e-ISSN: 2582-5208
International Research Journal of Modernization in Engineering Technology and Science
(Peer-Reviewed, Open Access, Fully Refereed International Journal)
Volume:06/Issue:11/November-2024 Impact Factor- 8.187 www.irjmets.com

IMPACT BEHAVIOR OF RAILWAY PRE-STRESSED GEOPOLYMER COMPOSITE SLEEPERS

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ABSTRACT

This study focuses on evaluating the Impact resistance of geopolymer composite railway sleepers along with mechanical properties of four concrete matrices: M-60 (standard M-60 concrete), M-60+GF (M-60 with glass fiber), GPC-16M (geopolymer concrete with 16 molarity solution), and GPC-16M+GF (geopolymer concrete with 16 molarity and glass fiber). The research primarily examines compressive strength, flexural strength, and impact resistance, particularly for applications in railway sleepers. Using an instrumented pendulum-type impact testing machine, critical performance data such as load-time, displacement-time, and energy absorption were gathered. The results show that GPC-16M+GF exhibited the best performance across metrics. Its compressive strength was 25% higher than the control mix (M-60), and it demonstrated 65% greater flexural strength, highlighting its ability to withstand greater tensile forces. Additionally, GPC-16M+GF showed the highest load-carrying capacity and energy absorption, making it particularly resistant to the kinds of impact loads encountered in railway applications. These findings indicate that adding glass fiber to geopolymer concrete significantly enhances its mechanical strength and durability under impact, suggesting a strong potential for this material in improving the lifespan and reliability of railway infrastructure.

Keywords: Geopolymer Concrete (GPC), High-Performance Concrete (HPC), Glass Fibers (GF), Molarity, Prestressed Composite Sleepers, Impact resistance, Load-Time, Displacement-Time, Energy Absorption.

I. INTRODUCTION

Indian Railways is the backbone of the country's transport infrastructure integrating market and connects communities all over the country, and Railways play a key role in not only meeting the transport needs of the country, but also in binding together dispersed areas and promoting national integration. Despite the rapid growth of road networks throughout the length and breadth of the country, railways remain a major mode of transportation – both for a passenger as well as freight transport.

A major portion of the railway network in India is more than a century old. With the passage of time, this network is showing signs of ageing; but it still has to cater to the ever- increasing rail traffic. Not only the total number of trains plying on the network is rising, also the speed, the axle loads, and the number of bogies attached to the trains is also increasing. All this calls for a thorough and fast modernization of the sprawling railway network through development of new design concepts and use of advanced materials.

Prestressed Concrete (PSC) railway sleeper is an imperative component of ballasted railway tracks. The primary function of the railway sleeper is to transmit the wheel load to the ballast medium. In addition to the above it has additional functions such as maintaining track alignment and gauge, retaining longitudinal and lateral rail movements, and providing strength and stability to track structure. In India the traditional ballasted track system of steel rails, rail pads, fasteners, and concrete sleepers laid on ballast and sub-grade is still used widely, but the demand for transportation and logistics has increased greatly over recent years. An increasing frequency of passenger and freight trains has been a significant factor in the steady deterioration of the track system. This increase has been stimulated by the growing need of industry, especially for long distance freight conveying. Railway tracks in India have been deteriorating, not only due to increased traffic, but also because of heavier wheel loads and improper maintenance.

So far, geopolymer concrete seems promising. People are comparing these special railway sleepers, made from prestressed geopolymer composite, to regular ones made from traditional materials. They're evaluating the pros and cons of geopolymer sleepers, including their strength, environmental impact, cost-effectiveness, and ease of use.

Despite progress, there's still much to learn about using certain additives in geopolymer concrete. Few studies have explored how these additives interact, and progress in optimizing the mix has been slow due to costs and limited data. This study aims to enhance existing geopolymer railway sleepers, making them stronger and more durable. It also explores using materials like GGBS, fly ash, and HPC to reduce maintenance costs.

II. EXPERIMENTAL PROGRAM

This study explores the experimental approach to understanding the behavior of prestressed geopolymer composite railway sleepers under impact loading. The investigation aims to examine how prestressed geopolymer composite railway sleepers affect mechanical properties such as compressive strength and flexural strength. Furthermore, it extends to analyzing the impact behavior, focusing on (i) Load-Time history, (ii) Response-Time history (including acceleration, velocity, and displacement), and (iii) Energy absorbability results. The study attempts to enhance railway PSC sleepers using geopolymer composites and glass fibers in the current experimental investigation. All tests were conducted according to the Indian Standard Code of Practice and IRS Specifications.

III. MATERIALS

Geopolymer concrete production involves various materials, including cement, Class-F fly ash, and ground granulated blast furnace slag (GGBS). These binders were chosen for their high silica and alumina content, which are crucial for the geopolymerization process. Locally sourced crushed sand (M-Sand) was used as fine aggregate, passing through a 4.75 mm sieve and retained entirely on a 150-micron sieve to ensure optimal particle size distribution. Coarse aggregates with a maximum size of 20 mm were added to achieve the required strength and workability. Portable water was included to adjust the mixture's consistency for easy handling during casting. An alkaline activator solution was also used, with a mixing ratio of 0.25 sodium silicate (Na_2SiO_3) to sodium hydroxide (NaOH), enhancing the polymerization reaction and boosting the concrete's mechanical properties. Physical tests on both fine and coarse aggregates were conducted following IS 383-2016 and IS 2386 (Parts 1-4, reaffirmed in 2002), to verify material quality and suitability.

IV. METHODOLOGY

This study aims to experimentally examine the behavior of prestressed geopolymer composite railway sleepers under impact loading, focusing on mechanical properties like compressive and flexural strength. It analyzes impact behavior through Load-Time history, Response-Time history, and energy absorbability, aiming to improve railway PSC sleepers using geopolymer composites and glass fibers, in line with Indian Standards and IRS Specifications

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 Low Velocity Repeated Impact Test

The horizontal pendulum type impact testing machine used in the present investigation. The instrumented pendulum consists of steel impact hammer attached with a load cell or dummy striker, which swings to strike the Layered RC test specimen horizontally at the mid span. The hammer is attached to a rod, which in turn is connected to the frame. The hammer is 170 mm in diameter and 320 mm in length, which forms the main striking mass. The hammer attached with the load cell strikes the test specimen with an effective mass equal to mass of the hammer and the mass of the load cell.

