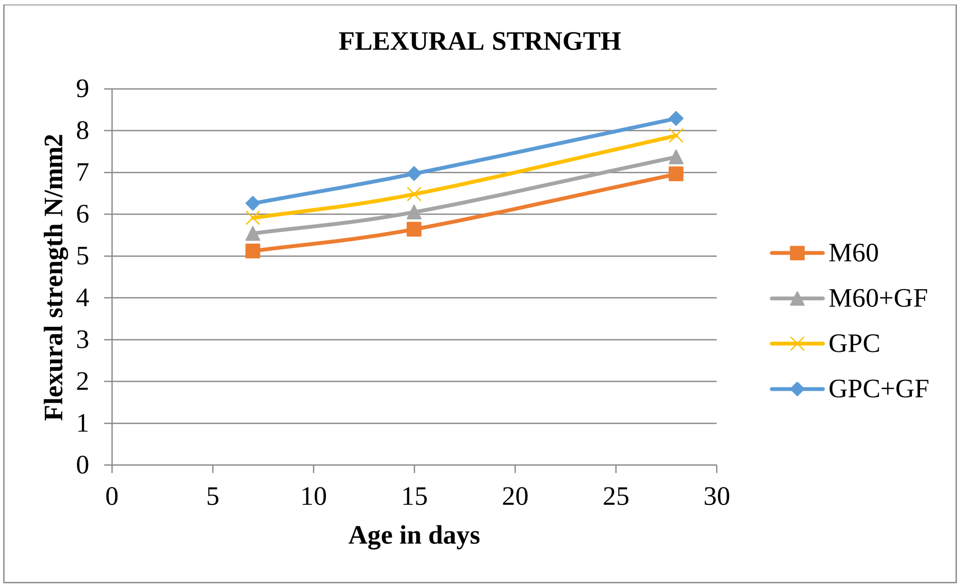

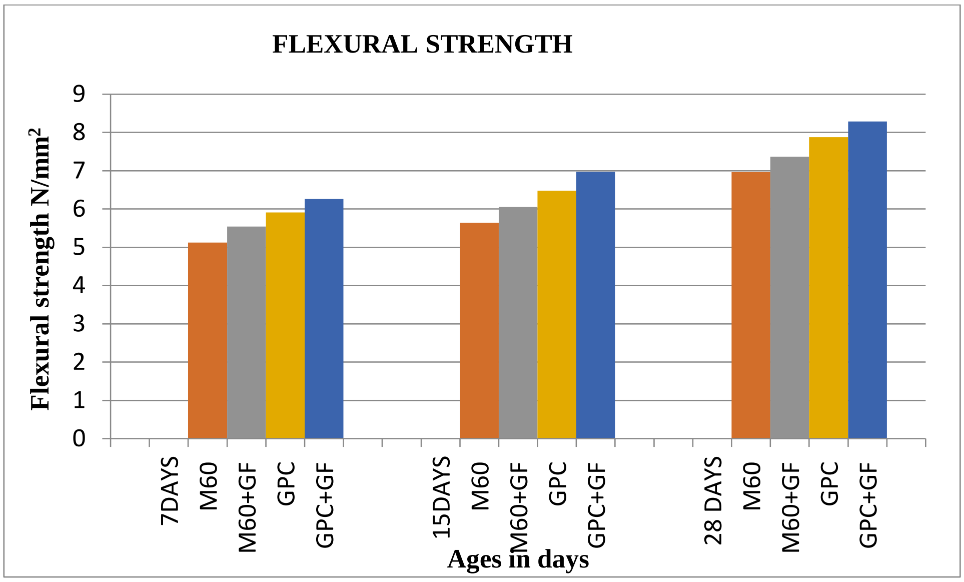

Fig 5.2 Comparisons of Flexural Strength of different concrete matrices

5.3 Results of Static Bending Test

The static bending tests revealed that all test specimens surpassed the standard load values specified by IRS T-39. The GPC-16M+GF mix showed the highest moment of resistance and moment of failure, indicating superior performance under static loading conditions. The results suggest that the use of geopolymer concrete and glass fibers not only improves the load-carrying capacity but also enhances the overall structural performance of the railway sleepers.

