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Impact Properties of Composite Materials: The Significance of Glass Microspheres
Odpornost kompozitnih materialov proti udarcem: pomen steklenih mikrokroglic

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Abstract
Due to their exceptional qualities, polymer matrix composite materials are finding more and more use in high-tech applications. The purpose of this work was to improve these composites' resilience to impact by adding glass microspheres to thermosetting phenolic resins. Glass fabric was used as the reinforcing material. The main objective of the study was to determine how different glass microsphere percentages affected the composites' mechanical characteristics. A fibre volume fraction of 0.6 was attained by utilising compression moulding to create the composites, which were made from four glass fabric plies. The mechanical properties were considerably improved by the addition of glass microspheres; the best results were noted at concentrations of 6–8%. More specifically, there was a noticeable improvement in tensile strength and a 6% rise in tensile modulus. Based on the results, the addition of glass microspheres to composite materials improves both their mechanical and energy-absorbing capabilities, thus making them more appropriate for use in impact applications.
Keywords: 2D woven fabric, polymer matrix composites, glass microspheres, thermosetting resins, impact strength, automotive applications

Izvleček
Polimerne kompozite zaradi njihovih izjemnih lastnosti čedalje več uporabljajo za visokotehnološke aplikacije. Namen te raziskave je bil izboljšati odpornost polimernih kompozitov proti udarcem z dodajanjem steklenih mikrokroglic termoreaktivnim fenolnim smolam. Za ojačitev je bila uporabljena steklena tkanina. Glavni cilj raziskave je bil ugotoviti, kako različni odstotki dodanih steklenih mikrokroglic v polimerno matrico vplivajo na mehanske lastnosti kompozitov. Ti so bili izdelani s stiskanjem štirih plasti steklenih tkanin, katerih utežni delež v kompozitih je znašal 0,6. Mehanske lastnosti kompozitov so se znatno izboljšale z dodajanjem steklenih mikrokroglic. Najboljše rezultate so dosegli pri 6–8 ut. odstotku dodanih mikrokroglic, kjer se je opazno izboljšala

natezna trdnost, za šest odstotkov pa se je povečal natezni modul. Dodatek steklenih mikrokroglic je izboljšal mehanske lastnosti kompozitnih materialov in sposobnost absorpcije energije, zato so tovrstni kompoziti primerni za izdelke, odporne proti udarcem.
Ključne besede: 2-D tkanina, polimerni kompoziti, steklene mikrosfere, termoreaktivne smole, udarna trdnost, uporaba v avtomobilski industriji

1 Introduction

Materials made of two or more different components together on a macroscopic level are known as composite materials [1]. To provide mechanical strength and load-bearing capacities, reinforcement materials in composites, such as fibres, textiles or particles, are essential. The matrix's role in the composite network is to bind these reinforcement materials together and distribute loads among them. The similar mechanical properties of composites have made them attractive alternatives for metals in recent years. From sports equipment to high-tech sectors such as aerospace, these materials are used in a wide range of industries [2]. Glass and glass microspheres were combined to manufacture composite using compression moulding, and it was determined that there was a relationship between the microspheres' properties and tensile strength, elastic modulus, bending strength, pendulum impact resistance and drop weight impact tests. It was observed that as the microsphere concentration increased the mechanical characteristics and impact resistance improved. The lightweight nature and high mechanical properties of glass fibre-reinforced composites with a polymer matrix make them suitable choices for investigation as possible alternatives to conventional metals. The procedures for manually placing specimens are covered in this article. Tensile strength, impact resistance and drop weight impact characteristics were among the aspects that have been described by different ASTM standards. The investigation's matrix material, phenolic resin, was reinforced with a variety of microsphere particles. The mechanical and impact capabilities of composite materials were greatly enhanced by the addition of microspheres, indicating the potential use of these materials to enhance the durability and performance of automobile components.

Recent work has challenged the widely held view that filled modules behave consistently across all matrices by examining the relationships between various polymer matrices. This study demonstrated that the specific matrix used can significantly affect the glass microspheres' effectiveness. After a detailed investigation of the variables affecting composite performance, it was shown that the addition of glass microspheres can improve material properties even at low concentrations. These results emphasise the adaptability and promising mechanical capabilities of microsphere-based composite materials, which could lead to innovations in a range of applications. Thermosetting and thermoplastic matrices are the two primary categories of matrix materials used in composite production. Thermosetting matrices are made using condensation polymerization and are liquid at room temperature. Vinyl ester, polyester, phenolic resins and green epoxies are a few examples. In general, these materials are fragile. In contrast, addition polymerization is used to create thermoplastic matrices, which are solid at room temperature. They lack crosslinks and feature branching or linear structures. One of thermoplastics' main qualities is their flexibility, which contributes to their impact resistance. They are stable at room temperature and can be solidified upon cooling after being cooled, or they can be softer when heated, allowing for recycling and moulding. As opposed to empty composites, the inclusion of micro- or nanoparticles improves the impact strength of composite materials. For riot shields, battle helmets, tactical vests and sporting equipment, such as tennis rackets and hockey sticks, high-impact strength is required [3].

