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The Effect of Metal Filler on the Mechanical Performance of Epoxy Resin Composites †

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Abstract: It is a common practice in the plastics industry to compound polymers with fillers to reduce the manufacturing cost and/or attain desired properties. By combining different fillers with various polymer matrices, polymer composites can be tailored to achieve property combinations which cannot easily be obtained from either the polymer matrices or the reinforcements alone. In the past decades, different metallic (Cu, Al, Steel, etc.) and ceramic fillers (SiC, Al_2O_3, CuO, TiC, TiO_2, TiN, ZrO_2, ZnO, ZnF_2, SiO_2, etc.) have been used as reinforcements in composite preparation because of their effectiveness in reinforcing polymers. In light of the above, this research is aimed at the fabrication and study of the basic mechanical properties of epoxy-resin composites filled with different weight percentages of metal filler. It includes the study of the mechanical properties of cast-iron-filler-reinforced epoxy-based polymer matrix composites. Epoxy composites containing cast iron in different weight percentages are prepared using casting technique. Data on neat epoxy are also included for comparison. All the tests were conducted at room temperature and according to ASTM standards. Density, hardness (Rockwell), tensile, flexural and impact tests were conducted, and the data were analyzed with the help of statistical charts to draw useful inferences. It was observed that the inclusion of cast iron filler affected most of the mechanical properties of neat epoxy. The density, hardness, impact strength, tensile and flexural properties of the developed composites exhibited a varying trend with respect to cast iron content. The increase in cast iron content showed significant improvement in tensile properties, hardness, impact strength and the density of the composites. The flexural strength was found to decrease at a higher cast iron content. This research also highlights the possible reasons for variation in the mechanical properties of developed polymer composites.

Keywords: density; hardness; tensile strength; impact strength; flexural strength; neat epoxy

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1. Introduction

In the present era of technological development, the variety of composite materials used in the manufacturing of various components and their areas of application are widening continuously. They have become indispensable members of the engineering material family along with metals, alloys, ceramics and polymers. A composite material includes a matrix and a filler, and both possess their own characteristic properties. These two components are immiscible in a composite, and are separated by a boundary interface layer. Composite materials can be manufactured to have different properties based on their need and applications. They have become an inherent part of different industrial applications such as in construction, machine building, sports, entertainment, automobile, aeronautics, etc. They also permit the gradual creation of new structures and compositions, such structural or compositional changes can avoid sharp boundaries between joined substances and stress concentrations. The composite products are available with increased strength and other enhanced mechanical and chemical properties.

Epoxy resins possess good mechanical, chemical and electrical properties and are used in construction components, adhesives and in protective coatings. It is a copolymer thermoset, made through the reaction of a resin with a polyamine hardener. Its applications spread over a wide range, including fiber reinforced plastics and general-purpose adhesives. The resin comprises monomers or short chain polymers with an epoxide group at both ends. Most common epoxy resins are produced from epichlorohydrin and bisphenol-A. The hardener is composed of polyamine monomers (such as triethylenetetramine). During mixing, the amine groups react with the epoxide groups and a covalent bond is formed. Each NH group reacts with an epoxide group in the resin during polymerization; the resulting polymer is heavily cross-linked and is therefore rigid and strong.

The polymerization (curing) may be managed using temperature, the selection of resin and hardener and the proportion of both of these compounds. The process can be completed in a few minutes to hours. Some combinations may require heating during the curing period, while few others benefit from time and ambient temperature. Epoxy-based composites find wide-ranging applications as coatings, adhesives, etc., and also as glass- and carbon fiber-reinforced composites. The epoxies' chemistry and the choice of commercially existing variations make it possible to cure polymers that have been manufactured with a wide range of properties.

Epoxies possess exceptional adhesive, chemical and thermal properties, outstanding mechanical behaviors and highly acceptable electrical properties. These behaviors can be modified according to the requirements. In the field of electronics, some combinations offer high thermal conductivity and insulation properties along with enhanced electrical resistance. Materials such as wood are glued with epoxy in applications where epoxies are employed as structural glue. The aerospace industry uses epoxy as a structural matrix, reinforced with fibers made from glass, Kevlar, boron, etc.