The horizontal pendulum hammer can be set to a known height of fall/drop. A mechanical stopper is arranged on one side of the hammer for the hammer to hold the hammer at this height before releasing and on release, the pendulum hammer swings down to impact the test specimen. The position of the mechanical stopper can be adjusted for different heights of fall/drop. The effective weight of hammer together with load cell is 50 tons. In the present investigation the PSC Sleepers for M60 (S1), M60+GF (S2), GPC (S3) and GPC+GF (S4) is investigated with a fall height of the pendulum. A mechanical rotator system of electric gear can be adjusted for lifting the hammer assembly.

To investigate the impact behavior of PSC sleeper test specimens of different material compositions following parametric study as follows

1. Load – Time History
2. Displacement – time History
3. Energy absorption capacity.

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

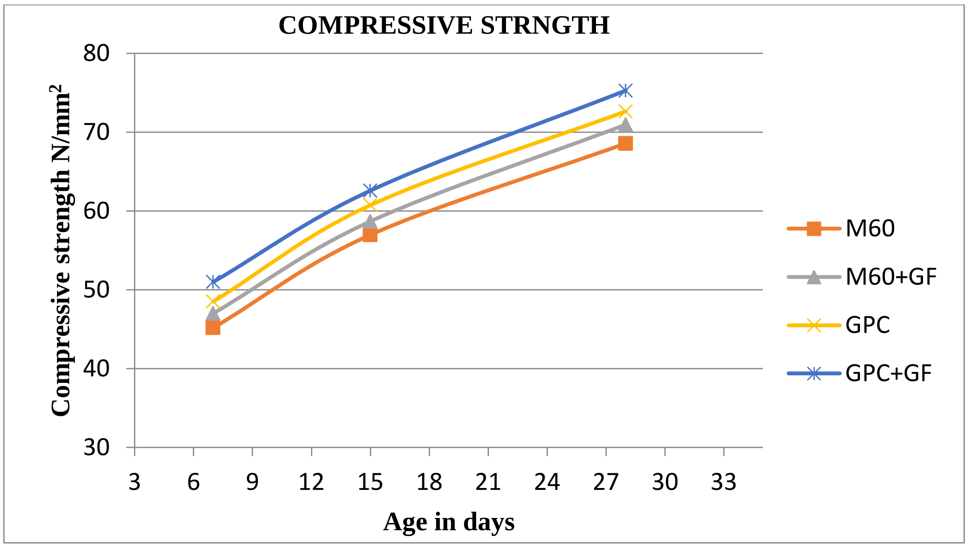
The investigation into the performance of prestressed concrete (PSC) railway sleepers using various concrete matrices revealed significant findings regarding compressive strength, flexural strength and Impact test.

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-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



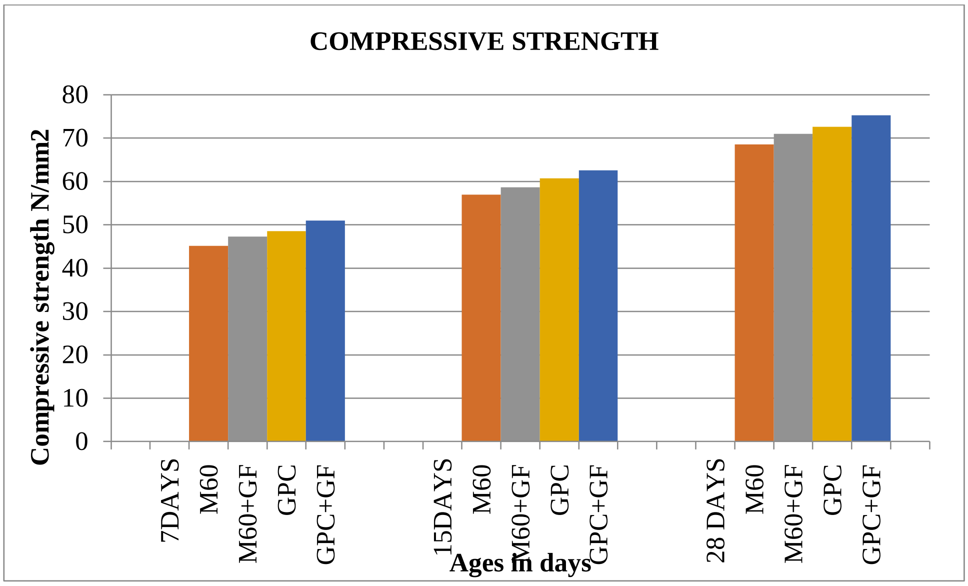


Fig 1 and 2: Comparison of Compressive Strength with Age of different concrete matrices

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/mm². The GPC-16M+GF mix exhibited the highest flexural strength of 8.29 N/mm² 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-2: Summary of 7, 15 and 28 days Flexural Strength of Test Specimens