1. 1 Recent advances in composite materials: fillers and reinforcements

Compared to fillers such as silica, potato flour and chonta palm wood, high-density polyethylene (HDPE) exhibits better energy absorption qualities when added with high-impact fillers with gamma-alumina and silica. All the mechanical properties are improved when the polymer matrix is hybridised with these fillers, surpassing the capabilities of simple polymer materials only [4, 5]. The integration of amino-functional, multi-walled carbon nanotubes (MWCNTs) enhances projectile resistance incarceration in epoxy/glass materials. However, higher concentrations of MWCNTs increase epoxy viscosity, making it difficult to wet glass fabrics properly, leading to reduced mechanical properties [6]. Incorporating glass micro powder into epoxy resin was found to increase the stiffness and bending strength of basalt-reinforced composites, although it displayed no discernible impact on their tensile force. This enhancement demonstrates the potential of microglass powder to improve the mechanical properties [7]. The effect of fillers on composites reinforced with epoxy and glass fibre was examined by researchers, who observed that fly ash increased impact strength by up to 300% at low concentrations but decreased compressive strength. However, small additions increased crack length and surface area. Nano-Al_2O_3 at 2 PHR (parts per hundred resin) showed an optimal balance in mechanical, thermal, and viscoelastic properties. The flexural modulus increased significantly with 0.5 PHR Al_2O_3 but higher amounts reduced the modulus [8, 9].

Researchers found that plain weave fabrics as reinforcement performed well against both high-speed and low-speed impacts, while basket weave fabrics provided better resistance at higher speeds. On the contrary, satin weave showed weaker impact resistance [10]. The study highlighted that the structure of woven fabrics plays a critical role in energy absorption. Additionally, treated fabrics showed increased yarn pull-out force due to restricted yarn movement and impact energy, though this does not fully indicate energy absorption. Increasing the fabric set improved the impact strength by ensuring primary yarn contact with the impactor and energy distribution through secondary yarns. In general, treated fabrics demonstrated better energy absorption compared to untreated fabrics [11]. The impact of the density, thickness and stacking sequence of aramid-kenaf fabric layers on composite properties was studied by many researchers. They found that increasing areal density and thickness improved energy absorption. Kevlar and kenaf fabrics were used for ballistic impact testing, showing that higher proportions of kenaf reduced ballistic properties. The treatment of kenaf fabrics with 6% sodium hydroxide improved tensile properties compared to untreated kenaf. The outer layers of Kevlar improved mechanical and flexural properties, while the inner layers improved the tensile strength [12] absorption of the compound, which does not directly correlate with its thickness. Instead, it is influenced by the interaction time, which depends on the projectile velocity and the thickness of the composite. Higher thickness can lead to composite failure due to delamination and tensile failure, whereas lower thickness may result in energy absorption through fibre breaking. The desired depth and speed of the projectile both affect the deformation [13, 14]. Researchers examined how the number of layers influenced composites with various fibres made of Kevlar, carbon and glass under ballistic impact. Five hybrid composites and a pure carbon composite were produced with different sequences of fibre layers. The results showed that placing glass fibre as the first layer provided superior energy absorption compared to carbon and glass, or glass and carbon fibres in the centre of the composite [15].

Various techniques were employed in previous research to improve the strength characteristics of polymeric composite materials, including the optimisation of the ratio of natural to synthetic reinforcements, fibre treatments and the addition of different additives to the matrix. However, the potential of glass microspheres in composite materials has not been fully explored. This study investigated the optimal concentration of glass microspheres in phenolic resin to achieve improved structural features. The results indicate that integrating glass microspheres improves the composites' mechanical characteristics and energy absorption, making them more appropriate for impact applications. Moreover, mixed composite materials have been identified as viable options for potential uses [16].

2 Materials and composite assembly

2.1 Materials

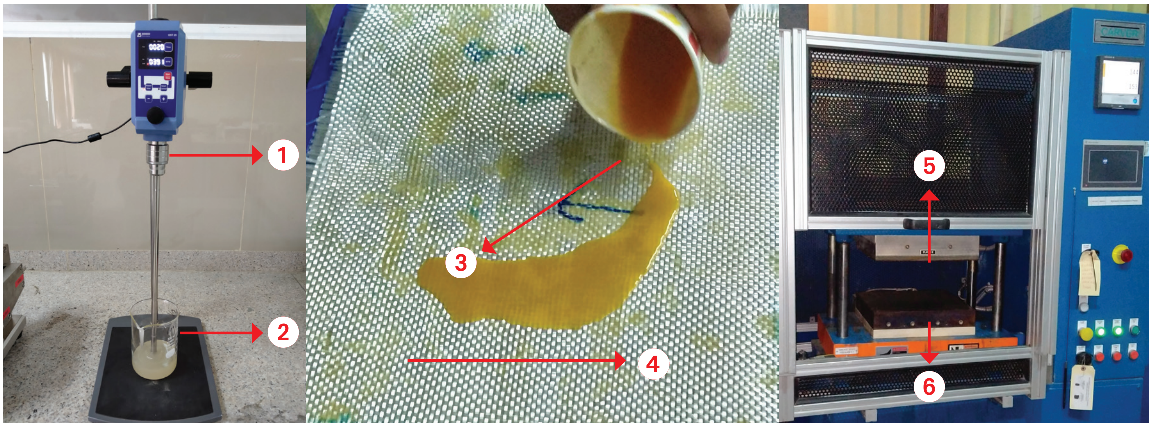
Plain weaved glass fabric with 514.55 g/m^2 and glass microspheres (Thomas No. C990Z93) with a molecular weight of 60.08 g/mol were used as reinforcement during this research. Reinforcement was obtained from the local market, while filler particles were imported from ALDRICH Chemistry, USA. The glass fabrics used in this study had a yarn count of 598.56 tex, with 22.86 yarns/cm in warp and weft directions. Glass microspheres, sized 9–13 µm, were incorporated into phenolic resin as an impact modifier for the composite material. The thermoset polymer named phenolic resin is sold under the Phenolic Resole NR 9430 brand name. Its pH range is 6.5 to 7.5, while its viscosity is 400–700 cps at 25 °C. The equipment and tools utilised in this research included a weight balance, measuring scale, beakers, fabric cutter/scissors, curing oven, agitator (OST 25), compression moulding apparatus, universal tensile testing machine (UTM), pendulum impact tester and drop weight impact tester.

