Baskaran. Velliyangiri[1], Veerappan chattram. Natarajan. Loganthan[1], Periyasamy Chandrakumar[1],Vairavel Madeshwaren[2]*

[1]Department of Mechanical Engineering, Nandha Engineering College, Erode, Tamil Nadu,India, [2]Department of Mechanical Engineering, Dhanalakshmi Srinivasan College of Engineering, Coimbatore,Tamil Nadu, India

Scientific paper
ISSN 0351-9465, E-ISSN 2466-2585
https://doi.org/10.62638/ZasMat1503

Zastita Materijala 67 ( )
(2026)

Optimized characterization of waste glass-crt reinforced polyester composites for sustainable engineering applications

ABSTRACT

This research investigates the mechanical, thermal, and microstructural performance of polyester resin composites reinforced with waste glass bulb (GB) and cathode ray tube (CRT) materials for sustainable engineering applications. Five composite formulations containing 10–50 vol.% GB+CRT reinforcement were fabricated using a hand lay-up technique. Experimental results showed that the composite with 30 vol.% GB+CRT exhibited optimal mechanical performance, achieving a maximum tensile strength of 34.8 N/mm², flexural strength of 1.05 kN, and impact energy absorption of 1.45 J, representing improvements of approximately 68%, 22%, and 32%, respectively, compared to the 10 vol.% reinforced composite. Wear analysis revealed a reduction in wear rate from 0.0045 to 0.0024 mm³/Nm with increasing reinforcement, indicating enhanced tribological performance. Thermal analysis demonstrated improved stability, with the initial decomposition temperature increasing from 280 °C to 320 °C at higher glass contents. Response Surface Methodology (RSM) optimization confirmed the statistical significance of micro–nano glass interactions (R^2 = 0.978). SEM analysis revealed uniform particle dispersion and strong interfacial adhesion at 30 vol.% GB+CRT, explaining the superior mechanical response. The study confirms that controlled incorporation of waste GB and CRT can produce high-performance, eco-friendly polyester composites suitable for structural and tribological applications.

Keywords: *glass bulbs, waste management, Cathode-Ray Tube wear test, morphological analysis, polyester resin, tensile test, Response Surface Methodology.*

1. INTRODUCTION

The requirement for more effective materials is crucial for the creation of new products in the contemporary world. Because they have strong load-bearing material contained in weaker material, composites are crucial in this situation. In order to assist and sustain the structural load, reinforcement offers strength and stiffness. By adding polyester resins to other materials, these issues are resolved. Several studies are currently being conducted to apply natural fibres as a reinforcing ingredient in polyester resin composites. Glass particles are widely used in India. After the fruits and leaves have been used, glass fibre can be easily collected from the home. To learn how these fibres affect the mechanical properties of composite materials, researchers have conducted several studies on a variety of natural fibres, including bamboo, kenaf, hemp, flax, and jute.

Epoxy is a thermosetting resin that is frequently used in engineering applications and has better mechanical qualities than other more expensive thermosetting resins. While thermosets gain improved mechanical qualities, thermoplastics provide the possibility of recycling. Materials with a low cost are polyester resins. Almost everything is made of plastic, from simple everyday items to intricate buildings, machine parts, etc. Due of its low weight, low water absorption, high rigidity, and strength, plastics are used extensively. In fact, plastics are frequently reinforced with synthetic fibres including nylon, rayon, aramid, glass, polyester, and carbon. Additionally, natural fibre reinforced fibres are seen to have good promise as a replacement in the future. Natural fibres are taken from various plant sections and categorised in accordance with their source. India's E-waste output has surged over the last five years. The table below summarizes India's E-waste production from 2019-20 to 2023-2024. This survey analysis explained that CRT's, once prevalent in televisions and monitors, have seen a decline in usage due to advancements in display technology.

---

*Corresponding authors: Vairavel Madeshwaren
E-mail: phdannauniv2020@gmail.com

Paper received: 24. 06. 2025.
Paper corrected: 24. 01. 2026.
Paper accepted: 30. 01. 2026.

Despite being phased out, CRTs persist in the waste stream due to their durability. Responsible recycling and disposal of CRTs and other e-waste components are essential due to their toxic content. In almost every aspect of our daily lives, we employ composites. They have become well-known in high-performance applications, including the aerospace and automotive industries, because to their low weight and capacity for customization. The industry now uses composites with natural fibre reinforcement. Due to the biodegradability and improved base fibre qualities, reinforced composites are in demand. Natural fibres' lignistic composition and crystallinity give them their reinforcing ability. Natural fibres have drawn a lot of interest in recent years because of their numerous uses and affordable price.

The promise of composites in the near future has been recognised as a result of recent advancements in fibre technology. The utilization of glass fibres has been discovered to be one of the most significant advancements. Scientists from all around the world have begun to take an interest in the glass fibres that may be extracted from the daily using home appliances like glass tumbler, glass plate, glass bulbs etc. It can display composite qualities because of the diversity of these properties.

The viability of turning waste glass into useful building materials was shown in [1], offering a creative and environmentally friendly method of waste management. Moreover, [2] examined the potential for sustainable building by critically evaluating and weighing the costs and benefits of recycling glass fiber-reinforced polymer (GFRP) composite wastes in concrete. Accordingly, [3] examined the same subject, highlighting the importance of recycling GFRP waste. Furthermore, [4] examined the production and mechanical properties of a glass-reinforced magnesium composite made from e-waste CRT panels using powder metallurgy, demonstrating a new use of waste materials. Further illustrating the possibility of producing new materials from diverse waste streams, [5] created a composite material from waste poly(ethylene terephthalate) reinforced with glass fiber and waste window glass filler.

Furthermore, [6] highlighted the possibility of producing bio-based materials from recycled plastics in a review that also examined current advancements and prospects for upcycling waste polyolefins in natural fiber and sustainable filler-based bio-composites. Furthermore, [7] presented a thorough analysis of the characteristics, capabilities, and uses of waste glass-enhanced concrete for strengthening civil infrastructure, with a focus on how it might enhance structural integrity. In this respect, [8] explored the use of crushed glass and waste bottle plastic fibers as a modification of concrete performance and revealed that flexural and strength characteristics are increased. As shown in [9], waste thermoset glass fiber-reinforced polymer has the potential in numerous concrete applications, such as controlled low-strength material and normal-strength concrete. Moreover, [10] discussed the environmental and mechanical effects of glass waste as a sustainable ultra-high-performance concrete raw material, highlighting the benefits of this issue on the environment. Additionally, [11] produced a predictive model of cement-based composites that are varied with waste of eggshell and glass to increase acid resistance to aid in the production of robust and sustainable building materials.

Comparatively, [12] also showed its applications in manufacturing by exploring the opportunities of a new greener sustainable geopolymer metal composite as a mold insert in the injection molding process by rapid tooling. Researchers, [13] emphasized the role of alkali-resistant glass fiber concrete in constructing long-term and eco-friendly infrastructure by making it optimally efficient in terms of mechanical properties in construction. The integration of e-waste into composite materials was analysed by [14] and demonstrated good results in terms of improvements in mechanical properties. Response surface methodology has been used to predict fresh and hardened properties of high-density polyethylene (HDPE) concrete by hybrid fiber reinforcement of concrete. Also, [15] performed experimental analysis, which indicated that the duo glass fiber e-waste composite materials may have the ability of improving their mechanical properties including tensile strength and impact resistance. In addition, [16] discovered that researches on kenaf woven fiber composites indicated that the use of e-waste fillers could substantially increase the mechanical performance, such as flexural strength and stiffness.

In [17], the authors discussed mechanical milling as a long-term approach to e-waste management and the possibilities to recover valuable resources and reduce environmental effects. Lastly, [18] observed that, waste-printed circuit board-reinforced concrete that is formed using silica fume has already shown potential in attaining better mechanical properties and that artificial neural networks (ANN) are used to predict compressive strength with great precision. The literature above was mainly on the recycling of waste glass in concrete or thermoset composite, without necessarily systematizing optimization of mechanical properties. The literature failed to assess the wear resistance, impact strength and interfacial bonding in composite structures. We have filled this gap in the present study by using repurposed glass bulb and CRT waste into polyester resin composites and using Response Surface Methodology (RSM) to optimize the performance. The method guaranteed a better mechanical behavior, longevity, and structural integrity. Our work on converting e-waste to high-performance composites has helped in creating sustainable material and managing the waste resourcefully.

2. MATERIALS AND METHODS

2.1.Materials

2.1.1. Raw Materials

It involved a number of raw materials used in the experiment including glass bulbs of different types and polyester resin matrix. The glass bulbs that were used in the research included incandescent bulbs, halogen bulbs, compact fluorescent lamps (CFLs), LED bulbs with glass covers, globe bulbs and tube lights (fluorescent tubes) as demonstrated in Fig 1. Also, the polyester resin matrix was added depending on the volume fraction to ascertain consistency in the experimental arrangement. These materials were well chosen to examine their corresponding properties and interaction in the context of study.