Properties	Age (Days)	M-60 (N/mm²)	M-60+ GF (N/mm²)	GPC+16M (N/mm²)	GPC+16M+GF (N/mm²)
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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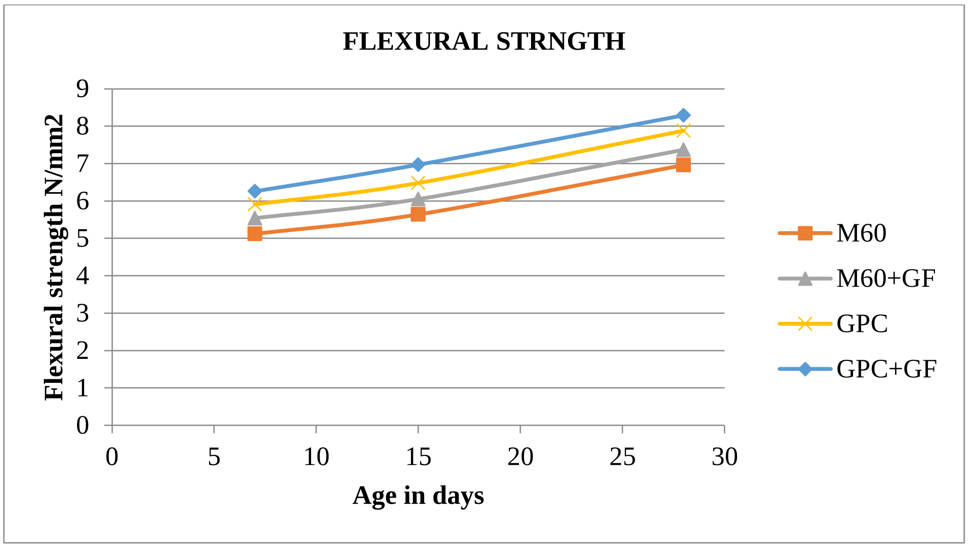

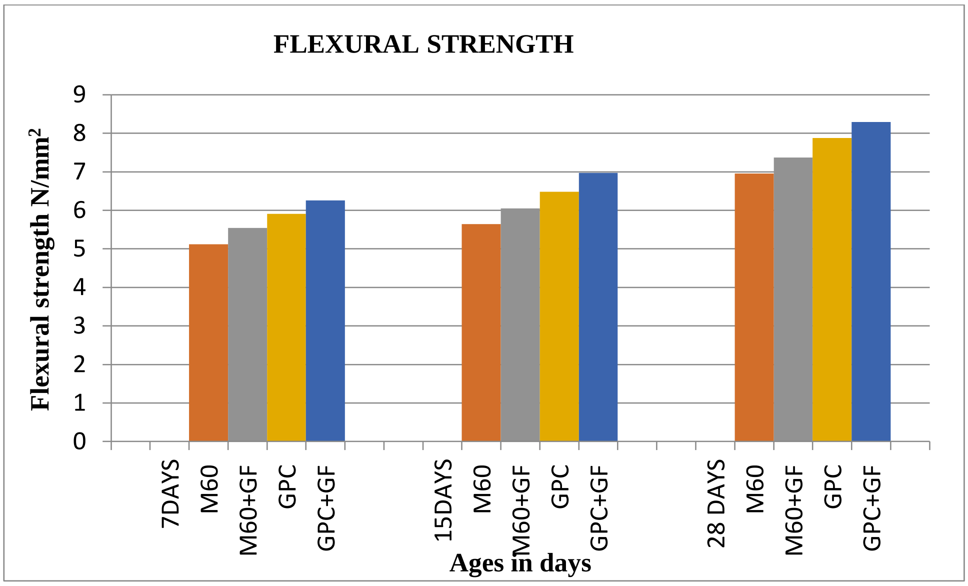

Fig 3 and 4: Comparisons of Flexural Strength of different concrete matrices

5.3 Results of Impact behavior of PSC geopolymer sleepers of Low Velocity Repeated Impact Test.

A. Load-Time Variation

The load time variation which has to be expressed in terms of pattern of variation in time, the peak load value and the duration of impact on the specimen is obtained at regular intervals using load cell attached to the impact hammer. Figure 5-16 shows Load –Time variation for psc sleeper test specimens M-60, M-60+GF, GPC-16M and GPC-16M+GF obtained at different stages of impact blows.

Table-3: Shows the Peak Load obtained at 1st, 100th and last impact blows

Test Specimen	Peak load at 1st Blow in kN	Peak load at 100th Blow in kN	Peak load at Last Blow in kN
M60	333.26	133.59	120.76
M60+GF	370.29	176.27	141.67
GPC	383.67	200.76	153.89
GPC+GF	401.26	220.17	161.27