2.2 Composite fabrication

The phenolic resin was used to create reinforced polymer laminates measuring 304 mm × 304 mm × 2 mm, which were reinforced with glass fibre and filled with glass microspheres. As indicated in Figure 1a, glass microspheres were introduced to phenolic resin and stirred for 20 minutes at 391 rpm with a mechanical stirrer. The presence of glass microspheres caused the phenolic resin's viscosity to rise. The solution's viscosity was decreased during stirring by using dimethyl formamide solvent. The resin was then applied to the woven glass fabrics using the hand layup method as presented in Figure 1b. Initially, a wet lay-up technique was utilised to make the composite, which was then subjected to pressure on a compression moulding machine as shown in Figure 1c. In the hand-laying process, a phenolic resin mixed with glass microspheres was applied to each layer sequentially, resulting in the formation of a four-layer composite. The hand-laminated sample was placed on a compression moulding machine for the curing of the phenolic resin. The curing process lasted for 5 hours and 10 minutes at a temperature of 140 °C and under a pressure of 3 tonnes. During the curing process, the machine's temperature was first adjusted to 100 °C for four hours. It was then raised to 120 °C for thirty minutes and to 140 °C for the final 40 minutes. The purpose of exerting pressure was to solidify the materials and remove any air or voids between them. Following the completion of the curing process, the sample was taken out of the compression moulding machine and cut into different sizes in accordance with ASTM standards for evaluation. The experimental design with various percentages of glass microspheres is detailed in Table 1.

Table 1: Experimental design utilising various glass microsphere concentrations

Sample code	2D woven reinforcement	Matrix	Glass microspheres (%)
P	Glass fibre	Phenolic resin	0
PG2	Glass fibre	Phenolic resin	2
PG4	Glass fibre	Phenolic resin	4
PG6	Glass fibre	Phenolic resin	6
PG8	Glass fibre	Phenolic resin	8
PG10	Glass fibre	Phenolic resin	10



a) b) c)

Figure 1: Incorporation of micro fillers in resin (a); application of resin to glass fabrics (b); and compression moulding (c)

Legend: 1 – electric stirrer, 2 – micro fillers in resin, 3 – glass fabric, 4 – resin application on fabric, 5 – upper mould, 6 – lower mould

2.3 Testing

The mechanical performance of the manufactured composite samples was evaluated using several tests: tensile, three-point bending, pendulum impact (Charpy impact) and drop weight impact. One kind of destructive structural assessment intended to assess a material's mechanical attributes, especially its strength and stiffness, is the tensile test. A universal testing machine (UTM) and the standard test method (ASTM D3039) were used to measure the tensile properties of polymer matrix composite materials. This method outlines the procedure for determining the in-plane tensile properties of polymer matrix composites reinforced by high-modulus fibres. The testing involved preparing specimens with precise dimensions and loading them in tension at a controlled rate until failure to evaluate parameters such as tensile strength, modulus of elasticity, strain and elongation at break. The fabricated samples, measuring 203.2 mm by 25.4 mm, were put through testing, and the mean of three samples was recorded for every test. The three-point bending test for fibre-reinforced composites is a mechanical test utilised to analyse the flexural force, stiffness and behaviour of laminate under bending load.

The standard test method for flexural properties of polymer matrix composite materials (ASTM D7264) specifies the procedures to determine the flexural properties, such as flexural strength, flexural modulus and flexural strain, of polymer matrix composites under defined conditions. The test is conducted by placing the specimen on two supports and applying a load at a controlled rate until failure, using either a three-point or a four-point bending setup. Parameters such as span length, crosshead speed and specimen dimensions are meticulously followed as prescribed by the standard. The dimensions of the samples must be 120 mm × 13 mm.