The load values for the Center Top of M-60, M-60+GF, GPC-16M, and GPC-16M+GF are 80.2 kN, 84.2 kN, 90.56 kN, and 98.23 kN, respectively, reflecting an increase of 33.6%, 40.33%, 51%, and 63.71% over the standard load of 60 kN (IRS T-39). Relative to the M-60 specimen, the percentage increases are 5%, 13%, and 23% for M-60+GF, GPC-16M, and GPC-16M+GF, respectively.

In the Moment of Resistance (MR) test, load values average of RHS and LHS for M-60, M-60+GF, GPC-16M, and GPC-16M+GF are 235.65 kN, 238.30 kN, 243.65 kN, and 248.96 kN, corresponding to increases of 2.45%, 3.6%, 6%, and 8.24% over the standard 230 kN. Compared to M-60, the increases are 1.1%, 3.39%, and 5.64%.

For the Moment of Failure (MF) test, Average of RHS and LHS of M-60, M-60+GF, GPC-16M, and GPC-16M+GF specimens achieved 422.23 kN, 428.28 kN, 432.80 kN, and 436.76 kN, respectively, surpassing the standard 370 kN by 14.11%, 15.75%, 17%, and 18.04%. The increases relative to M-60 are 1.43%, 2.5%, and 3.44%.

Table 5.3 Details of Static bending strength test values

Sleeper	Center top	Rail seat bottom			
	(kN)	Moment of resistance (kN)		Moment of failure (kN)	
		LHS	RHS	LHS	RHS
STANDARD LOAD	60	230	230	370	370
S1 M-60	80.20	233.20	238.10	420.20	424.50
S2 M-60+GF	84.20	235.10	241.50	426.34	430.23
S3 GPC-16M	90.56	240.50	246.80	431.21	434.39
S4 GPC-16M+GF	98.23	245.32	252.6	434.89	438.64

5.4 Results of Full-Scale Static Bending test

A Full-Scale Static Bending Test on prestressed concrete (PSC) railway sleeper specimens was conducted under monotonic loading until failure to assess load-deflection behavior, including First Crack Load and Ultimate Load, as well as Ductility Index, Toughness Index, Energy Absorption Capacity, and Crack Patterns. Experimental results for these parameters were obtained for various concrete matrices in PSC sleeper specimens.

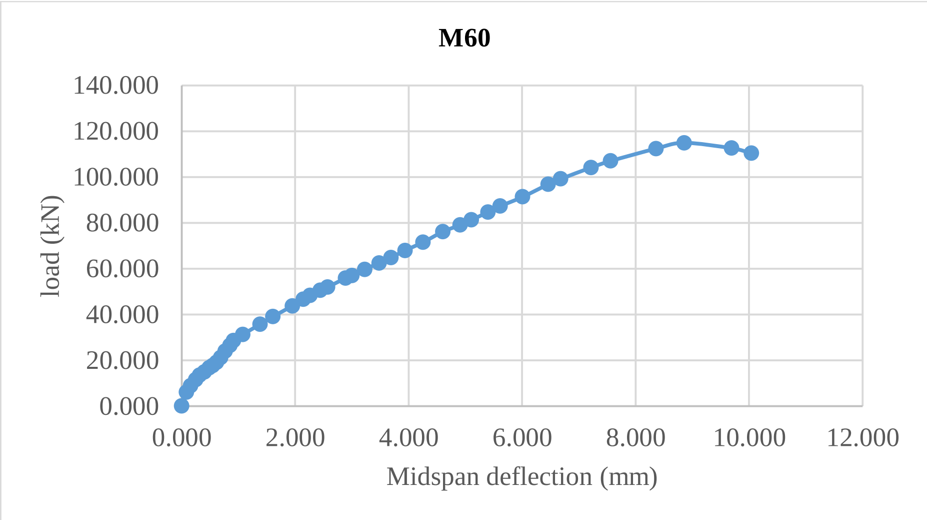

Fig 5.3 Load - Deflection curve for S1:M60

The ultimate load carrying capacity for High Performance Concrete (S1:M60) is 114.91kN, first crack load 28.58kN.