Cast iron tends to be brittle, generally refers to gray iron and has carbon (2.1–4 wt.%) and silicon (1–3 wt.%) as the main constituent elements. It possesses excellent properties such as a low melting point, relatively good fluidity and castability, resistance to wear, deformation and oxidation and very good machinability. The fracture of the grey cast iron results in a grey appearance due to its graphitic microstructure. As an engineering material, cast iron is used in a variety of industrial applications such as in construction, machinery, automotive parts, etc. The tensile and impact capability of the grey cast iron is less than that of steel, whereas its compressive strength is on par with low and medium carbon steel.

Cu and Al are common metal fillers used in composite reinforcement to improve electrical and thermal conductivity. Copper (Cu) improves electrical conductivity, making composites suitable for electronic applications, whereas aluminum (Al) enhances thermal conductivity, thus making composites useful for the dissipation of heat. By contrast, steel increases mechanical strength and stiffness.

Hardness, wear resistance and thermal stability are improved in composites with ceramic fillers like SiC and Al_2O_3. Silicon Carbide (SiC) improves abrasion resistance and high-temperature performance, whereas Aluminium Oxide (Al_2O_3) improves wear resistance and overall durability. The specific filler material chosen is based on the desired behavior of the composite, allowing engineers to tailor materials for specific applications in a cost-effective manner.

Due to of its advantageous properties, cast iron is utilized as a filler material in epoxy composites. For starters, its high density and hardness improve the structural integrity of the composite, increasing its capability and wear resistance. Second, the heat transfer ability of cast iron aids in heat dissipation, lowering the risk of overheating in applications such as engine components. Furthermore, its resistance to corrosion improves the composite's durability in harsh environments. Furthermore, the low cost of cast iron makes it an economical choice. Overall, the synergy of cast iron's mechanical, thermal, and corrosion-resistant properties with epoxy makes it an effective filler, improving the performance and longevity of epoxy composites in a variety of industrial applications.

2. Literature Survey

In an attempt to gauge the influence of metal filler on the characteristics of epoxy resin for use in semi-metallic soft tools, Chung et al. [1] considered fillers such as aluminum powder, cast iron powder and aluminum short fibers. It was observed that Al powder provided advantages such as the improved dimensional accuracy, tensile strength, wear resistance and thermal conductivity of semi-metallic soft tools. Cast iron filler contributed to the tensile strength and wear resistance. Al short fibers contributed to dimensional accuracy and thermal conductivity when compared to Al-powder-filled soft tools. It was observed that Cu-Epoxy composites outperformed metals in terms of resistance to wear compared to Al-Epoxy composites. This is because of its high hardness and stiffness properties.

The study conducted by Bhagyashekar and Rao [2] explains the tribological behavior of epoxy filled with Al and Cu metallic fillers. The study revealed a "wear stabilization phenomenon", clearly indicating, to a lesser proportion, the effectiveness of the filler loadings beyond the threshold value (5%). It can be seen that Cu-Epoxy composites have a superior wear resistance compared to Al-Epoxy composites. This is because of their high hardness and stiffness properties.

Durand et al. [3] conducted several experiments by varying the particle types (ceramic), particle sizes and particle volume fractions within thermosetting epoxy resin. The composite wear was up to 50 times lower than the neat epoxy. It was found that composites with carbide particles (SiC and TiC) exhibited a higher wear resistance than those with oxide particles.

M. Sudheer, K. M. Subbaya and Dayananda Jawali [4] found that epoxy resin composites reinforced with potassium titanate whisker improve the density, hardness and heat deflection temperature of neat epoxy. A significant improvement in the tensile and flexural properties was also shown, but only in certain combinations (5–10 wt.%).

The studies by J. Stabik, A. Dybowska, J. Pluszyñski, M. Szczepanik and Suchon [5] demonstrated the fabrication of polymer composites with significant magnetic properties. The compositions containing up to a 30% volume of ferrite powder could be prepared by centrifugal casting. The viscosity increased at higher volumes of filler material. Superior results for magnetic induction were achieved for a 30% volume of barium ferrite.

Suresha B, Chandramohan G and Sampath Kumaran P [6] concluded that reduced friction and enhanced wear-resistance properties could be attained by adding graphite and SiC particulate fillers. A higher resistance to sliding wear could be reached by SiC filled glass–epoxy composite when compared to a plain glass–epoxy composite.