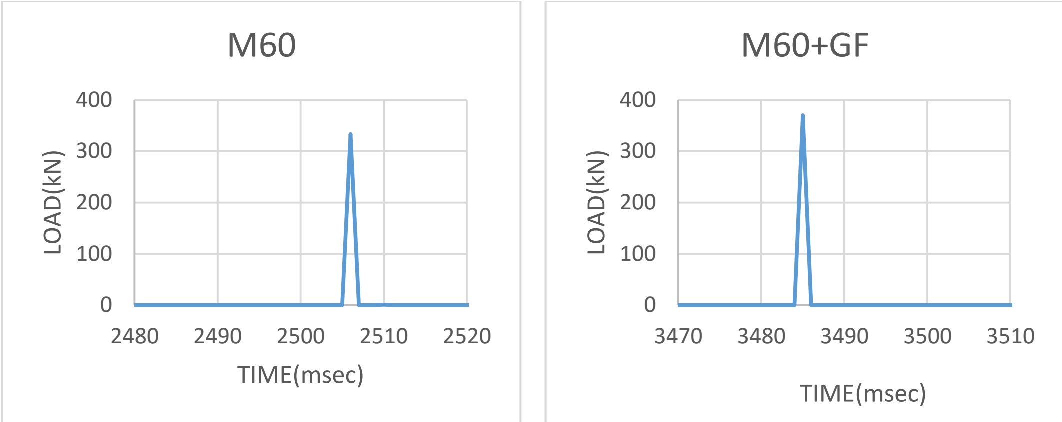

Fig 5 and 6: Load- times variation for M60 (S1) and M60+GF (S2) at 1st Blow

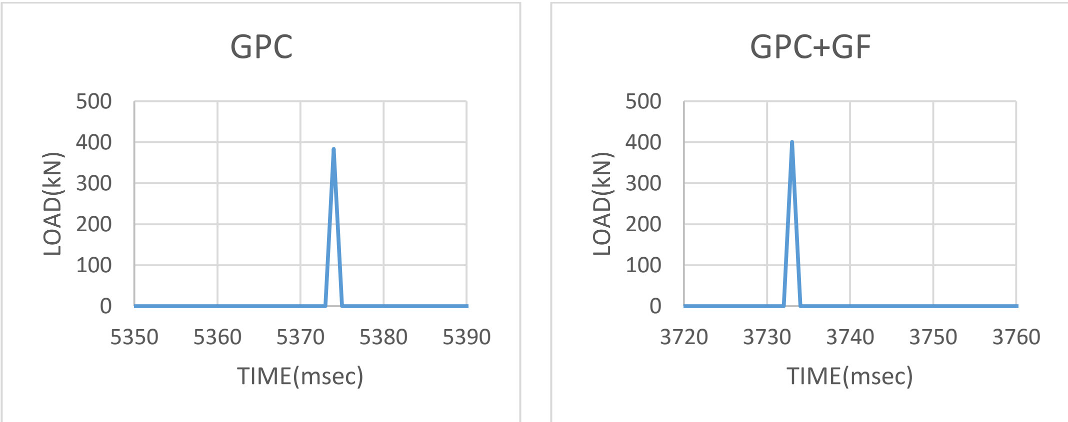

Fig 7 and 8: Load- times variation for GPC (S3) and GPC+GF (S4) at 1st Blow

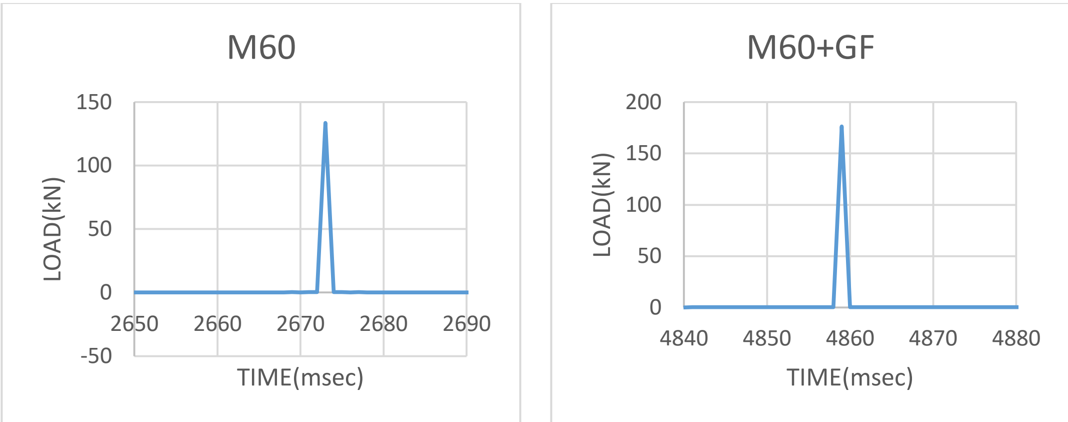

Fig 9 and 10: Load- times variation for M60 (S1) and M60+GF (S2) at 100th Blow

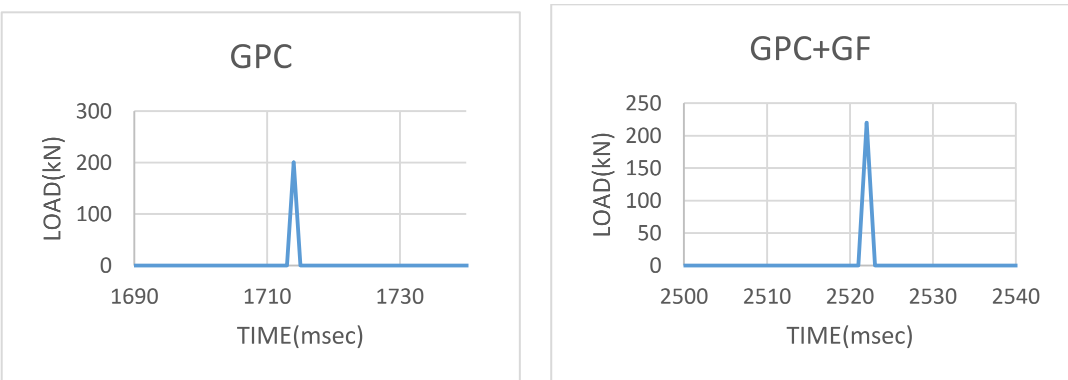

Fig 11 and 12: Load- times variation for GPC (S3) and GPC+GF (S4) at 100th Blow

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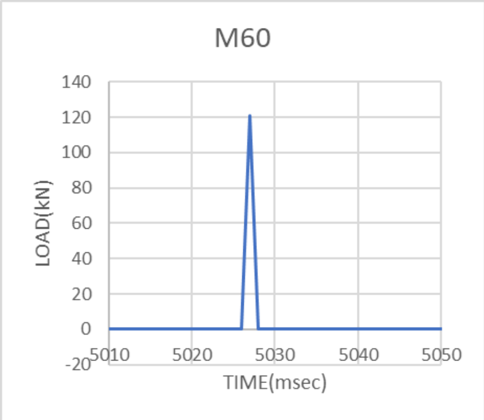


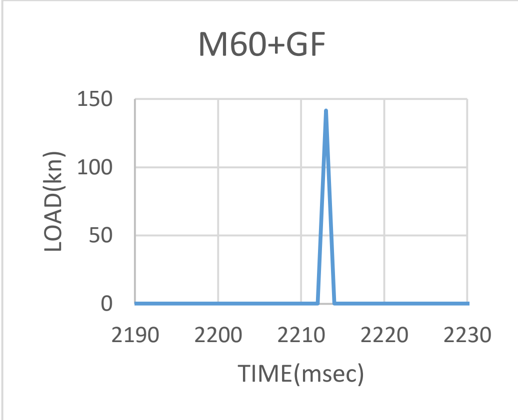
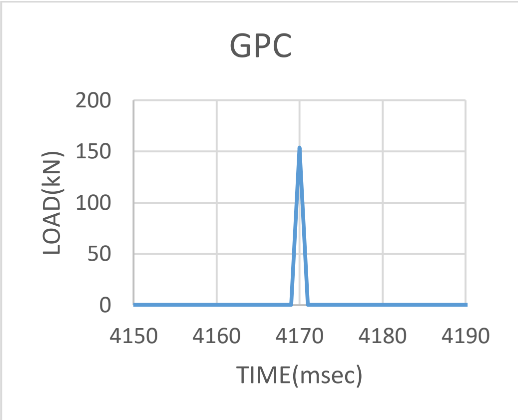