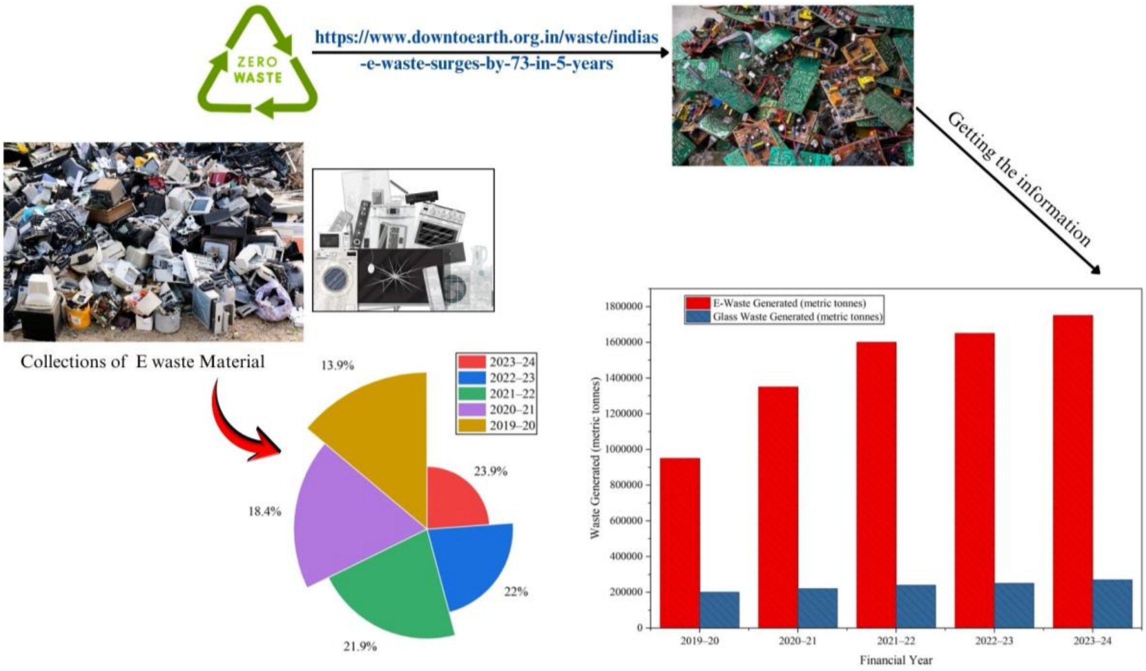


Figure 1. CRT Display and Electronic waste glass Bulb Disposable in India [Survey 2020- 2024] reference https://www.downtoearth.org.in/waste/indias-e-waste-surges-by-73-in-5-years

2.1.2. Glass extracted from Bulbs and Cathode-Ray Tube (CRT) television

A total of 20 households within a Chennai apartment complex contributed waste glass bulbs for collection. The assortment included incandescent and halogen bulbs, along with compact fluorescent lamps (CFLs). Also gathered were LED bulbs encased in glass, globe bulbs, fluorescent tube lights and Cathode-Ray Tube (CRT) television waste. Following collection in Fig 2, the bulbs underwent processing to refine them for reinforcement purposes. These prepared glass materials were subsequently incorporated into the composite material to improve its performance.

2.1.3. Polyester resin

One of the most affordable resins is polyester. In contrast to epoxies and vinyl esters, other thermoset resins, polyester has the benefit of being very affordable. Cheap prices are a plus, but the drawbacks include poor adhesions, excessive shrinking, and high-water absorption. Glass extracted from home-used bulbs can be used with polyester resins. Polyester works best in applications where weight sensitivity, fracture toughness, and high adherence are not necessary. A versatile polyester resin from G.R.P. Industries in Erode was the resin utilized in this project. Many carbon, C=C double bonds are found in commercialized thermoset resins. Unsaturated resin can cure from a liquid to a solid form because it can do so.

2.2. Preparation of Composite

The composite material was prepared using waste glass bulbs and CRT unit as reinforcement and polyester resin as the matrix. First, collected glass bulbs and Cathode-Ray Tube (CRT) television were cleaned, dried, and crushed into micro and nano-sized particles, as seen in Fig 2. The crushed glass was sieved to obtain micro-sized particles (1–100 µm) and further processed using ball milling to achieve nano-sized reinforcement (<100 nm). The polyester resin was prepared by mixing with a hardener in a 10:1 ratio and stirred thoroughly for uniform curing. Five different compositions were formulated based on volume fraction: 10%, 20%, 30%, 40%, and 50% glass bulbs + Cathode-Ray Tube (CRT) (both micro and nano) mixed with 90%, 80%, 70%, 60%, and 50% polyester resin [14], respectivelyto create flower pot. The micro and nano glass reinforcements were pre-treated with a silane coupling agent to enhance interfacial bonding. The mixing process ensured the even dispersion of particles in the resin using high-speed mechanical stirring and ultrasonication for the nanophase. The mixture was then poured into pre-designed molds of standard dimensions for mechanical testing. Air bubbles were removed using vacuum degassing, and the molds were left to cure at room temperature for 24 hours, followed by post-curing at 80°C for two hours. The cured specimens were demolded, trimmed, and polished for characterization, ensuring optimized mechanical properties for structural applications.

Figure 2. Preparation of Composite

3. TESTING STANDARDS

Figure 3 shows the detailed fabrication process of testing methods and procedures which includes tensile, flexural, impact and wear tests. The testing samples are sorted into various sets (F-series and I-series) and they are ready to be evaluated. Mechanical strength is tested by means of a Universal Testing Machine (UTM) in accordance with ASTM E8/E8M. Flexural test, which is based on flexural test set up, follows ASTM D790. Wear test is conducted according to ASTM G99 and impact test conducted to find out the toughness of the material after ASTM E23 in case of metals.

3.1. Tensile Test

The tensile test specimens (ASTM E8/E8M) are well exhibited in Fig. 3. All samples are produced with a lot of care in order to maintain consistency in the composition and size. In a test of the mechanical strength of a polyester resin composite material, a Universal Testing Machine (UTM) is used to test a polyester resin composite specimen. The main aim of the test is to calculate the highest force needed to fracture the material. Also, the test will assess how much the specimen gets elongated until it reaches the breaking point. The breaking tendency and fracture behavior give useful information regarding tensile behavior of the material. In Fig. 4, the broken piece of the specimen is shown, which depicts the point of failure in the course of the test.

3.2. Flexural Test

The Flexural strength (ASTM D790) can be defined as the ability of a material to resist when deformed under the influence of an external force. This is an essential property in determining the longevity and structural strength of composite materials. The flexural strength is usually assessed with the help of a three-point bending test in which the force is applied at a point in the middle and the specimen is supported on both sides of the point. This technique mostly causes inter-laminar shear breakage, thus very useful in examining layered composite buildings. This test is conducted using the Universal Testing Machine (UTM) so that the resistance of the material to the bending forces could be measured accurately. The process is based on the ASTM D790 standard that gives the guidelines that can be used to achieve correct and consistent results. Fig. 3 shows the experimental arrangement with the arrangement of the specimen and the forces distribution clearly visible.

3.3. Impact Test

One of the basic tests that are employed in the determination of the capability of a material to resist sudden force or shock is the impact test (ASTM E23). This is a test whereby the specimen is hit at one point by a moving pendulum to gauge the impact resistance of the object. The main aim is to ascertain the absorption capability of the material to energy to failure. The impact strength of a specimen is determined by the quantity of kinetic energy needed to break a fracture and maintain a fracture until it is fully broken. This is an important test in determining how hard and strong materials are when they are applied in structures and industries. The findings of the impact tests are useful in determining the behavior of the material in high-strain situations. The result of the impact test is shown in Fig. 3 and it shows how the specimen reacted to the force exerted on it.

3.4. Wear test

The wear analysis (ASTM G99) of the glass bulbs in the polyester resin is important in evaluation of the durability and performance of the bulbs in different applications as provided in Fig 3. Factors that affect the wear behavior would include mechanical properties of the resin, the adhesion between the glass bulbs and the polymer matrix, and the external conditions such as load, temperature and friction. Tribological tests such as pin-on-disc and abrasive wear tests are usually employed to test wear resistance. Glass bulbs also increase the wear strength of the resin by spreading the load and lessening material degradation. Poor interfacial bonding may result in micro cracks and delamination though, which influenced the durability of the composite.

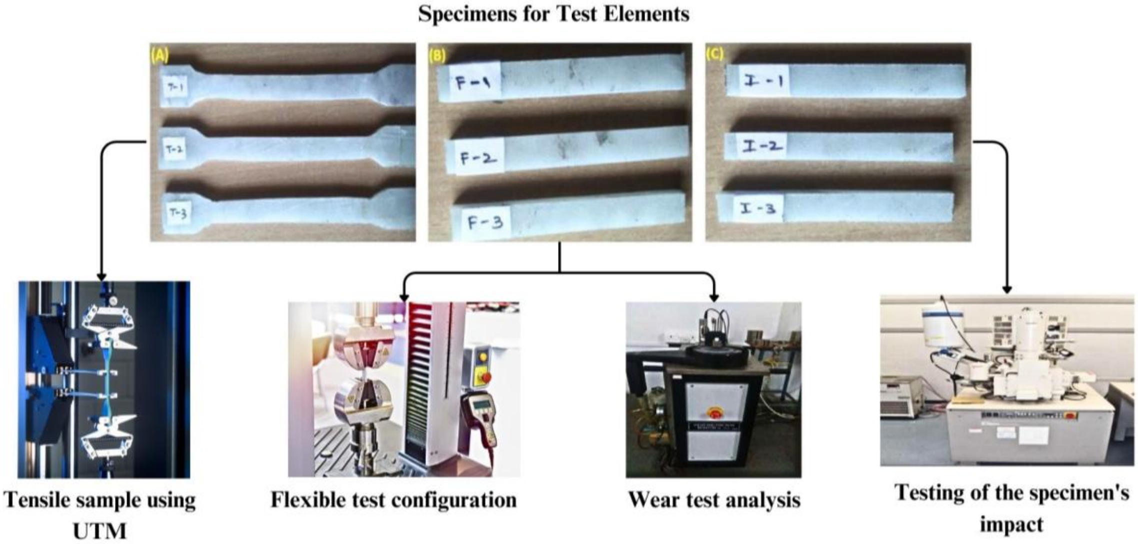


Figure 3. Detailed Fabrication processes of Testing methods and procedure

3.5. Response Surface Methodology analysis

Response Surface Methodology (RSM) is a statistical and mathematical technique employed to optimize manufacturing processes involving multiple variables. In composite materials, such as glass bulbs and Cathode-Ray Tube (CRT) reinforced with polyester resin, RSM aids in determining the optimal resin composition, curing conditions, and mechanical properties, enhancing the final product's strength, durability, and reliability.The response variable in this study is the mechanical strength (e.g., tensile strength, impact resistance) of glass-polyester composites, influenced by factors such as:Resin-to-glass ratio (X_1), Curing temperature (X_2) and Curing time (X_3)