The Charpy impact test, referred to as the pendulum impact strength test, determines a material's resilience and capacity to absorb impact. In this test, a movable arm with an attached weight is raised to a specific height and then released. This arm swings like a pendulum and strikes a V-notched sample. The energy absorbed by the sample is determined by measuring the height of the arm before and after impact, which reflects the energy required to break the sample. Charpy impact testing of the composite material was conducted according to ISO-179 standards. A strip of every laminate was prepared, with a dimension of 80 mm × 10 mm. The impact force of the composite material was the determined applying the following formula:

$$Impact\ strength = a_c = \frac{Wb*1000}{bh} \quad (1)$$

where W_b represents the energy at break expressed in J, a_c represents the impact strength stated in kJ/m^2, b represents sample width and h represents the sample thickness.

The ASTM D7136 standard test method for measuring the damage resistance of a fibre-reinforced polymer matrix composite to a drop-weight impact event is a method for assessing the impact strength and damage tolerance of composites. In this test, a particular mass is lowered from a predetermined elevation to a composite to simulate real-world impact conditions. Materials energy absorption and resulting damage are then assessed [17]. The test is carried out using a composite plate of 101.6 mm × 152.4 mm. Damage is induced perpendicularly to the plane of the flat plate using a semicircular striker tip. The resistance to damage is assessed by evaluating the cracks formed in the flat plate.

2.3 Experimental setup

A universal tensile tester (UTM) was used for mechanical testing according to ASTM D3039, facilitating the evaluation of both tensile strength and elongation. The three-point bending configuration, also compliant with ASTM D7264, allowed the flexural tests to be performed on the same machine. Impact resistance was assessed using a Charpy impact testing machine, following ISO-179, while energy absorption during free fall was measured with a drop weight impact tester, in line with ASTM D7136. Surface examination, fibre distribution and microstructural analysis, including failure analysis, were carried out using an optical microscope, in accordance with ASTM 7570. Three specimens were evaluated based on every mechanical description and the average results were used for analysis. For comparison of the mechanical properties of glass microspheres in phenolic resin with plain woven composites, the combinations were coded as PG2, PG4, PG6, PG8 and PG10, while the neat composite laminate with zero glass microsphere particles in phenolic resin was named P.

3 Results and discussion

3.1 Tensile properties of the prepared composites

Glass woven fabric composites were examined during tensile testing to determine the impact of various glass microsphere contents. Figure 2 illustrates variations in tensile strength by varying glass microsphere ratios. The tensile strength was higher for PG6 and PG8 than for P, PG2, PG4 and PG10. The maximum tensile force values for PG6 and PG8 were 307.83 MPa and 282.14 MPa, respectively. Tensile stress was considerably reduced and PG10 exhibited better extension than pure phenolic resin. While tensile strength decreased, PG2 and PG4 composites provided more extension than P, accordingly. The incorporation of glass microspheres into composites was only observed to improve their tensile properties at concentrations of 6% and 8%.

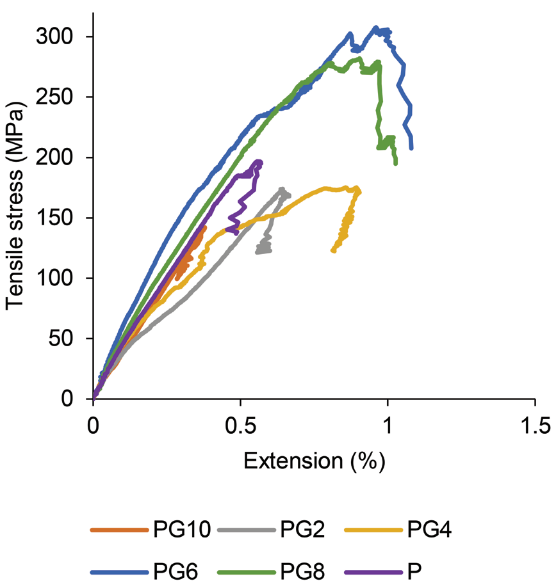


Figure 2: Tensile stress versus an extension of glass microsphere composites

As glass microspheres are infused with resin and subsequently applied to composite materials, sufficient extension was shown. By adding 6% glass microspheres in phenolic resin, the modulus increased to 47.17 GPa as a result of fracture propagation. The modulus of phenolic resin was 41.96 GPa. A greater surface area stress-concentrated zone was produced by glass microspheres. The modulus of the composite increased in the samples PG2, PG4 and PG6 due to the stress distribution facilitated by the glass microspheres. Table 2 summarises the modulus of glass microspheres-based composites.

Table 2: Glass microsphere composites' modulus and tensile strength

Sample code	Tensile modulus (GPa)	Tensile strength (MPa)
P	41.96	214.3618
PG2	43.19	174.0243
PG4	45.59	175.197
PG6	47.17	307.838
PG8	39.79	282.1484
PG10	36.30	196.7399

3.1.1 Optical microscopic representation of the PG6 tensile fracture specimen

Figure 3 is an optical microscopic image of the PG6 sample to analyse the surface topography of the deformed composite.