Fig 13 and 14: Load- times variation for M60 (S1) and M60+GF (S2) at last Blow



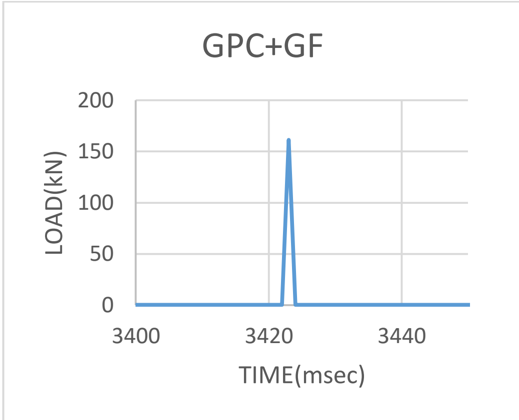


Fig 15 and 16: Load- times variation for GPC (S3) and GPC+GF (S4) at last Blow

Figure 5– 16 and table 3, shows the peak load obtained for 1st ,100th and last impact blows for M60 (S1), M60+GF (S2), GPC (S3) and GPC+GF (S4) it can be seen that as number of impact blows increase peak load decreases. The highest peak load obtained for the GPC+GF (S4) is 455.00 kN for 1st blow and 178.23 kN for last blow (200th blow) as compared to PSC railway sleepers test specimen (S1, S2 and S3)

The variation of peak load with no of impact blows for psc railway sleepers test specimens M60 (S1), M60+GF (S2), GPC (S3) and GPC+GF (S4) are as shown in figure 17.

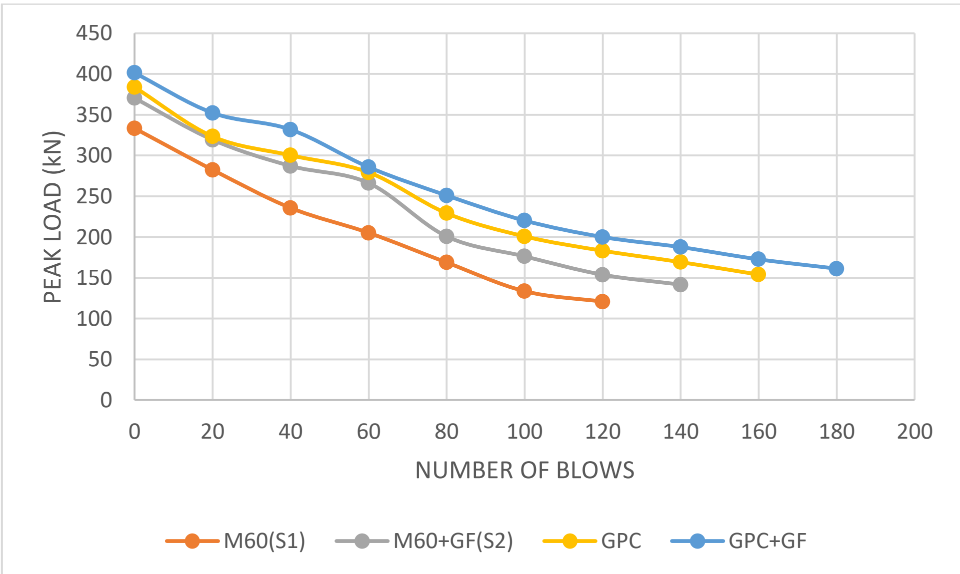


Fig 17: Variation of Peak Load v/s Number of blows for all test sleeper specimens

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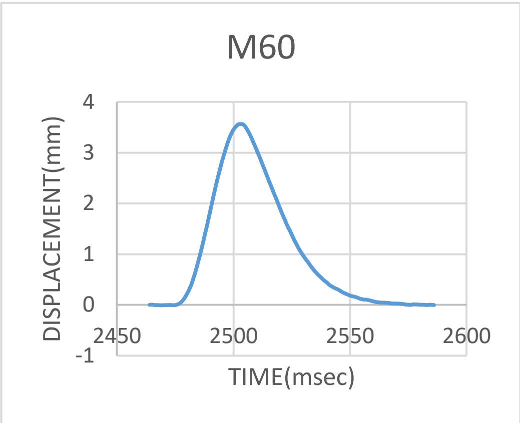
B. Displacement Time History

The displacement-time variations for the M60 (S1), M60+GF (S2), GPC (S3) and GPC+GF (S4) for different number of impact blows are recorded and are as shown in figure 18- 25 and table 4.

Table 4: Shows the Displacement variation obtained at 1st, 100th and last blow

Test Specimen	Displacement at 1st Blow in mm	Displacement at 100th Blow in mm	Displacement at Last Blow in mm
M60	3.55	9.21	9.97
M60+GF	3.3	8.50	9.52
GPC	3.01	8.03	9.03
GPC+GF	2.85	7.80	8.72



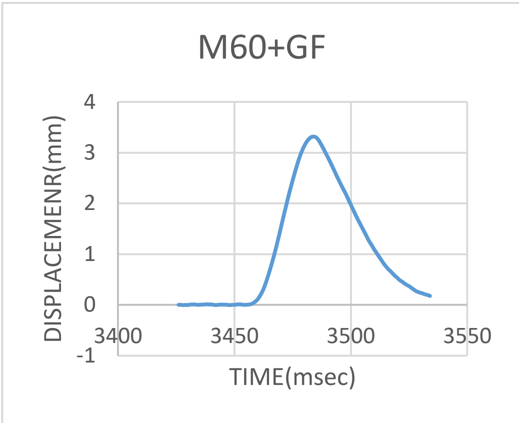
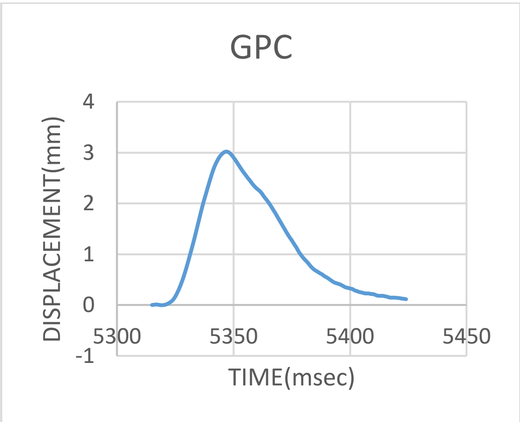