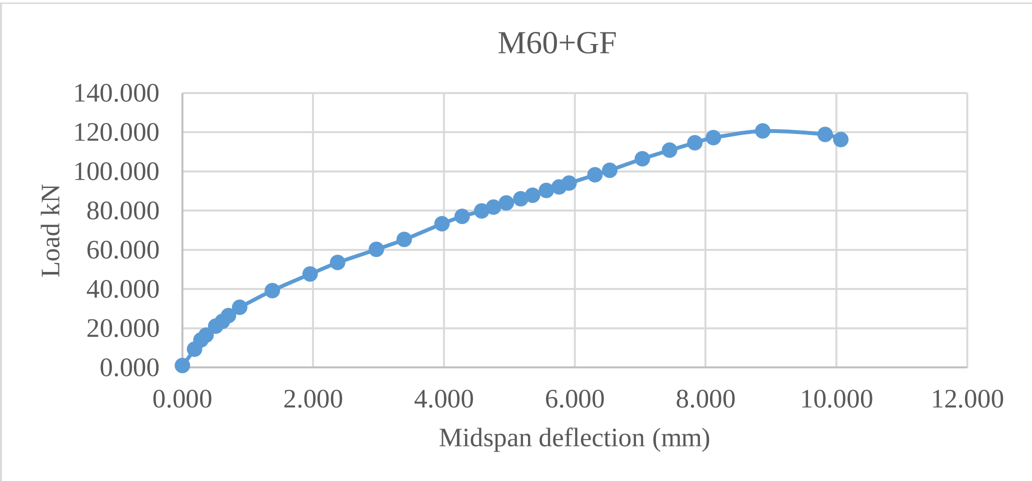

Fig 5.4 Load - Deflection curve for S2:M60+GF

The ultimate load carrying capacity for High Performance Concrete with glass fibre (S2:M60+GF) is 120.56kN and first crack load 30.65kN