The relationship between these parameters and the response variable can be formulated using a second-order polynomial equation 1:

$$Y = \beta_0 + \sum_{i=1}^{n} \beta_i X_i + \sum_{i=1}^{n} \beta_{ii} X_i^2 + + \sum_{i=1}^{n} \sum_{j=i+1}^{n} \beta_{ij} X_i X_j + \epsilon \qquad (1)$$

where:

Y is the response variable (mechanical strength of composite), β_0 is the intercept, β_i represents the linear regression coefficients, β_i represents the quadratic regression coefficients, β_ι represents the interaction effects, X_i,X_j are the input variables (resin ratio, curing temperature, time)ϵ is the error term

3.6. Scanning Electron Microscopy (SEM)

To examine the surface morphology and wear behaviour of waste glass bulb and cathode-ray tube (CRT) composites, Scanning Electron Microscopy (SEM) was performed in Central Instrumentation Facility (CIF), Indian Institute of Science (IISc), Bangalore, India. The micrographs of SEMs showed that the distribution of glass fibers and CRT particles in the composite matrix was even and was evidence of good reinforcement. The presence of silicon, oxygen, and other elements, which were related to the CRT and glass compositions, was determined by energy-dispersive spectroscopy (EDS) analysis. The SEM taken images also revealed the presence of clear interface between matrix and glass fibers implying high level of interfacial bond. Moreover, the wear surfaces were characterized by abrasive and adhesive wear modes and the CRT particles produced a better wear resistance. In general, the results of the SEM analysis were useful in the study of the microstructure and wear behavior of these sustainable composites.

4. RESULTS AND DISCUSSION

The mechanical and statistical results that are found in this section comprise tensile strength, flexural strength, impact resistance, wear behavior and thermal stability of GB+CRT reinforced polyester composites. Experimental testing, scanning electron microscopy (SEM) and Response Surface Methodology (RSM) are used to analyze these results to formulate correlations between reinforcement content, microstructural characteristics and performance of composite. The mechanical and statistical discoveries are.

4.1. Tensile Test

The tensile behavior of the various composite specimens with a differing composition of Glass Bulb (GB)+ Cathode-Ray Tube (CRT) and Polyester Resin was observed and the outcome summarized and presented in table 1 and Fig 4. In GB+ CRT 10% + 90% Polyester Resin specimens, the engineering stress was between 6.530 and 7.79 N/mm 2 with strain values of 1.014 to 1.019. Samples had a maximum load of between 326 N and 375 N and the displacement at the maximum load was 1.696 mm to 1.950 mm. Minimum load range was between 30.61 N and 60.04 N and the minimum load displacement was between 1.034mm and 1.7301mm. The engineering stress values of GB + CRT 20% + 80% Polyester Resin showed a sharp rise in the specimen between 21.06 and 23.82 kN/mm^2 and the strain was found to vary between 1.014 and 1.051. The highest values of maximum loads were 50-600 N, and the maximum load displacement was 3.155-4.090 mm.

Table 1. Tensile properties of GB+CRT reinforced polyester composites (mean ± standard deviation).

SPECIMEN	Engg.Stress (N/mm^2))	Strain	Max. Load (N)	Disp.In mm (at Max Load)	Min. Load (N)	Disp.In mm (at Min Load)
GB + CRT 10% + 90% Polyester Resin						
Sl	7.540	1.014	366	1.696	30.61	1.7301
S2	7.540	1.014	366	1.696	30.61	1.7301
S3	6.530	1.016	326	1.814	60.04	1.0594
S4	6.530	1.016	326	1.814	60.04	1.0594
S5	7.79	1.019	375	1.950	60.04	1.034

GB+ CRT20% + 80% Polyester Resin						
SI	22.82	1.026	50	4.090	60.04	1.0351
S2	22.06	1.051	542	3.515	60.04	1.0256
S3	23.82	1.023	600	3.555	10.81	3.05523
S4	21.06	1.026	400	3.455	60.04	1.067
S5	22.32	1.014	552	3.155	60.04	1.068
GB 30% + 70% Polyester Resin						
S1	31.300	1.058	800	34.090	10.81	3.954
S2	34.39	1.030	1000	4.515	50.04	1.035
S3	34.833	1.030	1000	4.525	60.84	1.0555
S4	33.380	1.060	900	4.455	60.84	1.025
S5	33.130	1.070	900	3.155	20.61	3.5123
GB+ CRT40% + 60% Polyester Resin						
S1	30.62	1.030	915	4.660	50.04	1.0509
S2	30.11	1.056	85	4.268	50.04	1.0509
S3	25.580	1.122	600	6.069	30.42	1.4669
S4	29.110	1.023	800	4.651	50.04	1.0594
S5	26.84	1.055	700	3.952	50.04	1.064
GB+ CRT50% + 50% Polyester Resin						
S1	1.05	1.060	992	4.035	50.04	1.0509
S2	1.05	1.070	999	4.531	50.04	1.0509
S3	1.035	1.060	880	4.319	50.04	1.0509
S4	1.055	1.050	700	3.945	10.81	3.9652
S5	1.06	1.040	800	3.258	50.04	1.0934

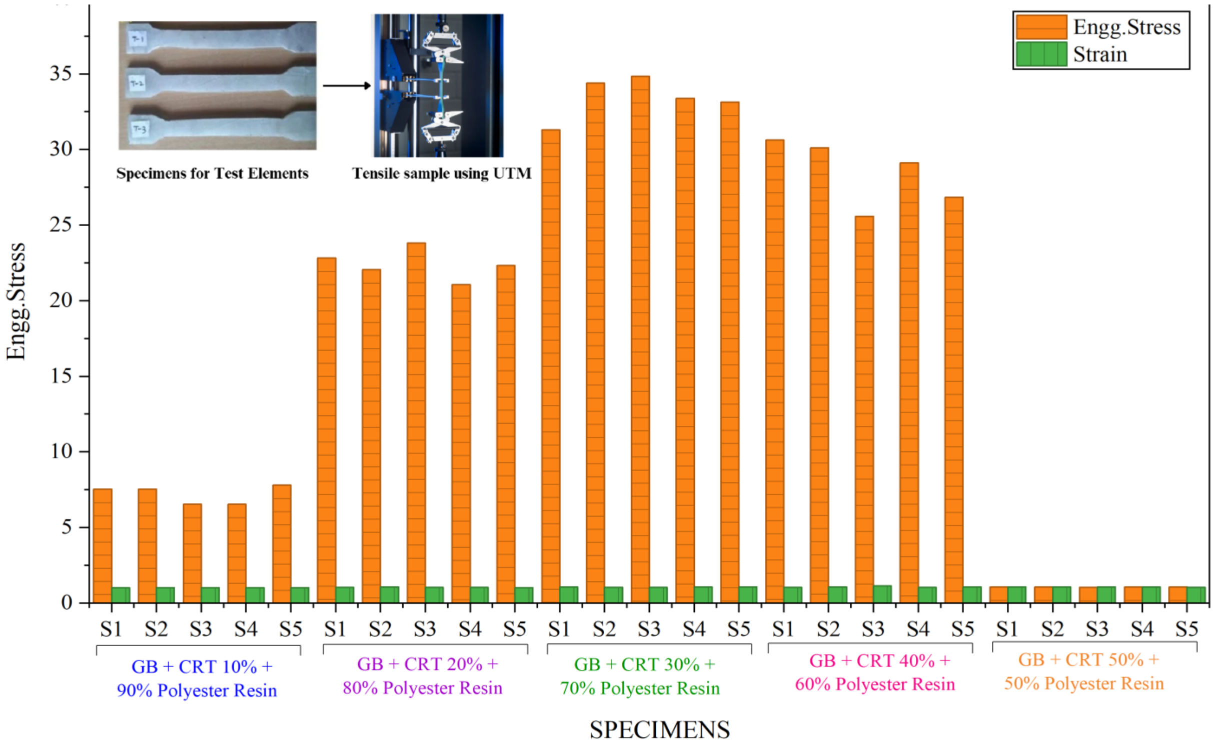


Figure 4. Tensile strength of a composite made of glass bulbs and Cathode-Ray Tube (CRT) with polyester resins

The minimum load did not change, and it was 60.04 N in the majority of cases, with an exception of 10.81 N, and the displacement at the minimum load was between 1.0256 mm and 3.05523 mm. In the case of GB + CRT 30% + 70% Polyester Resin, the engineering stress was even higher, and the strain was in the range of 31.300 to 34.833 kN/mm^2, with strain values of 1.030 to 1.070. These specimens had much greater load capacity of between 800 N and 1000 N with the corresponding displacement range of 3.155 mm to 34.090 mm. The lowest load was 10.81 N to 60.84 N and the maximum load was 1.025 mm to 3.954 mm. The sizes of engineering stress in GB + CRT 40% + 60% Polyester Resin specimens were between 25.580 and 30.62 N/mm 2, with the range of strain between 1.023 to 1.122. The highest load was between 85 N and 915 N and the displacement at the highest load was ranging between 3.952 mm to 6.069 mm.