Fig. 18 and 19: Displacement variation for M60 (S1) and M60+GF (S2) at 1st Blow



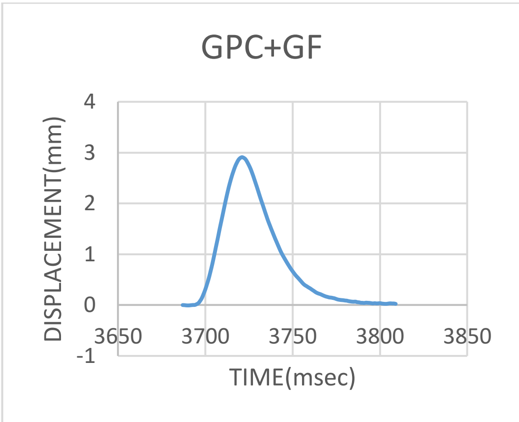
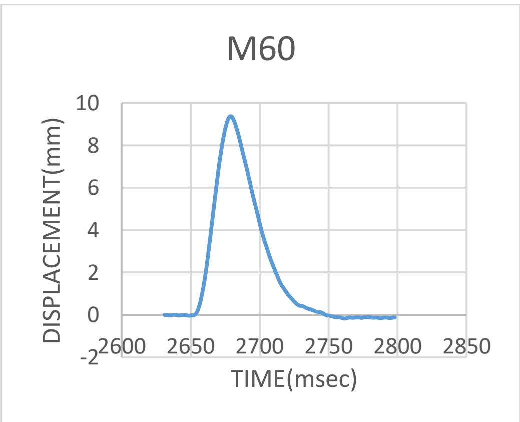


Fig. 20 and 21: Displacement variation for GPC (S3) and GPC+GF (S4) at 1st Blow.



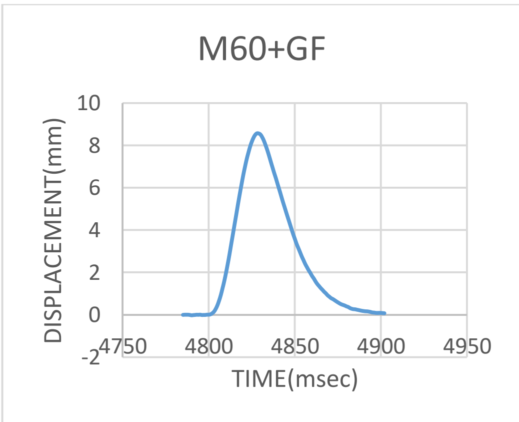


Fig. 22 and 23: Displacement variation for M60 (S1) and M60+GF (S2) at 100th Blow.

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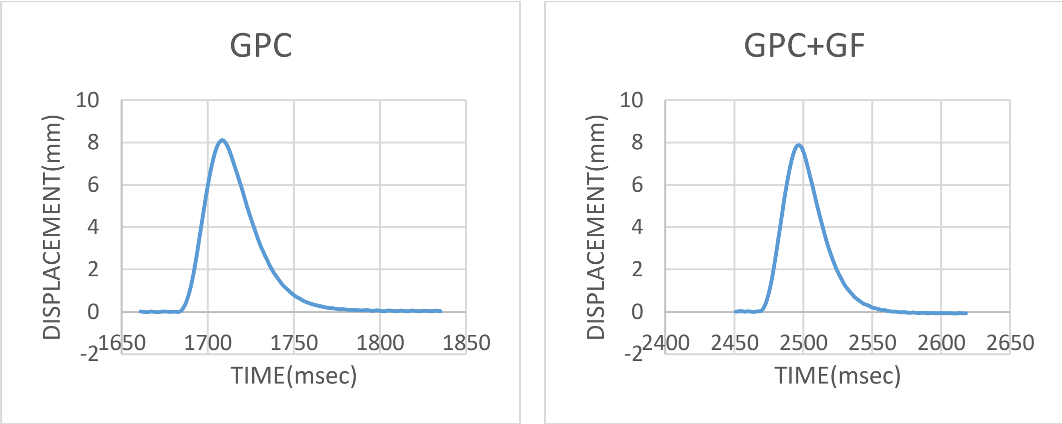

Fig. 24 and 25: Displacement variation for GPC (S3) and GPC+GF (S4) at 100th Blow.

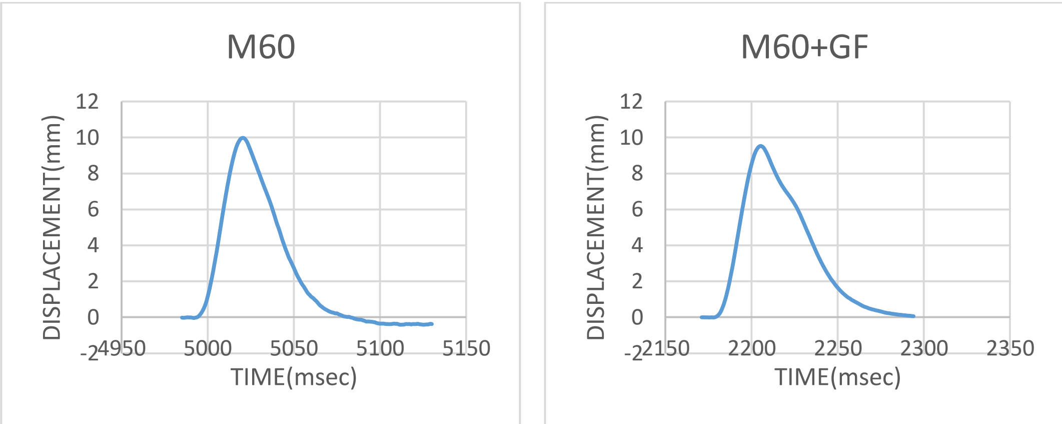

Fig. 22 and 23: Displacement variation for M60 (S1) and M60+GF (S2) at Last Blow.