Z. Brito and G. Sanchez [7] have studied the influence of metallic filler on the thermo -mechanical behavior of epoxy and determined that the filler reduces the thermal stability of the epoxy matrix and increases its mechanical strength.

M.C Murugesh and K.Sadashivappa [8] studied the influence of the addition of filler material such as TiO_2 and graphite on epoxy. The higher the percentage of filler materials such as TiO_2 and graphite, the lower the thrust and delamination factor will be, which they claim allows for better bonding between the filler and the matrix ensuring it has an enhanced capacity for sustaining the force.

3. Specimen Fabrication

We used epoxy resin (LY556) as the matrix and recycled cast iron powder as the metal filler and for reinforcement. The chips obtained during the machining of a cast iron product were collected, cleaned and heated to remove the moisture/oil content. The next step is the powdering process which can be performed using a vibration mill, a ball mill or a hammer mill. The hammer mill is the best option for the powdering process and was chosen in this work (Figure 1). The size of the crushed cast iron powder selected in this work is 75 µm (Figure 2). Figure 3 shows an open mold cavity for specimen preparation.

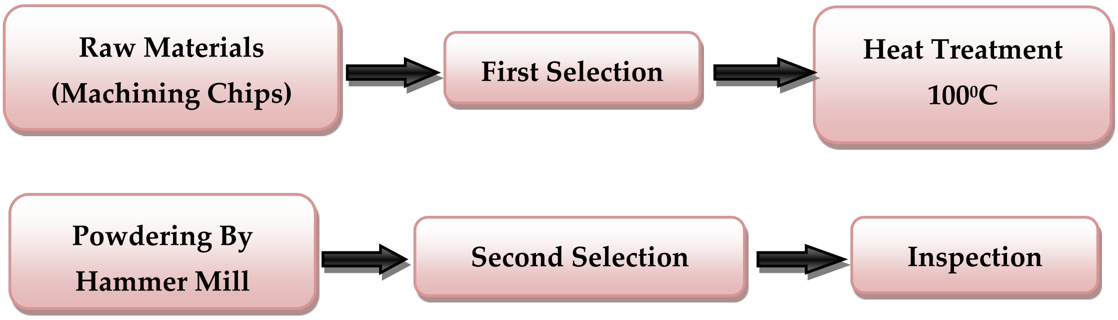

Figure 1. Manufacturing process of recycled cast iron powder.

Figure 2. Gray cast iron powder.

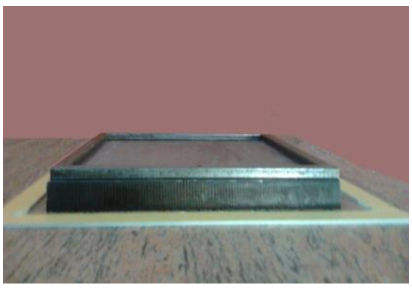

Figure 3. Open mold cavity (die).

Table 1 gives the details of samples prepared.

Table 1. Details of samples prepared.

Sample Code	Matrix	Filler	wt.%
C0	Epoxy	-	-
C5	Epoxy	Cast iron	5
C10	Epoxy	Cast iron	10
C15	Epoxy	Cast iron	15
C20	Epoxy	Cast iron	20
C25	Epoxy	Cast iron	25

4. Experimentation and Testing

4.1. Density

The Archimedes principle was used to determine the density of the composite specimen (Figure 4). The fluid used for the immersion of the composite specimen was distilled water maintained at room temperature, and a precision digital weighing balance was used to find the mass (Figure 5). Readings of the measuring jar before and after the immersion of specimen were taken and their difference was calculated. The mass of the specimen divided by this difference will give the density of the specimen [9,10].

Figure 4. Archimedes principle.

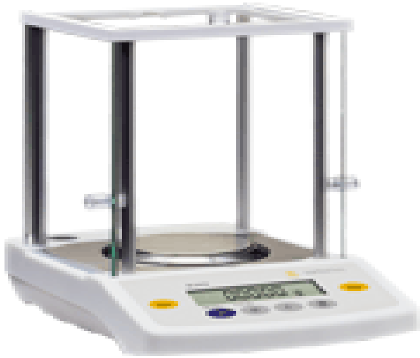

Figure 5. Digital weighing balance.