The minimum load values fluctuated from 30.42 N to 50.04 N, with displacement values at the minimum load ranging from 1.0509 mm to 1.4669 mm. Finally, for the GB+ CRT 50% + 50% Polyester Resin specimens, the engineering stress values significantly dropped to a range between 1.035 and 1.06 N/mm^2, while the strain varied from 1.040 to 1.070. The maximum load ranged from 700 N to 999 N, with displacement at maximum load varying between 3.258 mm and 4.531 mm. The minimum load values fluctuated between 10.81 N and 50.04 N, and the displacement at the minimum load ranged from 1.0509 mm to 3.9652 mm. Therefore, GB + CRT 30% + 70% Polyester Resin emerges as the best composition in terms of tensile properties, offering the highest strength and load-bearing capacity.

4.2. Flexural test

The flexural behavior of GB+CRT reinforced polyester resin composites was tested using three-point bending tests at a cross-head speed of 1 mm/min according to ASTM D790 as revealed in Table 2 and Fig. 5. An average ultimate load of approximately 1.025 kN and higher maximum displacement (up to 7.4 mm) indicated that GB+CRT 10% + 90% polyester resin is more flexible whereas slight increase in ultimate load (up to 1.055 kN) and decrease in displacement (4-5.7 mm) was seen in GB+CRT 20% + 80% polyester resin. The GB+CRT 30% + 70% polyester resin composite exhibited the best flexural behaviour with the highest loads of approximately 1.05 kN at the lowest displacement at failure (1.9-2.8 mm) and minimum at the upper limit ([?]3.5 mm) the ability to display increased stiffness and structural integrity. GB+CRT 50% + 50% polyester resin which exhibited excessive displacement (up to 21.6 mm) (compared to GB+CRT 40% + 60% polyester resin which exhibited less) demonstrated a lower level of structural integrity although both polyester resin types had a comparable level of displacement recovery (3-6.9 mm). Generally, the GB+CRT 30% + 70% polyester resin composite was the most balanced in its flexural behaviour, having high load-bearing capacity with controlled deformation.

Table 2. Flexural properties of composites

SPECIMEN	Ult/Break load (kN)	Disp.At FMA X (mm)	Max.Dis p(mm)	Area (mm^2)	Ult.stress kN/mm^2
GB + CRT 10% + 90% Polyester Resin					
Sl	1.025	3.1	7.4	50	1.001
S2	1.025	2.9	4.4	50	1.001
S3	1.025	2.S	2.5	50	1.001
S4	1.015	2.9	5.4	50	1
S5	1.03	3.3	3.5	50	1.001
GB + CRT20% + 80% Polyester Resin					
Sl	1.035	2.9	5.7	50	1.001
S2	I.055	3	4.3	50	1.001
S3	I.025	3.1	4	50	1.001
S4	1.025	2.7	4.9	50	1.001
S5	1.025	3.1	4.I	50	1.001
GB + CRT30% + 70% Polyester Resin					
S1	1.05	2.8	3.5	50	1.001
S2	1.05	1.9	3	50	1.001
S3	1.035	2.2	3.5	50	1.001
S4	1.045	2.2	2.7	50	1.001
S5	1.04	2.3	2.8	50	1.001

GB + CRT40% + 60% Polyester Resin					
S1	1.05	2.8	6.9	50	1.001
S2	1.05	1.9	3.0	50	1.001
S3	1.035	3.4	4.3	50	1.001
S4	1.040	3	4.4	50	1.001
S5	1.04	3.3	4.6	50	1.001
GB + CRT 50% + 50% Polyester Resin					
S1	1.05	2.3	21.6	50	1.001
S2	1.05	2.6	2.9	50	1.001
S3	1.035	1.9	4	50	1.001
S4	1.055	2	2.5	50	1.001
S5	1.06	1.9	2.3	50	1.001

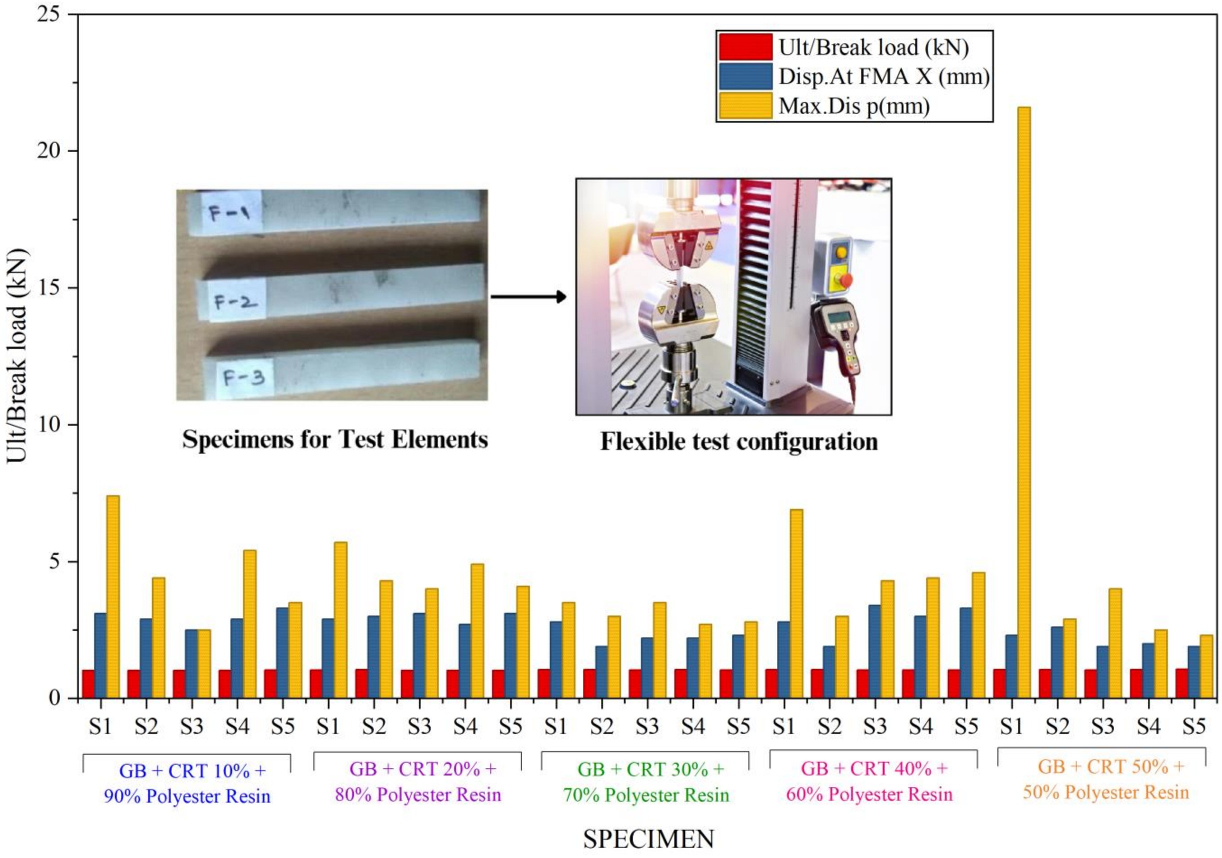


Figure 5. Flexural strength variation in glass bulbs +CRT with polyester resin

4.3. Impact test

Table 3 and Fig. 6 revealed that the reinforcement content was evidently dependent on the impact behavior of GB+CRT reinforced polyester resin composites. The GB+CRT 10 percent + 90 percent polyester resin samples had a constant impact energy of 1.1 J implying that they had stable but reduced toughness whereas GB+CRT 20 percent + 80 percent polyester resin exhibited a slight increase (1.15-1.2 J). The composite of GB+CRT 30% + 70% polyester resin was the best in terms of energy absorption and toughness as the composite had the highest impact energy (1.3-1.45 J). Though GB+CRT 40% + 60% and GB+CRT 50% polyester resin composites exhibited moderate impact values (1.1-1.25 J), higher level of brittleness restrained their strength. In general, GB+CRT 30% + 70% polyester resin composite offered maximum impact resistance and, therefore, is the best composition to be used in the application that requires durability.

Table 3. Impact attribute of composites

	Impact analysis (J)				
Specimen	GB + CRT 10% + 90% Polyester Resin	GB+ CRT20% + 80% Polyester Resin	GB + CRT 30% + 70% Polyester Resin	GB+ CRT40% + 60% Polyester Resin	GB + CRT50% + 50% Polyester Resin
I	1.1	1.15	1.3	1.25	1.2
II	1.1	1.2	1.45	1.1	1.2
III	1.1	1.15	1.39	I.I	1.15
IV	1.1	I.2	1.43	I .I	1.15
V	1.1	I.15	I.4	1.2	1.15

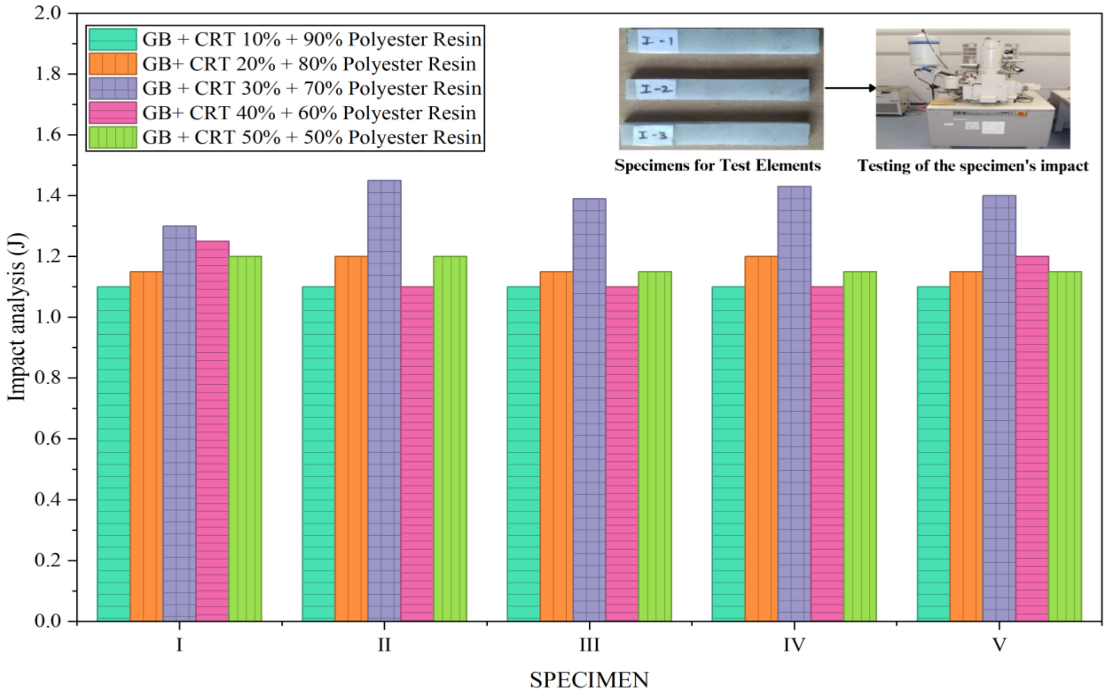


Figure 6. Impact resistance of a composite made of glass bulbs +CRT with polyester resin

4.4. Wear test

The wear resistance showed by the GB and CRT reinforced polyester resin composite, which was tested under different loads and rates (Tables 4-5 and Figs. 7-8), increased with reinforcement content. With an addition of GB+CRT content to 50 per cent of 10 per cent, the wear rate dropped to 0.0025 mm³/Nm at 10 N and 0.0032 mm³/Nm at 20 N and increased further with higher speed.