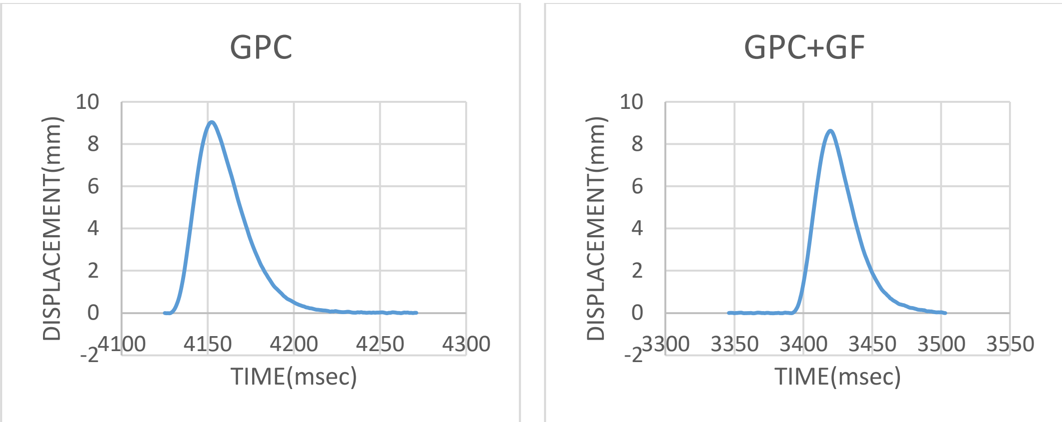

Fig. 24 and 25: Displacement variation for GPC (S3) and GPC+GF (S4) at Last Blow.

Figure 18– 25 and table 4, shows the displacement variation obtained for 1st ,100th and last impact blows for M60 (S1), M60+GF (S2), GPC (S3) and GPC+GF (S4). It can be seen that as number of impact blows increases displacement increases. The displacement obtained for the GPC+GF (S4) is 2.85mm at 1st blow and 8.72mm for last blow (180th blow). Whereas 3.55mm, 3.3mm, and 3.01mm for 1st blow obtained for other test specimens (S1, S2 and S3).

C. Energy Absorption Capacity

During the low velocity repeated impact load on PSC railway sleepers test specimens, impact input energy (Ebo = mgh) partly gets absorbed by the dynamic behaviour of that element. This absorbed energy capacity gives its ability to sustain the dimensional integrity or internal resistance capacity during the low velocity impact experiment. The load-time variation data are used to calculate energy absorption capacity for M60 (S1), M60+GF (S2), GPC (S3) and GPC+GF (S4). given in figures 26-29 and table 5.

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Table – 5: Shows the Energy Absorbed obtained at 1st and last blow.

Test Specimen	Energy absorption in 1st Blow in Joules	Energy absorption in last Blow in Joules
M60	559.05	138.84
M60+GF	566.80	149.06
GPC	571.90	163.76
GPC+GF	577.75	179.13

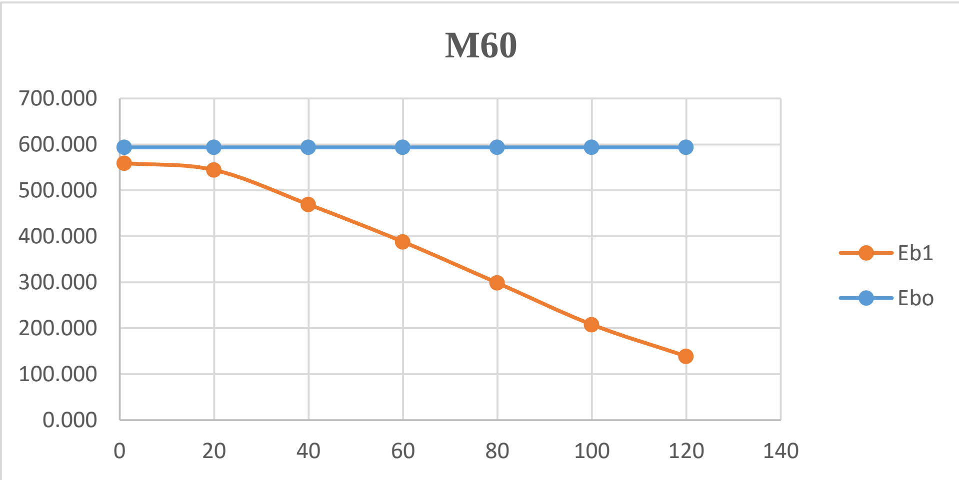

Fig 26: Variation of Energy (Ebo and Eb1) with increased number of blows for PSC sleeper test specimen **M60 (S1).**