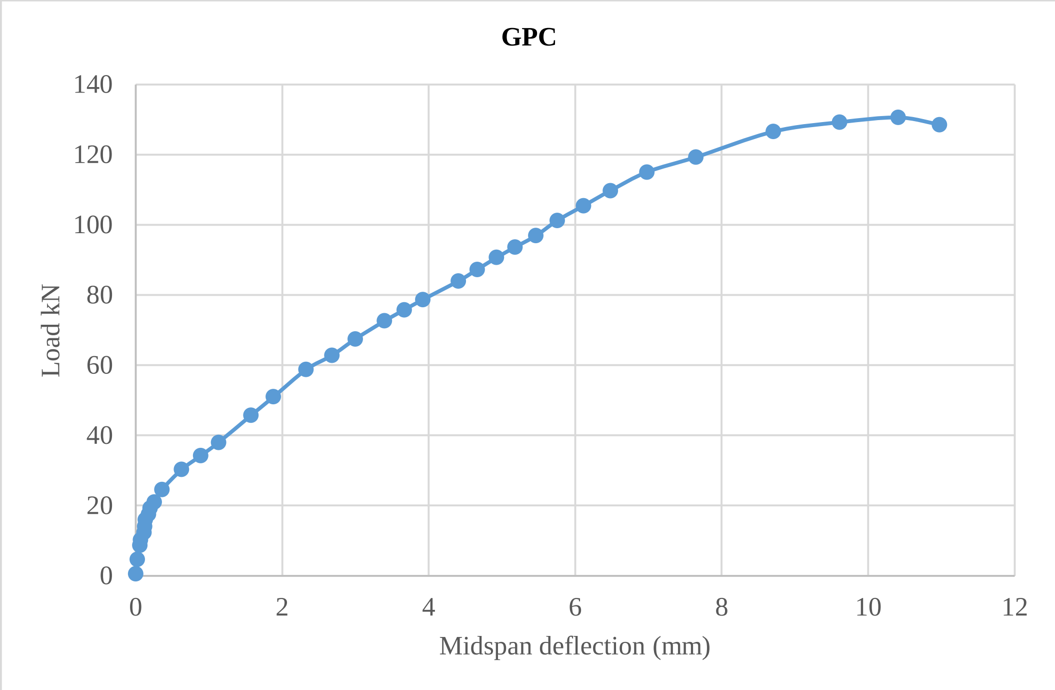

Fig 5.5 Load - Deflection curve for S3:GPC

The ultimate load carrying capacity for geopolymer concrete (S3:GPC) is130.56kN and first crack load 34.20kN

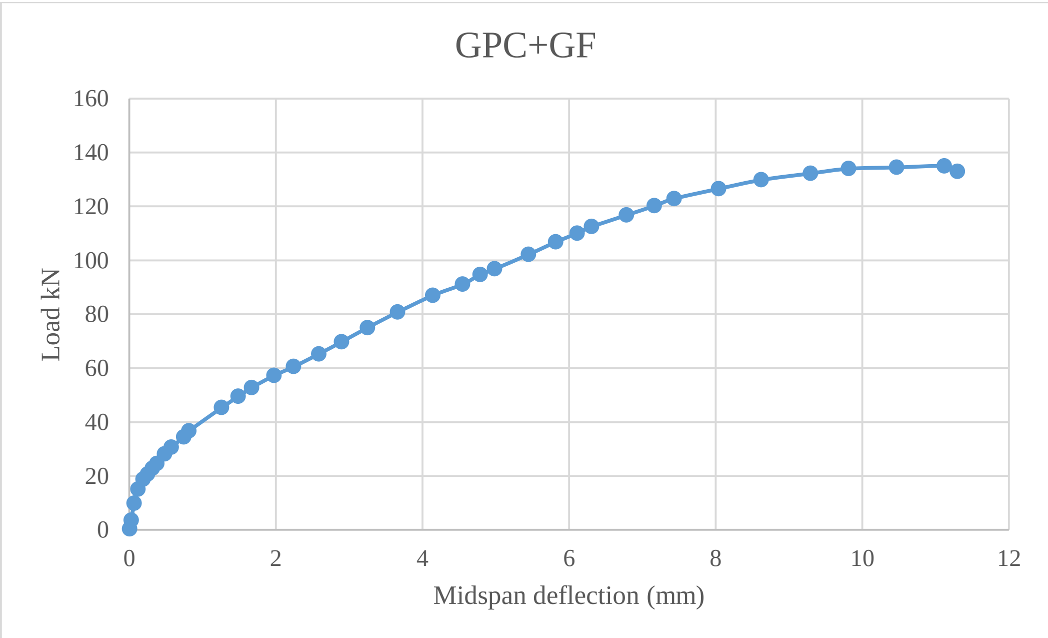

Fig 5.6 Load - Deflection curve for S4:GPC+GF

The ultimate load carrying capacity for geopolymer concrete with glass fiber (S4:GPC+GF) is134.97kN and first crack load 36.72Kn.