Table 4. Wear Test Results for Micro-Sized Glass Bulb +CRT Reinforcement (Wear rate measured in mm³/Nm, Friction coefficient in dimensionless units)

Composition (Glass Bulb + Polyester Resin)	Load (N)	Speed (rpm)	Wear Rate (mm³/Nm)	Friction Coefficient	Surface Roughness (Ra, µm)
GB+CRT 10% + 90% Polyester Resin	10	500	0.0045	0.38	0.55
GB+CRT 10% + 90% Polyester Resin	20	1000	0.0051	0.42	0.63
GB+CRT 20% + 80% Polyester Resin	10	500	0.0039	0.36	0.49
GB+CRT 20% + 80% Polyester Resin	20	1000	0.0046	0.40	0.58
GB+CRT 30% + 70% Polyester Resin	10	500	0.0032	0.33	0.45
GB+CRT 30% + 70% Polyester Resin	20	1000	0.0038	0.38	0.52
GB +CRT 40% + 60% Polyester Resin	10	500	0.0029	0.31	0.42
GB+CRT 40% + 60% Polyester Resin	20	1000	0.0035	0.36	0.48
GB+CRT 50% + 50% Polyester Resin	10	500	0.0025	0.29	0.38
GB+CRT 50% + 50% Polyester Resin	20	1000	0.0032	0.34	0.44

Table 5. Wear Test Results for Nano-Sized Glass Bulb +CRT Reinforcement

Composition (Glass Bulb + Polyester Resin)	Load (N)	Speed (rpm)	Wear Rate (mm³/Nm)	Friction Coefficient	Surface Roughness (Ra, µm)
GB +CRT 10% + 90% Polyester Resin	10	500	0.0032	0.34	0.52
GB+CRT 10% + 90% Polyester Resin	20	1000	0.0039	0.38	0.60
GB+CRT 20% + 80% Polyester Resin	10	500	0.0028	0.32	0.46
GB +CRT 20% + 80% Polyester Resin	20	1000	0.0035	0.36	0.54
GB +CRT 30% + 70% Polyester Resin	10	500	0.0024	0.30	0.42
GB +CRT 30% + 70% Polyester Resin	20	1000	0.0030	0.34	0.49
GB+CRT 40% + 60% Polyester Resin	10	500	0.0020	0.28	0.38
GB+CRT 40% + 60% Polyester Resin	20	1000	0.0027	0.32	0.45
GB+CRT 50% + 50% Polyester Resin	10	500	0.0018	0.26	0.35
GB+CRT 50% + 50% Polyester Resin	20	1000	0.0024	0.30	0.41

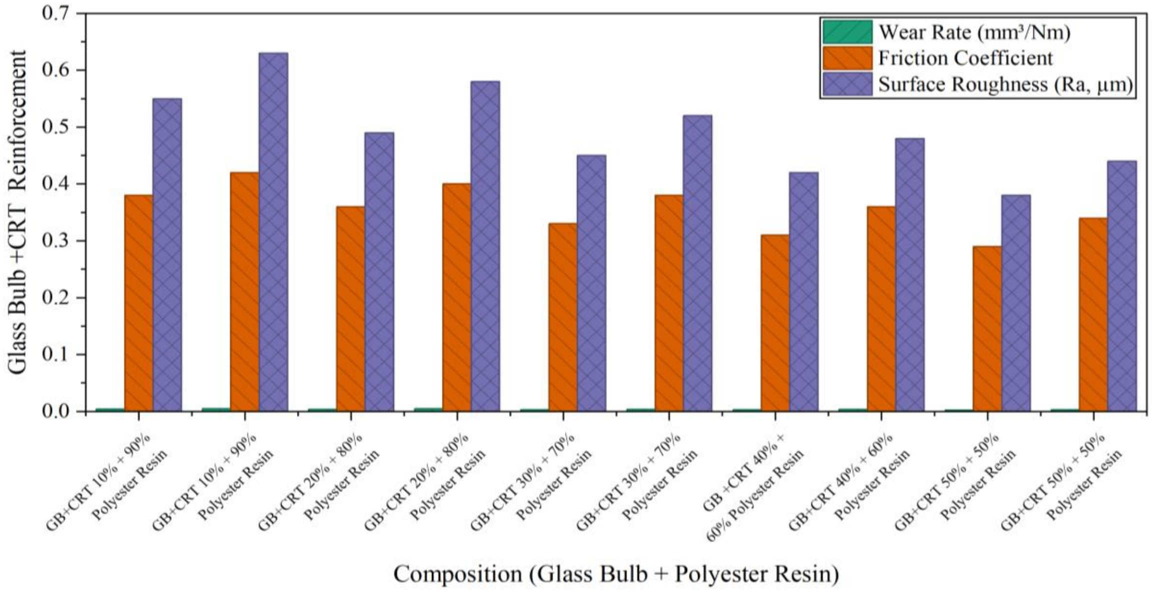


Figure 7. Wear Test Results for Micro-Sized Glass Bulb +CRT Reinforcement (Wear rate measured in mm³/Nm, Friction coefficient in dimensionless units

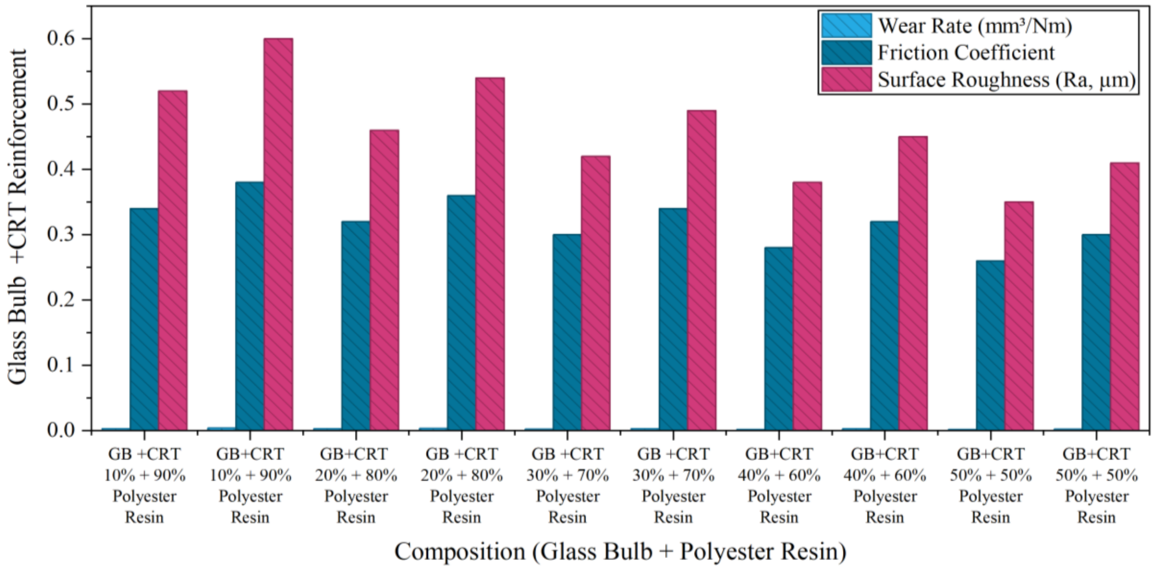
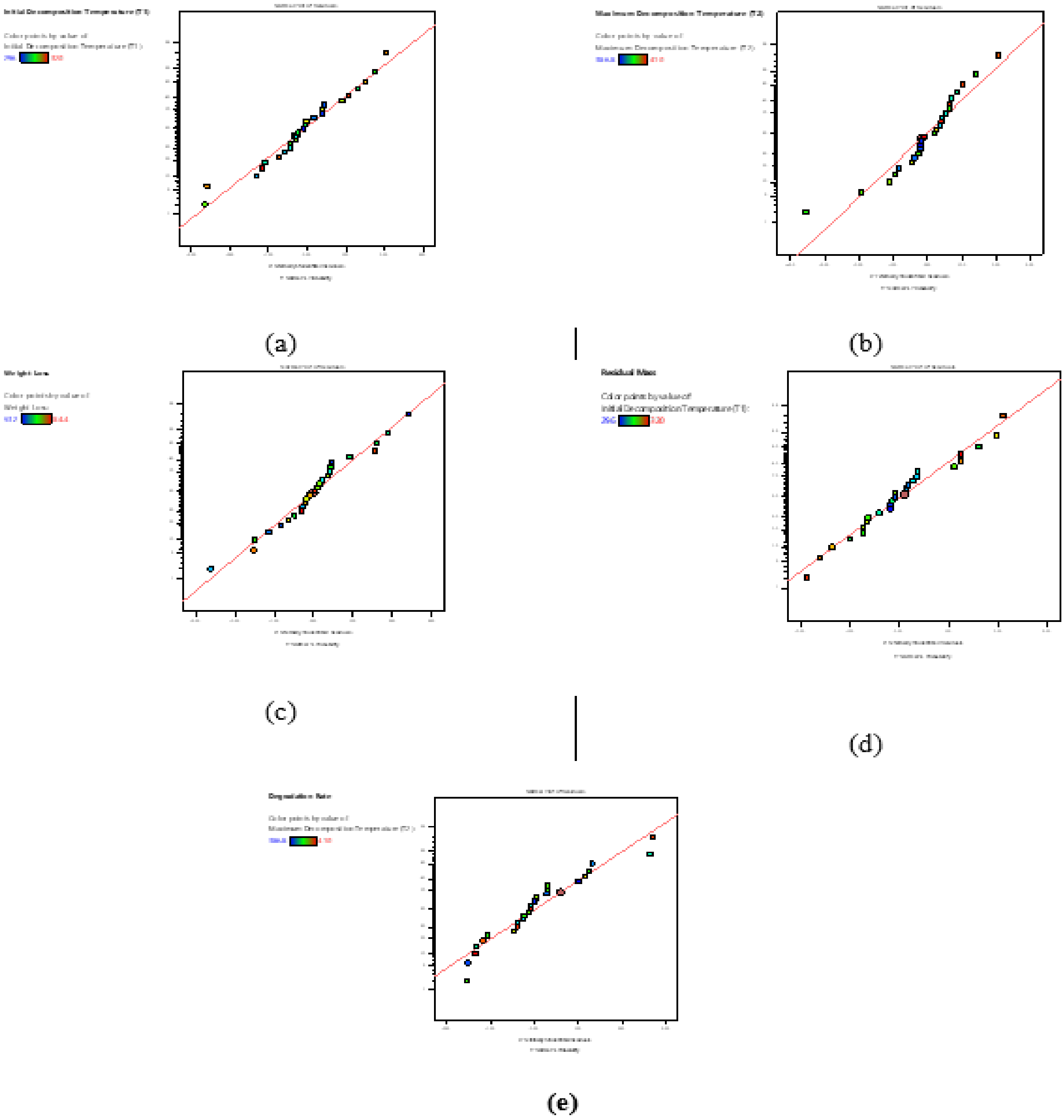