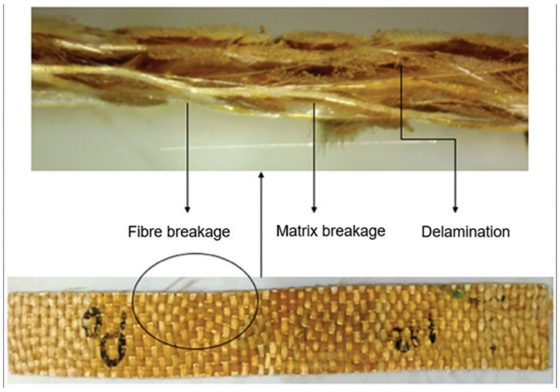


Figure 3: Optical microscopic image of the PG6 composite material before and after fracture

The figure reveals various forms of damage, including fibre breakage, matrix failure and delamination.

3.2 Flexural properties of composites

The glass flexural capacity used as a reinforcement fibre in fabric form was assessed by incorporating glass microspheres into phenolic resin. Testing was carried out to ascertain how the chemical processing affected the bending properties of the material. Distinctions among untreated laminates and those containing glass microspheres are shown in Figure 4. The fabricated composites demonstrated adequate flexural strength, even in the absence of glass microspheres in the composite material. This resulted from the woven fibres' anisotropic nature. The results of the bending tests indicate that the addition of glass microspheres to phenolic resin reduced deformation. The force-deformation curves demonstrated brittle behaviour, which is consistent with the inherent brittleness of the glass. Initially, all composite curves displayed a linear trend with increasing load, eventually transitioning to a non-linear trend. In particular, the PG8 sample exhibited the least deformation at 238 MPa, attributed to the incorporation of 8% glass microspheres into the phenolic resin.

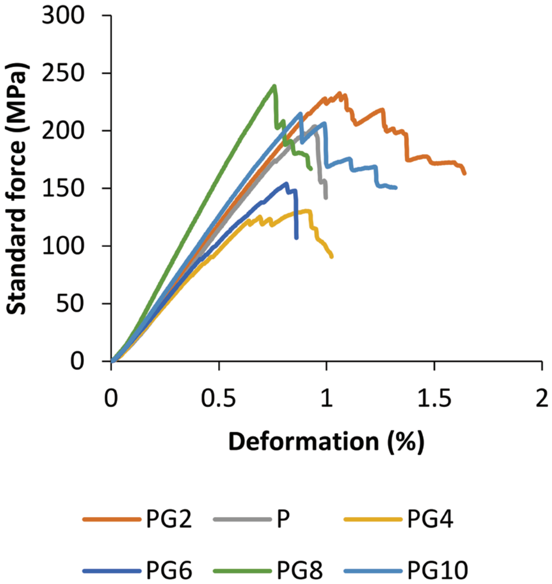


Figure 4: Flexural stress versus deformation curves of glass microspheres-based phenolic resin composite

The flexural strength of the composites containing pure phenolic resin glass fibre (P) was significantly higher than most other samples, except for PG8, which exhibited a strength of 238.66 MPa. This can be attributed to the fibre's ability to support the absorption and propagation of employed loads. Bending strength was utilised to compare the strength of various glass microsphere-based composites. Only PG8 of these composites showed a substantial improvement in strength over the initial sample (P). Conversely, increasing the percentage of glass microspheres to 2%, 4%, 6% and 10% caused flexural property to reduce. According to experimental results, the incorporation of a suitable quantity of glass microsphere filler increased the flexural capabilities of the PG8 composite. However, the glass fibre could no longer support the exerted force. The PG6 and PG8 samples had the highest tensile and bending abilities, suggesting that the glass microsphere content enhanced strength. The scientific conclusion is that because of the substantial interaction between the polymer and the fibre, the outer layer of the glass fibre was more rigid and robust. The procedure with optimal glass microsphere concentrations of 6% and 8% met the specifications for endurance and surface ability. The percentage of glass microspheres increased the flexural stress and modulus at these optimum values. Table 3 presents the results of the flexural strength and flexural modulus of glass microspheres-based composites.

Table 3: Results of the flexural testing of glass microspheres-based composites

Sample code	Flexural strength (MPa)	Flexural modulus (GPa)
P	232.52	24.46
PG2	203.82	24.89
PG4	130.46	25.42
PG6	231.2336	28.14
PG8	238.66	34.37
PG10	214.65	26.43

3.2.1 Optical microscopic image of the PG6 flexural fracture specimen

Figure 5 illustrates the bending behaviour and subsequent fracture in composite materials containing 6% glass microspheres in phenolic resin. It also shows the fractures in similar composites prepared with fibres. This fracture did not appreciably impair the PG6 composite's ability to withstand flexural stress.