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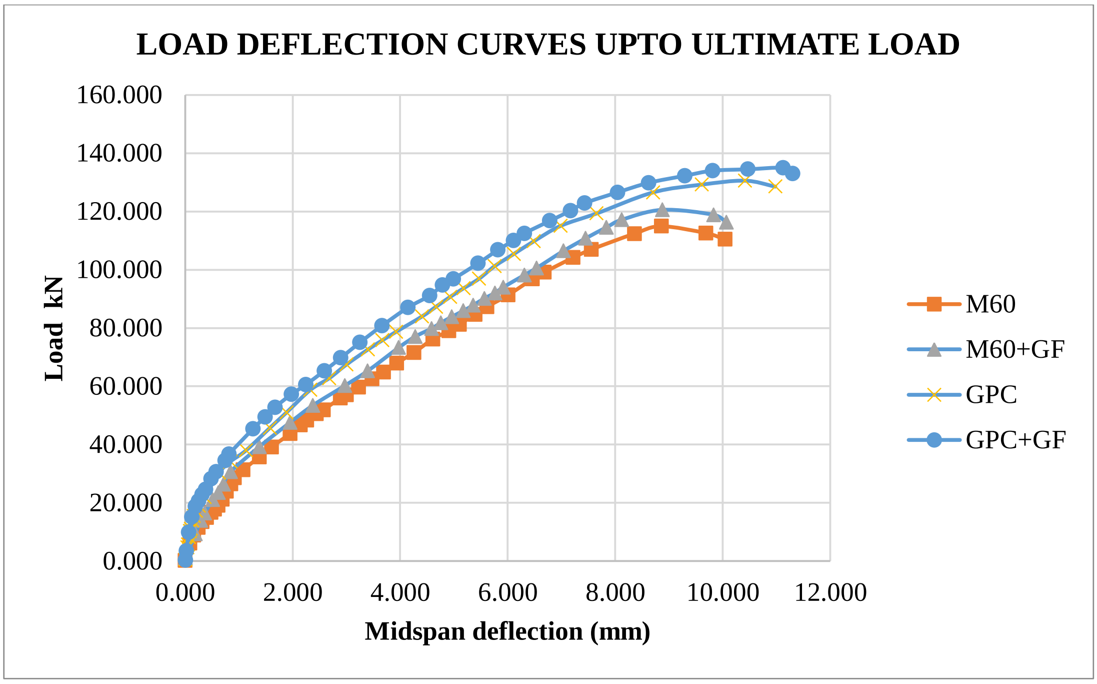

Fig 5.7 Load Deflection Curve up to Ultimate load

The load deflection behavior up to ultimate load is shown in the above figure. The first crack loads of the four mixes in the present investigations of M-60, M-60+GF, GPC-16M and GPC-16M+GF is 28.58kN, 30.65kN, 34.20kN, 36.72kN, respectively. It is observed that from experimental results, first crack load has been increased by 6.75%, 16.43%, 22.16%, with respect to control MIX M60.

5.5 Results of Ductility Index

From the results there is increase in Ductility w.r.t M60 by 20.68%, 27.81% and 40.95%for M-60, M-60+GF, GPC-16M and GPC-16M+GF prestressed geopolymer concrete railway sleeper specimens respectively. It is observed that the Ductility Index for GPC+GF is higher than all other concrete matrices.

Table 5.4 Ductility Index

Specimen	Yield deflection	Ultimate deflection	Ductility index
S1 M- 60	0.915	8.85	9.67
S2 M-60+GF	0.842	8.76	11.67
S3 GPC-16M	0.851	10.41	12.36
S4 GPC-16M+GF	0.815	11.12	13.63