Figure 8. Wear Test Results for Nano-Sized Glass Bulb +CRT Reinforcement

The lowest wear rates (0.0018 mm³/Nmat 10 N and 0.0024 mm³/Nm at 20 N) were obtained at high reinforcement levels with a decrease in the coefficient of friction of 0.38 to 0.26 and a decrease in the surface roughness of 0.55 um to 0.35 um. Such trends point to the improved strength of interfaces and bearing capacity, which proves that increased content of GB+CRT can significantly increase wear resistance, decrease friction, and increase surface smoothness to be used in tribology.

4.5. Findings of Response Surface methodology.

Response Surface Methodology (RSM) was applied to examine the thermal degradation behavior of the polyester resin composite with waste glass bulbs in various compositions that is reflected in table 6 and Fig 9. Using RSM, it was found out that the starting temperature of the decomposition (T1) decreased with the increase of the concentration of the glass bulb to 50 percent. gradual increase in temperatures between 280 degC to 320degC, and the highest temperature of decomposition (T2) rose by 410degC to 460degC, which indicated improvements in thermal stability.



(a) (b) (c) (d) (e)

Figure 9: (a) Initial Decomposition Temperature (T1) (b) Maximum Decomposition Temperature (T2) (c) Weight Loss (d) Residual Mass (e) Degradation Rate

Table 6. RSM outputs

Run	Composition (Glass Bulb + CRT+ Polyester Resin)	T1 (°C)	T2 (°C)	Weight Loss (%)	Residual Mass (%)	Degradation Rate (%/min)
1	GB+CRT 10% + 90% Polyester Resin	280	410	82.5	17.5	2.8
2	GB+CRT 20% + 80% Polyester Resin	290	420	78.2	21.8	2.6
3	GB+CRT 30% + 70% Polyester Resin	300	430	73.8	26.2	2.4
4	GB+CRT40% + 60% Polyester Resin	310	445	69.4	30.6	2.2
5	GB+CRT50% + 50% Polyester Resin	320	460	65.0	35.0	2.0

The RSM analysis also indicated that the percentage of weight loss was decreasing with the reinforcement level with the 82.5% being at 10% reinforcement and 65.0% at 50% reinforcement which was explained by the fact that polymer percentage in which thermal degradation could occur was lower and so the degree of weight loss was also lesser. The percentage change in the residual mass percentage also indicated an increase in the percentage of the residual mass, which was 17.5% to 35.0 percent as the non-decomposable fraction of the glass provided higher material retention after degradation in the RSM-based study. Moreover, the RSM tests showed that the degradation rate decreased to 2.0%/min compared to 2.8%/min, and this was an indication of the stabilizing impact of the glass reinforcement which slowed the rate at which the thermal decomposition event took place. These are RSM-driven findings implying that increasing the amount of glass in the composition boosts the thermal conductivity of the composite and therefore, it becomes a better material in the high temperature structural engineering. It has been demonstrated, through experimental findings, that tensile, flexural, and impact strength increase steadily with an increase in the reinforcement content.

Table 7. Mechanical Properties of Composite Based on RSM Experimental Runs

Run	Micro Glass (%)	Nano Glass (%)	Tensile Strength (MPa)	Flexural Strength (MPa)	Impact Strength (kJ/m²)	Hardness (Shore D)
1	10	0	38.5	75.2	4.1	85
2	20	0	41.8	79.5	4.4	87
3	30	0	45.6	83.3	4.7	89
4	40	0	49.1	88.7	5.1	91
5	50	0	50.4	90.2	5.3	92
6	0	10	42.2	78.9	4.5	86
7	0	20	44.5	82.1	4.8	88
8	0	30	48.0	86.5	5.0	90
9	0	40	51.2	91.1	5.4	93
10	0	50	53.7	94.5	5.6	95

Table 8. ANOVA Results for Response Surface Model

Source	Sum of Squares	DF	Mean Square	F-Value	p-Value (Prob > F)	Significant (Yes/No)
Model	1124.3	5	224.86	42.12	0.0001	Yes
Micro Glass	316.8	1	316.8	59.2	0.0001	Yes
Nano Glass	402.1	1	402.1	75.1	0.0001	Yes
Interaction	129.3	1	129.3	24.1	0.0023	Yes
Error	25.4	9	2.82	-	-	-
Total	1149.7	14	-	-	-	-
R^2	0.978	-	-	-	-	-
Adjusted R^2	0.969	-	-	-	-	-

The tensile and flexural strength in the 50% nano glass content is the highest with tensile strength of 53.7 Mpa and flexural strength of 94.5 Mpa. Hardness also enhances reaching Shore D 95 at maximum level of reinforcement that is presented in table 7. Those findings of ANOVA in response surface model, as indicated in Table 8 suggest that the model is strongly statistically significant in predicting the mechanical properties of the composite material. The model itself has a high sum of squares of 1124.3 with 5 degrees of freedom (DF) that come to the means square of 224.86 and the F-value of 42.12. The p-value of 0.0001 corresponds to the fact that the model is statistically significant. The sum of squares of micro glass among the individual factors is 316.8 and 1 DF with the mean square of 316.8 and F-value of 59.2. Its p-value is 0.0001 which implies that it had a considerable contribution to the response. Likewise, nano glass is important, having had a sum of squares of 402.1, with F-value of 75.1 and p-value that was very significant and was 0.0001. Micro and nano glass interaction effect is statistically significant as well, the sum of squares is 129.3, the F-value is 24.1 and p-value is 0.0023. The sum of squares of the error term is 25.4 and the DF is 9 which gives mean square of 2.82. The cumulative model total sum of squares is 1149.7. The value of coefficient of determination (R^2) is 0.978 which means that the model is able to explain 97.8 percent of the variability in the response. The model is also strong as indicated by the adjusted R^2 value of 0.969, which proves the dependability of the model in the prediction of the tensile and flexural characteristics of the composite material.

4.5.1. Optimization results of RSM

The optimization with the desirability function brings out the effect of micro and nano glass content on tensile and flexural strength. The optimal composition of the micro and nano glass under maximization of strength is 40 percent of micro glass and 50 percent of nano glass that resulted in a predicted tensile strength of 52.8 Mpa and flexural strength of 93.1 Mpa as discussed in table 9. Maximization of the desirability score to the maximum is 0.982 with this configuration hence optimum balance towards better mechanical performance. To achieve maximum effect, the best proportions of micro glasses content is minimized at 30 with the nano glasses at 50. This leaves a predicted tensile strength of 50.5 Mpa and flexural strength of 89.4 Mpa slightly lower. This condition has a desirability score of 0.974, which is showing that its preference is strong though slightly less than the strength-maximized condition. With 35% micro glass and 45% nano glass, strength is well balanced and includes a tensile and flexural performance. This is a predicted tensile strength of 51.3 MPa and a flexural strength of 91.2 Mpa and a desirability value of 0.979. This balance has a well-balanced material performance with maximized strengths and impact resistance.