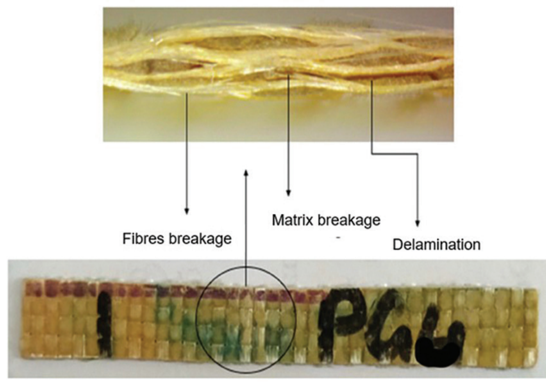


Figure 5: Optical microscopic representation of the PG6 composite material before and after the flexural test

3.3 Composite impact characteristics

Charpy impact measurement revealed that the pure phenolic resin composite exhibited the highest impact strength, absorbing 37.37 kJ/m², indicating superior energy absorption compared to composites containing glass microspheres. Composites with glass microspheres (PG2, PG4, PG6, PG8 and PG10) demonstrated lower impact strength, with values ranging from 14.11 kJ/m² to 25.11 kJ/m² as shown in Table 4. This reduction in impact strength can be attributed to the brittleness of the glass microspheres, which reduces materials' properties for energy capturing during impact. While the addition of glass microspheres enhances the stiffness and modulus of the composites, it compromises their toughness, making them less suitable for applications requiring high-impact resistance. This trade-off highlights the need to balance stiffness and toughness when designing composite materials for specific applications. Figure 6 shows the work-standard travel curves for different composite samples (P, PG2, PG4, PG6, PG8 and PG10) during the Charpy impact testing. The pure phenolic resin composite (P) showed the highest initial peak force (~126 N) and the highest displacement, indicating its superior impact strength. In contrast, composites with glass microspheres (PG2, PG4, PG6, PG8 and PG10) exhibited lower peak forces and reduced impact strength, which is explained by the glass microspheres' delicate tendency. Among these, PG6 and PG8 showed relatively higher impact resistance, with PG6 showing a notable peak force around 25 N, suggesting that a glass microsphere content may provide a balanced improvement in toughness without significantly compromising strength. Overall, while glass microspheres reduced impact strength compared to pure phenolic resin, they enhanced the composite's ability to absorb energy before failure, with PG6 and PG8 being the most promising formulations for applications requiring a trade-off between impact resistance and material strength.

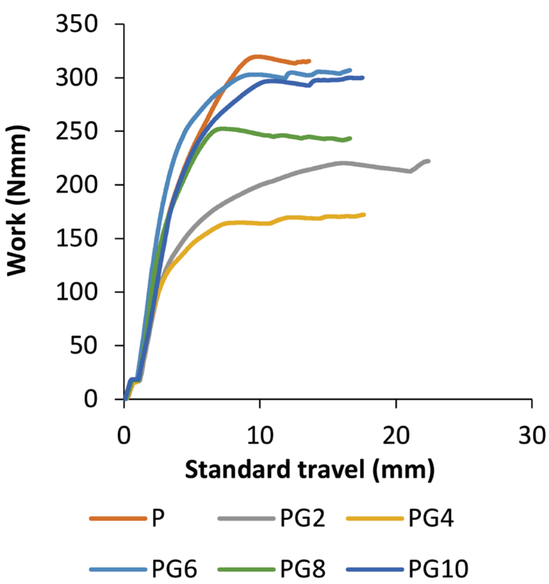


Figure 6: Glass microsphere composites' work vs standard travel curves

3.3.1 Optical microscopic representation of PG6 impact energy absorption

Figure 7 is an optical microscopic image of the PG6 composite material showing the impact area before

Table 4: Charpy impact values of glass microsphere-based composites

Sample code	Pendulum impact energy, a_c (kJ/m^2)
P	37.37
PG2	15.86
PG4	14.11
PG6	25.11
PG8	24.86
PG10	24.44

and after testing. The PG6 composite recorded the second highest energy absorption value of 25.11 KJ/, surpassed only by the pure phenolic resin-based composite material. The impact energy was significantly compromised. The impact energy of glass microsphere-based composite materials, such as the PG6 composite, was compromised due to the inherent brittleness of glass microspheres. When subjected to impact, the glass microspheres tended to crack and fracture easily, and absorbed less energy than more ductile materials. This brittleness reduced the ability to dissipate impact energy, leading to lower overall impact strength. Additionally, the inclusion of glass microspheres can create stress concentration points within the composite, further facilitating crack initiation and propagation under impact loading.

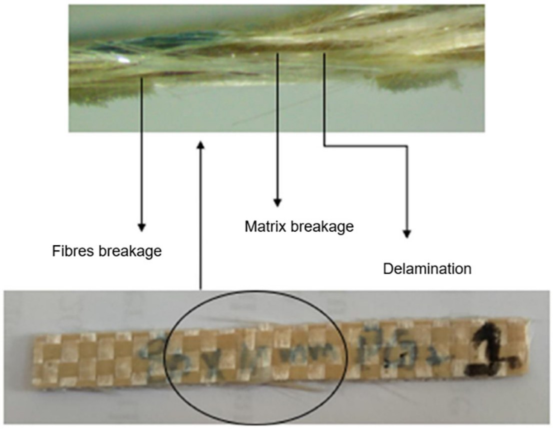


Figure 7: Optical microscopic image of the PG6 composite material before and after Charpy impact tests

Thus, while the PG6 composite demonstrated better energy absorption than other glass microsphere composites, it still fell short of the impact energy absorption capabilities of pure phenolic resin composites.