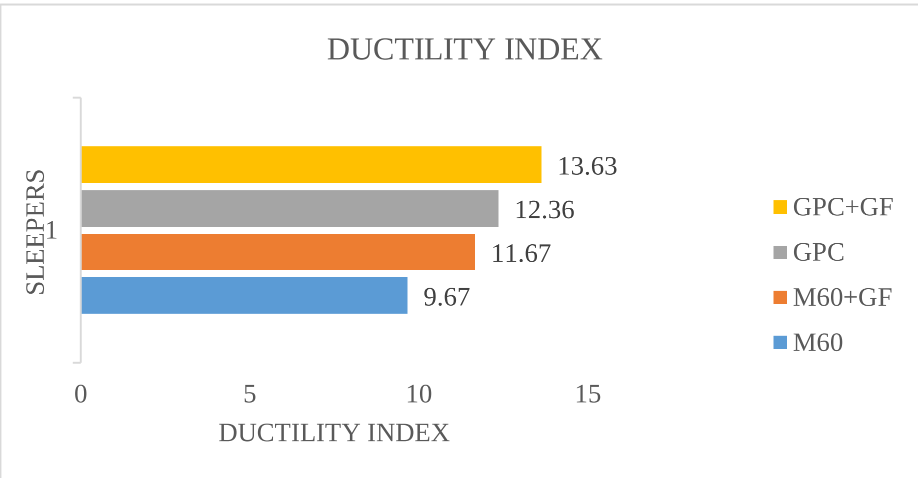

Fig 5.8 Ductility Index

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5.6 Results of Energy Absorption Capacity

The experimentally obtained values of Energy absorption capacity M-60, M-60+GF, GPC-16M and GPC-16M+GF prestressed concrete railway sleeper test specimens are 585.23 kN-mm, 615.30 kN-mm, 781.70 kN-mm and 863.01 kN mm respectively. It is observed from that from experimental results, energy absorption capacity has been increased by 5.13%, 33.57% and 47.46% respectively with respect to M60.

Table 5.5 Energy Absorption Capacity

Mix	Energy absorption capacity (kN-mm)
S1 M- 60	585.23
S2 M-60+GF	615.30
S3 GPC-16M	781.71
S4 GPC-16M+GF	863.01

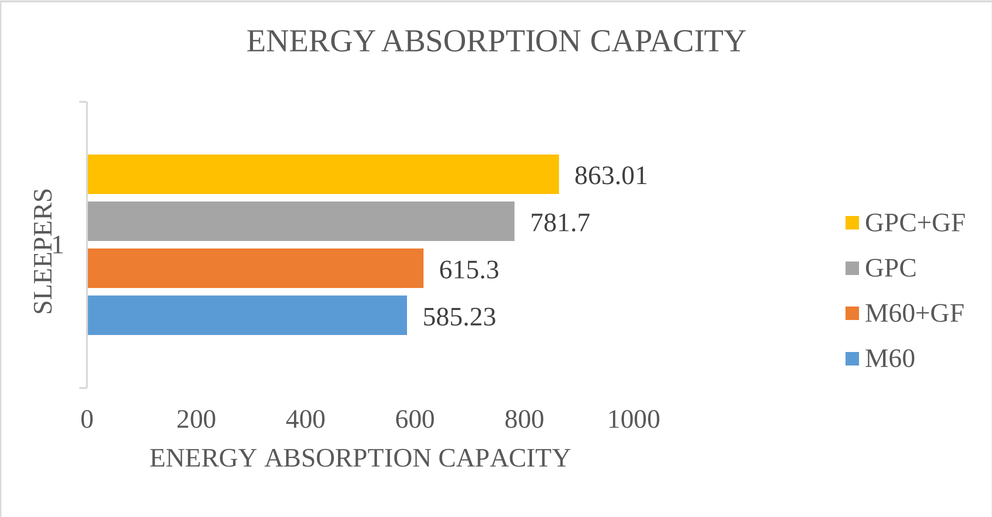

Fig 5.9 Energy Absorption Capacity

5.7 Results of Toughness Index

From the results there is increase in toughness w.r.t M60 by 6.58%, 21.31% and 28.84% for capacity M-60, M-60+GF, GPC-16M and GPC-16M+GF prestressed concrete railway sleeper specimens respectively. There is significant increase in toughness index of GPC+GF when compared to other concrete matrices.