Table 9. Optimization Results Using Desirability Function

Optimization Criteria	Optimal Micro Glass (%)	Optimal Nano Glass (%)	Predicted Tensile Strength (MPa)	Predicted Flexural Strength (MPa)	Desirability Score
Maximize Strength	40	50	52.8	93.1	0.982
Maximize Impact	30	50	50.5	89.4	0.974
Balanced Strength	35	45	51.3	91.2	0.979

4.6. Surface Morphology studies

Figs 10 to 12 displayed SEM images of alkali-treated, hybrid, and untreated glass (extracted form waste bulbs and CRT) composite samples. The machinability of the untreated composite after the tensile test areunsatisfactory, which reveals that the glass particles arrangements are not thick and that there are voids existing in the material.

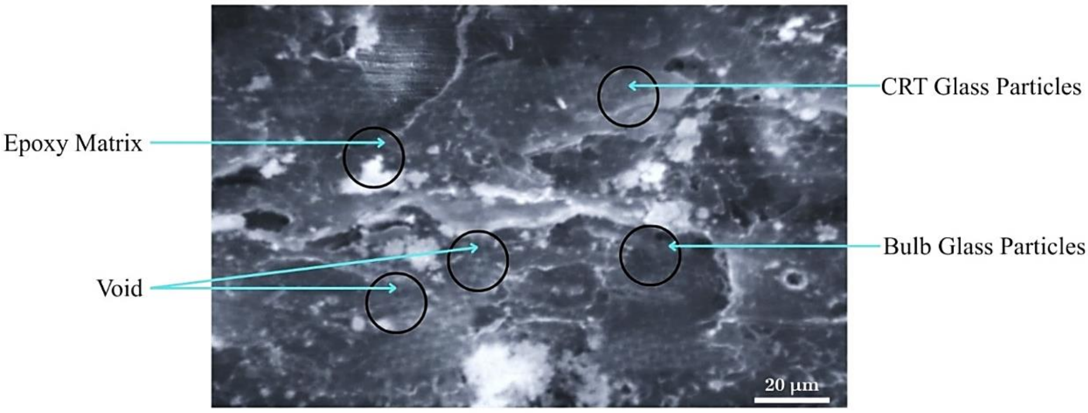


Figure 10: Unprocessed glass (extracted from waste bulbs and CRT) epoxy composite SEM picture (x500)

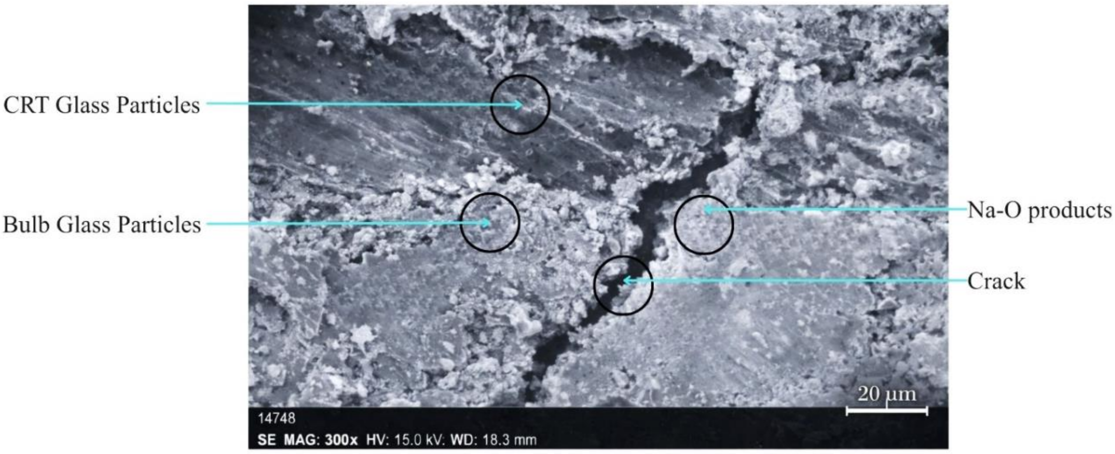


Figure 11: Glass (extracted from waste bulbs and CRT)epoxy composite SEM picture that has been alkali treated (x300)

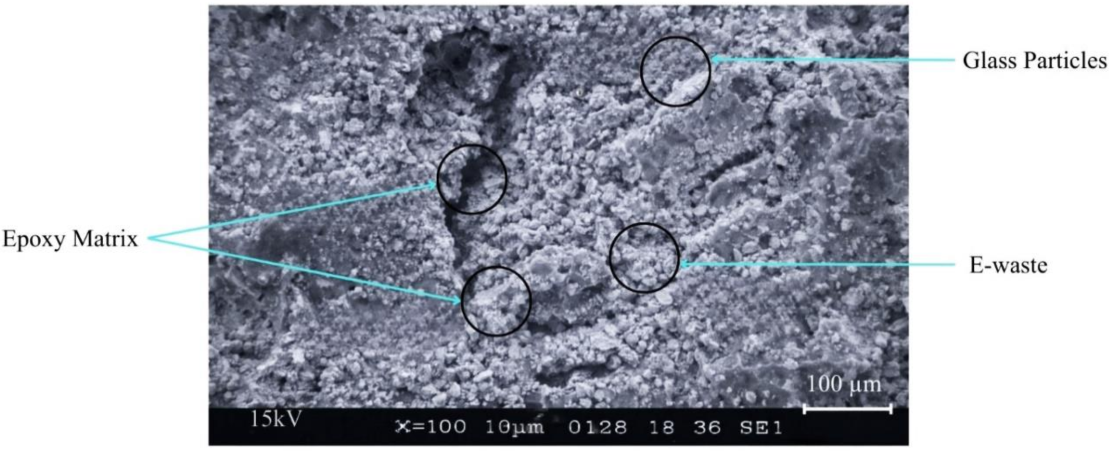


Figure 12. Glass (extracted from waste bulbs and CRT)epoxy composite SEM picture (x100) µm

Following tensile tests, the alkali-treated glass composite sample is shown in SEM view in Fig. 11. This image demonstrates how the treatment enhanced the property by increasing matrix and glass adhesion, which in turn enhanced mechanical strength. The SEM features of the glass bulb and CRT reinforced polyester compositeare shown in Fig 12. This can infer from the image that the glass effect dominates the dispersion of hybrid resin. Therefore, the outcomes of this experiment reveal better results when compared to the treated glass bulbs.

5. DISCUSSION

It is possible to attribute the improved mechanical performance to the best balance between effective load transfer and matrix continuity, which is seen at 30 vol.% GB+CRT reinforcement. At this composition, the dispersed micro- and nano-sized glass particles will be uniformly distributed to serve as effective stress-bearing reinforcements and improve interfacial shear strength and inhibit crack formation and growth. SEM results show high levels of particle-matrix adhesion with lack of voids at 30 percent reinforcement. The bottom of this range results in low efficiency of stress transfer due to insufficiency of reinforcement and the top range indicates that high filler contents (that is ≥40) are associated with particle agglomeration, greater porosity, and starving the matrix, consequently resulting in premature crack propagation and loss of mechanical integrity. This is the reason why tensile and impact performances are decreasing with increasing GB+CRT concentrations.

6. CONCLUSIONS

In this research, all mechanical and tribological test results are reported as the average of five specimens for each composition, and the corresponding standard deviations were calculated to assess data repeatability and experimental reliability. The low standard deviation values observed across tensile, flexural, impact, and wear measurements indicate consistent fabrication quality and stable material behavior. The use of mechanical characterization of glass bulb (GB) and Cathode Ray Tube (CRT) reinforced polyester resin composites showed that tensile, flexural, impact, and wear resistance properties varied significantly in relation to the composition. Result of Tensile tests revealed that the GB+CRT 30 percent + 70 percent polyester resin composite had better performance with the highest engineering stress of 31.300 to 34.833 N/mm2 and maximum loading capacity of 1000 N when compared to GB+CRT 10 percent and GB+CRT 20 percent compositions. An addition of further amount of GB+CRT to 50% + 50% polyester resin, however, resulted in a marked decrease in tensile strength with the values falling to approximately 1.035-1.06 N/mm^2 stress, which may be brittle at an even higher concentration of GB+CRT. Due to ASTM D 790 requirements the flexural strength values were obtained resulting in the ultimate load values of GB+CRT 10% + 90% polyester resin to maintain at approximately 1.025 kN; whereas the ultimate load values of the increased GB+CRT content, especially GB+CRT 30%, increased to better flexibilities and displacement at failure with the maximum being 7.4 mm. This indicates that there is optimum GB and Cathode Ray Tube (CRT) content of about 30 percent at which mechanical properties are maximized without jeopardizing the structural integrity. More observations were strengthened by further analysis through impact and wear testing. The impact resistance tests showed that, GB +CRT 30 percent composites had better energy absorbing capacity than the lower and higher GB +CRT content, which indicated the toughness and structural stability were balanced.

The wear resistance analysis showed that the composites containing GB+CRT 30 percent reagent had the lowest wear rate, which implied the best interfacial bonding of GB+CRT reinforcements and the polyester resin matrix. These tendencies were validated by the analysis with Response Surface Methodology (RSM), which makes the process parameters optimal in terms of mechanical performance. The analysis of Scanning Electron Microscopy (SEM) gave information on the microstructural integrity of the material, in which the GB and CRT were uniformly dispersed in the 30% composition with no or very little void formation and fiber-matrix bonding. Conversely, increased GB+CRT contents (40% and 50%) presented more porosity and microcracking, which is associated with the poor performance of the mechanical performance. All in all, the results are that a GB+CRT 30% + 70% polyester resin composite has the best tensile strength, flexural rigidity, impact toughness, and wear resistance; hence, it is the most appropriate composition in terms of its structure application.