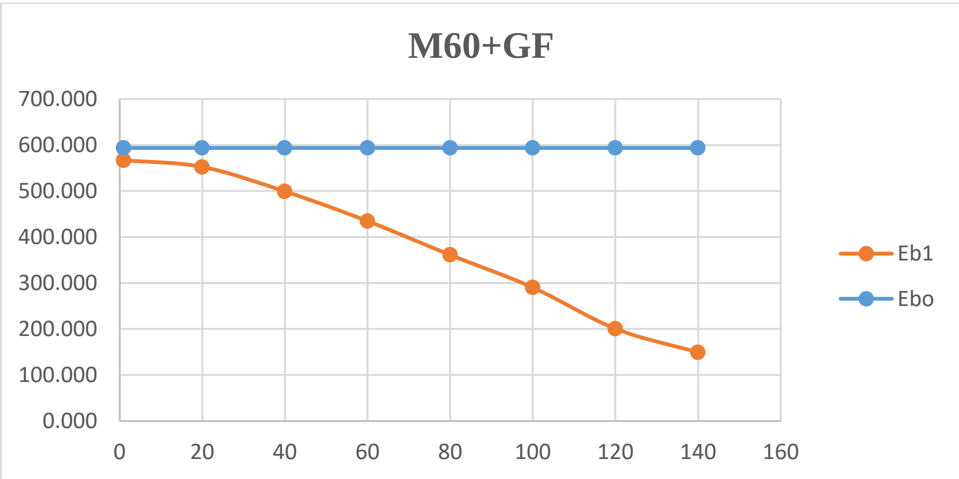

Fig 27: Variation of Energy (Ebo and Eb1) with increased number of blows for PSC sleeper test specimen **M60+GF (S2).**

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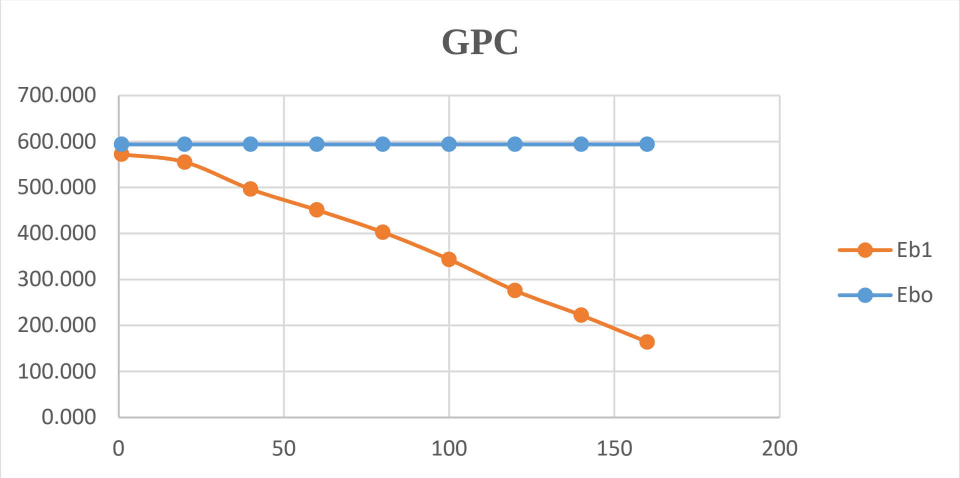

Fig 28: Variation of Energy (Ebo and Eb1) with increased number of blows for PSC sleeper test specimen **GPC (S3).**

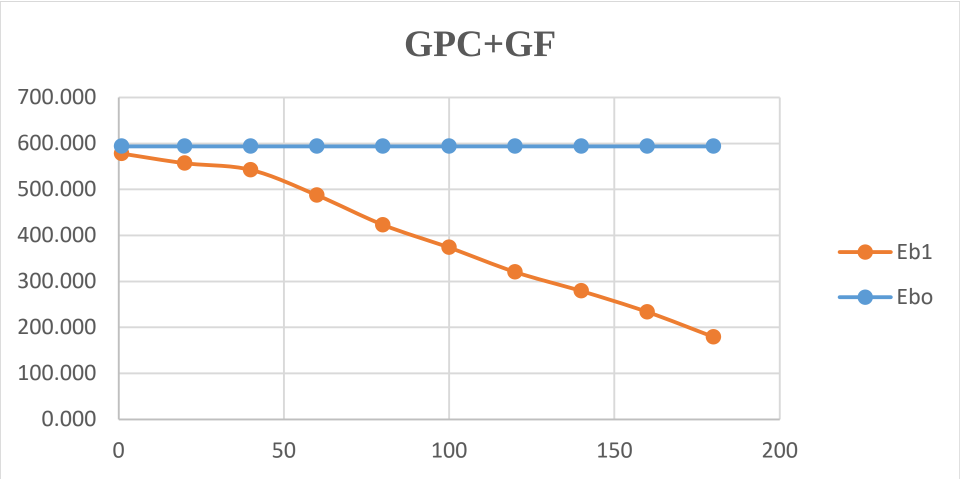

Fig 29: Variation of Energy (Ebo and Eb1) with increased number of blows for PSC sleeper test specimen **GPC+GF (S4).**

Figure 26-29 and table 5, shows the energy absorption capacity for PSC railway sleeper test specimen M60 (S1), M60+GF (S2), GPC (S3) and GPC+GF (S4). It is observed that the highest energy absorption capacity is obtained for GPC+GF (S4).

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.

From Low Velocity repeated impact test it can be concluded by the following

A. Load-Time variation.

The load-carrying capacities of the test beam specimens M60(S1), M-60+GF(S2), GPC-16M(S3), and GPC-16M+GF(S4) are 333.26 kN, 370.24 kN, 383.67 kN, and 401.26 kN, respectively. It was observed that the load-carrying capacity increased by 11.09% for M-60+GF, 15.12% for GPC-16M, and 20.40% for GPC-16M+GF compared to M60 (S1: Control). Therefore, it can be concluded that GPC-16M+GF exhibits a significant increase of 20.40% in load-carrying capacity compared to M60 (S1: Control).

B. Displacement-Time variation.

Displacement-time records for M60, M-60+GF, GPC-16M, and GPC-16M+GF were analysed across different numbers of impact blows. The results show that peak displacement amplitude increases with the number of impact blows. The maximum displacements recorded for the final impact blows were 9.97 mm for M60, 9.52 mm for M-60+GF, 9.03 mm for GPC-16M, and 8.72 mm for GPC-16M+GF.

C. Energy absorption capacity.

The energy absorption capacity obtained for the test sleeper specimens of M60, is 559.04 Joules and whereas for the M-60+GF, GPC-16M and GPC-16M+GF are 566.80 Joules, 571.89 Joules and 577.75 Joules respectively. It is experimentally evident that GPC+GF gives the highest energy absorption capacity as compared to the other PSC sleeper test specimens.

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