3.4 Impact test of the drop weight

The results of the drop weight impact evaluation for fibre-reinforced composites reveal significant information regarding the material's ability to store energy. The sample code "P", representing the pure phenolic resin-based composite, absorbed 21.40 J of energy. With the addition of 2% glass microspheres (PG2), energy absorption increased to 26.91 J, indicating that glass microspheres enhanced the impact resistance. Further increases in glass microsphere content continued this trend, with PG4 absorbing 27.72 J and PG6 absorbing the highest amount of 29.14 J, demonstrating the optimal concentration for the enhancement of impact resistance. Beyond this point, however, energy absorption decreased slightly, as seen with PG8 absorbing 25.23 J and PG10 absorbing 21.78 J as shown in Table 5. This decline suggests that while adding glass microspheres improves impact resistance up to a certain concentration, excessive amounts may lead to brittleness and reduced energy absorption. Overall, the results indicate that an optimal concentration of glass microspheres significantly enhances the composite's resilience to impact, with the PG6 composite exhibiting the best performance.

Figure 8 illustrates the force versus test time for composite samples with varying percentages of glass microspheres (PG2, PG4, PG6, PG8 and PG10) and a pure phenolic resin-based composite (P) during drop weight impact testing. Initially, all samples showed a sharp increase in force upon impact, with the pure resin composite (P) exhibiting a lower peak force than those with glass microspheres. The maximum forces for PG2 and PG4 were higher than those for the pure resin sample, indicating improved impact resistance. PG6 and PG8 maintained high peak forces, demonstrating significant enhancement of up to 8% glass microspheres. However, PG10 showed a decrease in peak force, suggesting diminishing benefits at higher concentrations. Force

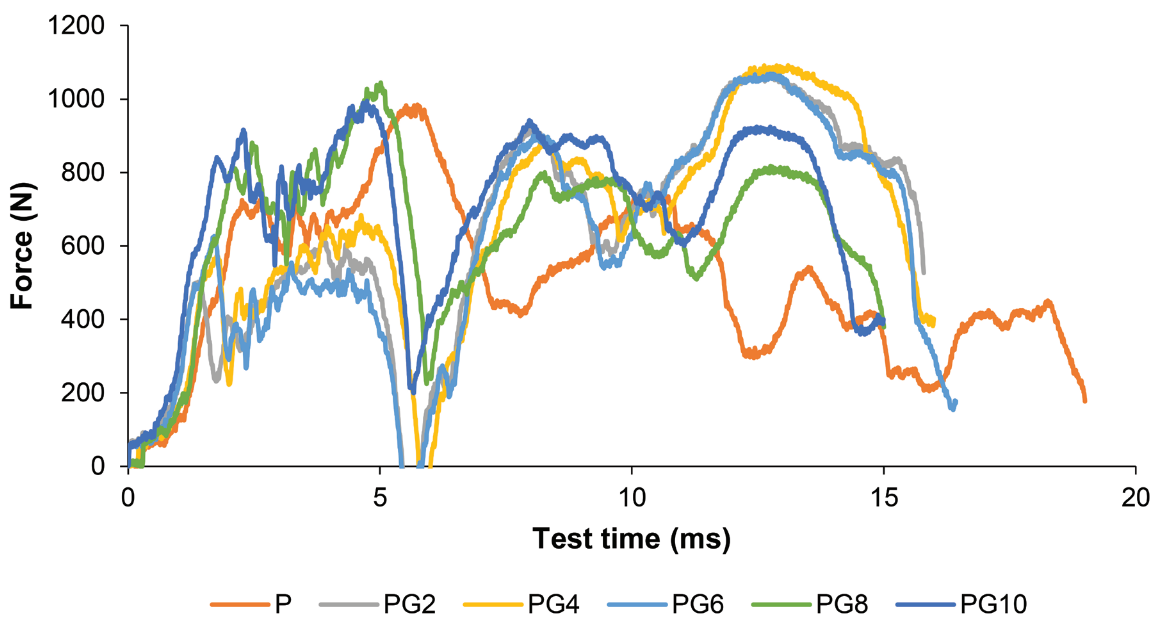


Figure 8: Comparison of the impact force of the impact weight test versus test time curves of various composite samples

fluctuations represent the material's response to impact energy, with a higher glass microsphere content leading to more consistent force levels, indicating better energy absorption. The pure resin sample failed more quickly, while PG6 and PG8 sustained higher forces longer, showing improved toughness and resistance to impact-induced failure. The study therefore confirms that incorporating 6–8% glass microspheres into the phenolic resin matrix optimises the composite's impact properties.