Table 5.6 Toughness Index

Mix	Toughness Index
S1 M- 60	38.90
S2 M-60+GF	41.46
S3 GPC-16M	47.19
S4 GPC-16M+GF	50.12

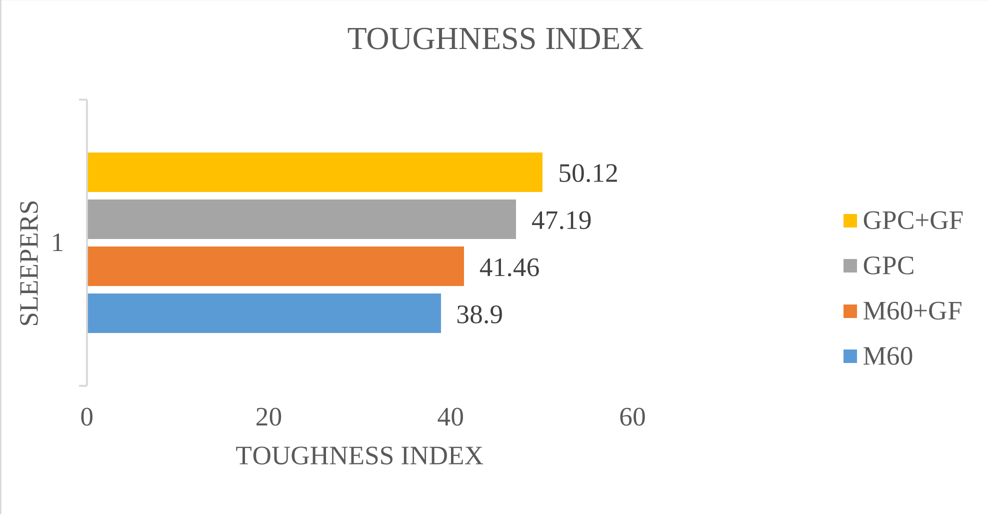

Fig 5.10 Toughness Index

Overall, the experimental results indicate that the incorporation of geopolymer concrete and glass fibers in PSC railway sleepers significantly enhances their mechanical properties, including compressive strength, flexural strength, and load-carrying capacity. These improvements suggest that such advanced materials can contribute to the development of more durable and efficient railway infrastructure, aligning with the sustainability goals of modern construction practices.

VI. CONCLUSION

The GPC+GF mix exhibited the highest compressive strength at 28 days, surpassing M60, M60+GF, and GPC by 25.47%, 14.28%, 18.25%, and 21.06% respectively. In terms of flexural strength, GPC+GF outperformed M60 by 65.8%, with M60, M60+GF, and GPC showing increases of 39.2%, 47.4%, and 57.6% respectively.

For Static bending strength tests, the load values for M-60, M-60+GF, GPC-16M, and GPC-16M+GF were 80.2 kN, 84.2 kN, 90.56 kN, and 98.23 kN, indicating increases of 33.6%, 40.33%, 51%, and 63.71% over the standard load of 60 kN. The moment of resistance values were 235.65 kN, 238.30 kN, 243.65 kN, and 248.96 kN, showing increases of 2.45%, 3.6%, 6%, and 8.24% over the standard value of 230 kN. The moment of failure values were 422.23 kN, 428.28 kN, 432.80 kN, and 436.76 kN, with increases of 14.11%, 15.75%, 17%, and 18.04% over the standard value of 370 kN.

For Full-scale Static bending tests, The first crack loads for M-60, M-60+GF, GPC-16M, and GPC-16M+GF were 28.58 kN, 30.65 kN, 34.20 kN, and 36.72 kN, with increases of 6.75%, 16.43%, and 22.16% compared to M60.

The yield and ultimate deflections for the various mixes were highest for GPC-16M+GF, while GPC+GF showed the greatest ductility increase of 40.95% over M60. Energy absorption capacity improved significantly for GPC+GF by 47.46% compared to M60, and toughness increased by 28.84% for GPC+GF relative to M60.

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