6.1. Future scope

Based on our study, the future of the waste glass bulb and Cathode Ray Tube (CRT)-reinforced composite in sustainable applications is bright, especially in the eco-friendly product design and the circular economy movements. The reinforced composite materials that are being made out of discarded glass bulbs and CRT can be further used to develop new applications like tough and beautiful flower pots. These composites do not only save waste to the environment, but they also provide better mechanical strength, weather resistance, and life span than the conventional materials. Future studies can be carried out on the optimization of the composition of glass bulb and CRT reinforcement with different polymer matrices to enhance load bearing, thermal stability, and biodegradability. Along with it, the development of manufacturing methods such as 3D printing and resin infusion can allow producing the sustainable flower pots in large quantities, making them not only practical to be used by people both commercially and at home but also to be a part of the green building, as well as a solution to waste management.

Abbreviation

CFL - Compact Fluorescent Lamp
LED - Light Emitting Diode
RSM - Response Surface Methodology
FSW - Friction Stir Welding
GFRP - Glass Fiber Reinforced Polymer
CRT - Cathode Ray Tube
PET - Poly (Ethylene Terephthalate)
UHPC - Ultra-High-Performance

Conflict of Interest

The authors declare that they have no conflicts of interest related to this work.

Author contribution

Author 1 contributed to the conceptualization of the study, development of the methodology, and execution of experimental analysis. Author 2 was responsible for data curation, statistical modeling using Response Surface Methodology (RSM), and validation of the results. Author 3 handled manuscript writing, performed a comprehensive review, and carried out the final editing for publication.

Acknowledgment

We extend our sincere gratitude to my Institution for their invaluable support and resources, which played a crucial role in the successful completion of this study. We would also like to acknowledge the insightful discussions and constructive feedback provided by our colleagues, which greatly enhanced the quality of this research. Lastly, we appreciate the time and effort of the reviewers whose comments helped refine this manuscript.

7. REFERENCES

[1] F. Pahlevani, V. Sahajwalla (2018) From waste glass to building materials – An innovative sustainable solution for waste glass, *Journal of Cleaner Production*, 191, 192–206. https://doi.org/10.1016/j.jclepro.2018.04.219

[2] Y. Tao, S.A. Hadigheh, Y. Wei (2023) Recycling of glass fibre reinforced polymer (GFRP) composite wastes in concrete: A critical review and cost-benefit analysis, *Structures*, 53, 1540–1556. https://doi.org/10.1016/j.istruc.2023.02.055

[3] P.M. Gopal, K.S. Prakash, E. Makki, V. Kavimani, J. Giri, T. Sathish (2023) E-waste CRT panel glass reinforced magnesium composite processed through powder metallurgy: Fabrication and mechanical performance evaluation, *Journal of Materials Research and Technology*, 27, 2939–2952. https://doi.org/10.1016/j.jmrt.2023.01.204

[4] B.G. Worku, T.A. Wubieneh (2023) Composite material from waste poly(ethylene terephthalate) reinforced with glass fiber and waste window glass filler, *Green Chemistry Letters and Reviews*, 16(1), 1–14. https://doi.org/10.1080/17518253.2023.2166726

[5] M.K. Singh, A.K. Mohanty, M. Misra (2023) Upcycling of waste polyolefins in natural fiber and sustainable filler-based biocomposites: A study on recent developments and future perspectives, *Composites Part B: Engineering*, 263, 110852. https://doi.org/10.1016/j.compositesb.2023.110852

[6] N. Maurya, Y. Srivastav, S. Rawat, Y. Ranjan, R. Srivastava, B.K. Shukla, S. Varadharajan (2023) Reinforcing civil infrastructure with waste glass-enhanced concrete: A comprehensive review of properties, performance, and applications, *Materials Today: Proceedings*. https://doi.org/10.1016/j.matpr.2023.06.162

[7] A.A. Firoozi, A.A. Firoozi, D. Oyejobi (2023) Enhancing concrete performance by utilizing crushed glass and waste bottle plastic fibers for improved strength and flexural properties, *Jurnal Teknologi*, 85 (6), 47–57. https://doi.org/10.11113/jurnalteknologi.v85.19591

[8] Y.F. Li, Y.W. Hsu, J.Y. Syu, B.Y. Chen, B. Song (2023) Study on the utilization of waste thermoset glass fiber-reinforced polymer in normal strength concrete and controlled low-strength material, *Materials*, 16 (9), 3552. https://doi.org/10.3390/ma16093552

[9] A.M. Ismaeel, F. Usman, G. Hayder, Y. Al-Ani (2023) Analysis of mechanical and environmental effects of utilizing waste glass for the creation of sustainable ultra-high-performance concrete, *Annales de Chimie: Science des Matériaux*, 47 (2). https://doi.org/10.18280/acsm.470205

[10] Z. Chen, M.N. Amin, B. Iftikhar, W. Ahmad, F. Althoey, F. Alsharari (2023) Predictive modeling for the acid resistance of cement-based composites modified with eggshell and glass waste for sustainable and resilient building materials, *Journal of Building Engineering*, 76, 107325. https://doi.org/10.1016/j.jobe.2023.107325

[11] A.T.M. Yin, S.Z.A. Rahim, M.M.A.B. Abdullah, M. Nabialek, A.E.A. Abdellah, A. Rennie, M.F.M. Tahir, A.M. Titu (2023) Potential of new sustainable green geopolymer metal composite (GGMC) material as mould insert for rapid tooling (RT) in injection moulding process, *Materials*, 16 (4), 1724. https://doi.org/10.3390/ma16041724

[12] H. Tahir, M.B. Khan, N. Shafiq, D. Radu, M.H. Nyarko, A. Waqar, H.R. Almujibah, O. Benjeddou (2023) Optimisation of mechanical characteristics of alkali-resistant glass fibre concrete towards sustainable construction, *Sustainability*, 15 (14), 11147. https://doi.org/10.3390/su151411147

[13] M. Chamberlain (2020) Re-purposing LED light bulbs, *Journal of Sustainable Materials*, 12 (3), 210–222.

[14] H.A. Dahish, M.K. Alkharisi (2024) Hybrid Fiber Reinforcement in HDPE–Concrete: Predictive Analysis of Fresh and Hardened Properties Using Response Surface Methodology, *Buildings*, 14 (11), 3479. https://doi.org/10.3390/buildings14113479

[15] T. Raja, V. Ayyakkannu, T. Rathinasamy (2024) Experimental analysis of mechanical properties of e-waste composite materials with dual glass fibers, *Journal of Reinforced Plastics and Composites*, 43 (13–14), 713–726. https://doi.org/10.1177/07316844241265115

[16] J.I.D. Raj, R.B. Durairaj, S.V. Ananth, P. Barmavatu (2024) Experimental investigation of the effect of e-waste fillers on the mechanical properties of Kenaf woven fiber composites, *Environmental Quality Management*, 34 (1), e22165. https://doi.org/10.1002/tqem.22165

[17] T.P. Yadav, R. Srivastava, K. Awasthi (2022) E-Waste Management through Mechanical Milling: A Sustainable Approach, *Strategies to Achieve Sustainable Development Goals (SDGs)*, 1–26. https://doi.org/10.1007/978-981-16-7962-9_1

[18] V.P. Marimuthu, A. Ramasamy (2024) Mechanical characteristics of waste-printed circuit board-reinforced concrete with silica fume and prediction modelling using ANN, *Environmental Science and Pollution Research*, 31 (19), 28474–28493. https://doi.org/10.1007/s11356-023-31267-5

IZVOD

OPTIMIZOVANA KARAKTERIZACIJA POLIESTERSKIH KOMPOZITA OJAČANIH OTPADNIM STAKLOM I CRT ZA ODRŽIVE INŽENJERSKE PRIMENE

Ovo istraživanje istražuje mehaničke, termičke i mikrostrukturne performanse poliesterskih smolastih kompozita ojačanih materijalima od otpadnog stakla (GB) i katodnih cevi (CRT) za održive inženjerske primene. Pet kompozitnih formulacija koje sadrže 10–50 vol.% GB+CRT armature proizvedene su tehnikom ručnog slaganja. Eksperimentalni rezultati su pokazali da je kompozit sa 30 vol.% GB+CRT pokazao optimalne mehaničke performanse, postižući maksimalnu zateznu čvrstoću od 34,8 N/mm^2, čvrstoću na savijanje od 1,05 kN i apsorpciju energije udara od 1,45 J, što predstavlja poboljšanja od približno 68%, 22% i 32%, respektivno, u poređenju sa kompozitom ojačanim 10 vol.%. Analiza habanja otkrila je smanjenje stope habanja sa 0,0045 na 0,0024 mm^3/Nm sa povećanjem armature, što ukazuje na poboljšane tribološke performanse. Termička analiza je pokazala poboljšanu stabilnost, sa početnom temperaturom razlaganja koja se povećava sa 280 °C na 320 °C pri većem sadržaju stakla. Optimizacija metodologijom odzivne površine (RSM) potvrdila je statističku značajnost interakcija mikro-nano stakla ($R^2 = 0,978$). SEM analiza je otkrila ujednačenu disperziju čestica i jaku međupovršinsku adheziju pri 30 vol.% GB+CRT, što objašnjava superiorni mehanički odziv. Studija potvrđuje da kontrolisana inkorporacija otpadnog GB i CRT može proizvesti visoko efikasne, ekološki prihvatljive poliesterske kompozite pogodne za strukturne i tribološke primene.

Ključne reči: *staklene sijalice, upravljanje otpadom, ispitivanje habanja katodne cevi, morfološka analiza, poliesterska smola, ispitivanje zatezanja, metodologija odzivne*

Naučni rad
Rad primljen: 24.06.2025.
Rad korigovan: 24.01.2026.
Rad prihvaćen: 30.01.2026.

1. Baskaran Velliyangiri –	*https://orcid.org/0000-0002-7512-2489*
2. Veerappan Chattram Natarajan Loganthan –	*https://orcid.org/0009-0001-8450-6855*
3. Periyasamy Chandrakumar –	*https://orcid.org/0009-0003-0223-9381*
4. Vairavel Madeshwaren –	*https://orcid.org/0000-0002-8687-7887*