Table 5: Energy absorption of pure phenolic resin composites compared to those reinforced with glass microspheres

Sample code	Energy absorbed (J)
P	21.40
PG2	26.91
PG4	27.72
PG6	29.14
PG8	25.23
PG10	21.78

3.4.1 Optical microscopic representation of PG6 drop weight impact energy absorption

The optical microscopic representation of the PG6 composite material, shown in Figure 9, highlights the effects of the drop weight impact test. The upper part of the image indicates three distinct failure modes: fibre breakage, matrix breakage and delamination. Fibre breakage is observed where the reinforcement fibres have snapped due to the impact. The matrix breakage shows where the phenolic resin matrix has cracked or shattered. Delamination represents the separation of layers within the composite material. The lower part of the image provides a broader view of the composite surface of the sample before testing, with the circled area indicating the specific location where the matrix breakage occurred. This detailed analysis helps to understand how the composite material absorbs and dissipates impact energy, with PG6 showing a substantial energy absorption value of 29.14 J, second only to the pure phenolic resin composite. The presence of glass microspheres in

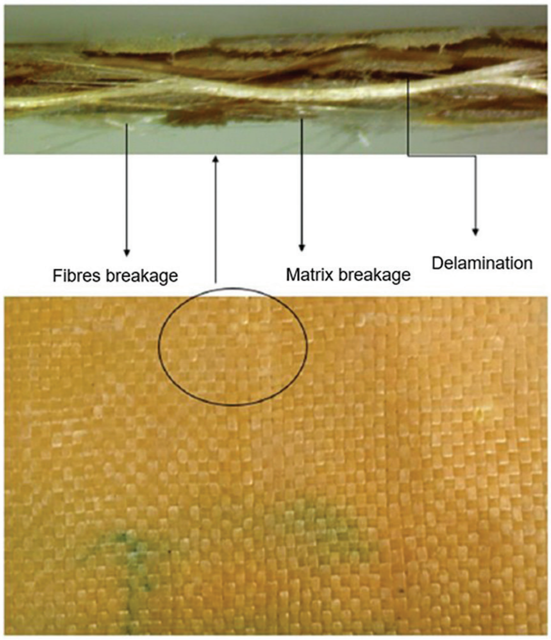


Figure 9: Optical microscopic image of the PG6 composite material before and after impact testing with drop weight

PG6 appears to improve its impact resistance by improving the interaction between the matrix and the fibres, thus delaying catastrophic failure mechanisms such as delamination and fibre breakage.

3.4.2 Force versus displacement

Figure 10 illustrates the force-displacement resistance of various composite samples, each containing different percentages of glass microspheres. The initial sharp increase in force for all samples indicates their resistance to impact. In particular, the PG6 and PG8 composites, containing 6% and 8% glass microspheres, respectively, exhibited higher peak forces and sustained the force over a greater displacement range, indicating superior impact resistance. In contrast, the pure phenolic resin composite (P) showed a lower maximum force and a rapid decrease in force, highlighting its lower impact resistance. The data suggest that incorporating glass microspheres of up to 8% enhances impact properties, while higher percentages, such as 10%, may negatively affect performance.

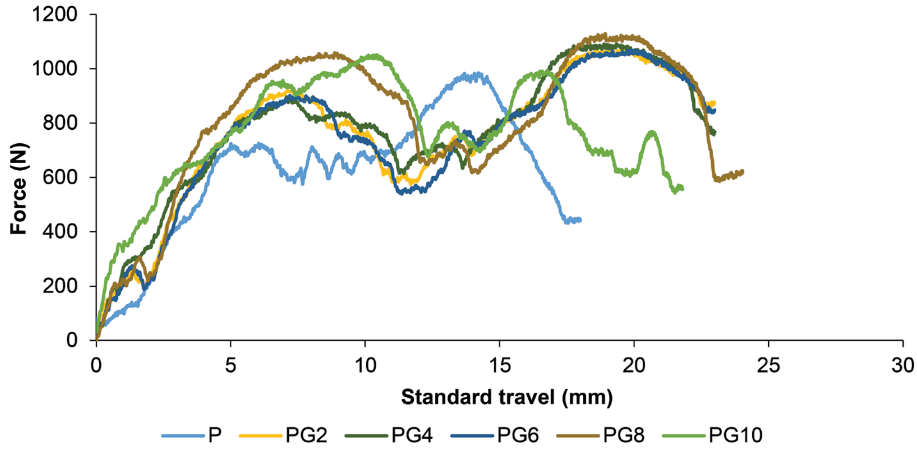


Figure 10: Force versus standard travel curves of various composite samples

4 Conclusion

Based on the extensive mechanical testing conducted in this study, the incorporation of glass microspheres into phenolic resin composites significantly enhanced their mechanical properties. Tensile testing revealed that glass microspheres increased the tensile modulus and achieved maximum tensile strength at concentrations of 6–8%. However, there was no improvement in Charpy impact strength, and the composites exhibited reduced pendulum impact energy compared to pure phenolic resin. Energy absorption increased with the addition of glass microspheres, reaching a peak at a concentration of 8%. The flexural modulus also peaked at a concentration of 8%, with a slight decrease observed beyond this concentration. Impact testing by drop weight also demonstrated that the optimal concentration for improved impact resistance enhancement was found in 6–8% concentrations of glass microspheres, with the PG6 compound absorbing the highest amount of energy at 29.14 J. Force versus time curves showed that composites with 6–8% concentrations of glass microspheres sustained higher peak forces and exhibited improved toughness compared to both pure resin and higher concentration composites. Therefore, this study confirms that 6–8% concentrations of glass microspheres optimise the phenolic resin composites' structural and impact attributes, which qualify them for potential applications such as automotive components, aerospace structures, marine equipment and construction materials that require high stiffness, strength and impact resistance.

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