4.2. Hardness

A Rockwell Hardness Tester (M-scale) was used to measure the hardness of the fabricated composite specimen (Figure 6, Make-Saroj Engg. Udyog Pvt. Ltd., Mumbai, India). A quarter-inch ball indenter was used for indentation. A load of 100 kg was applied for the measurement of hardness (red reading).

Figure 6. Rockwell hardness tester.

4.3. Tensile Properties

A Universal Testing Machine (Figure 7, Make-LJ Lloyd, London, UK, 20 kN capacity) was used to find the tensile properties of the fabricated specimen. A gauge length of 50 mm and crosshead speed of 1 mm per minute were selected for performing the tensile test.

Figure 7. Universal Testing Machine (UTM).

4.4. Flexural Properties

The flexural properties were examined with the help of a Universal Testing Machine (Make-LJ Lloyd, London, UK, 20 kN capacity). A 3-point bending test was conducted with a beam length of 50 mm and crosshead speed of 1 mm per minute (Figures 8 and 9). The results were plotted using Nexygen software 4.1.

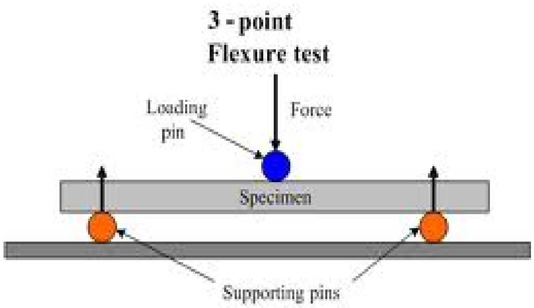

Figure 8. Three-point flexural test.

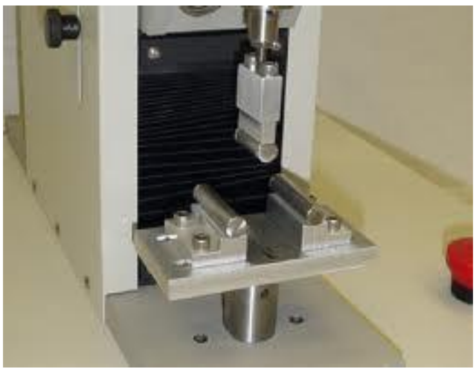

Figure 9. UTM for flexural test.

4.5. Impact Strength

The Izod impact experiment was performed on unnotched specimens using a CEAST pendulum impact tester (Figure 10, Max. capacity 25 J).

Figure 10. Pendulum impact testing machine.

4.6. Mechanical Testing Standards

Various ASTM mechanical testing standards used for the composite specimens are provided in Table 2.

Table 2. Mechanical testing standards used for composite specimens.

ASTM Standards	Properties to Be Tested
ASTM D792 [11]	Density
ASTM D785 [12]	Hardness (Rockwell M Scale)
ASTM D638 [13]	Tensile Properties
ASTM D790 [14]	Flexural Properties
ASTM D256 [15]	Impact Strength

5. Results and Discussion

The characteristics of the epoxy resin were improved by the addition of a few wt.% of cast iron into the epoxy matrix. The important factors which affect the mechanical behavior of polymer composites are the dimension of the filler material, filler–matrix interface adhesion and loading of the filler material. The interplay between these three factors cannot be separated, and various trends in the effects of the cast iron on composite properties were observed as a result.

5.1. Density

The mass–density of the composites is contingent on the relative proportion of the matrix and the reinforcing materials. The rule of mixture is a mathematical method which is widely used to define the theoretical density of a polymer composite (Table 3). The density variation with respect to cast iron content is shown in Figure 11. From the figure, it is apparent that, as the cast iron content in the composite increases, the mass–density of the composite also increases, this is because of the addition of the highly dense cast iron filler into the epoxy resin. The experimental density values are lower, in the range of 8% to 13%, than the theoretical value calculated using the rule of mixture. This is because of defects such as voids and pores created during the process of fabricating the composite. Similar observations were made by Maruthi et al. [16] in the case of a hybrid banana–jute phenol formaldehyde composite.

Table 3. Density of epoxy/CI composites.

Sample Code	Rule of Mixture, (gm/cc)	Experimental, (gm/cc)
C0	1.17	1.17
C1	1.5469	1.3337
C2	1.773	1.6265
C3	2.0142	1.7818
C4	2.177	1.9647
C5	2.4363	2.1273

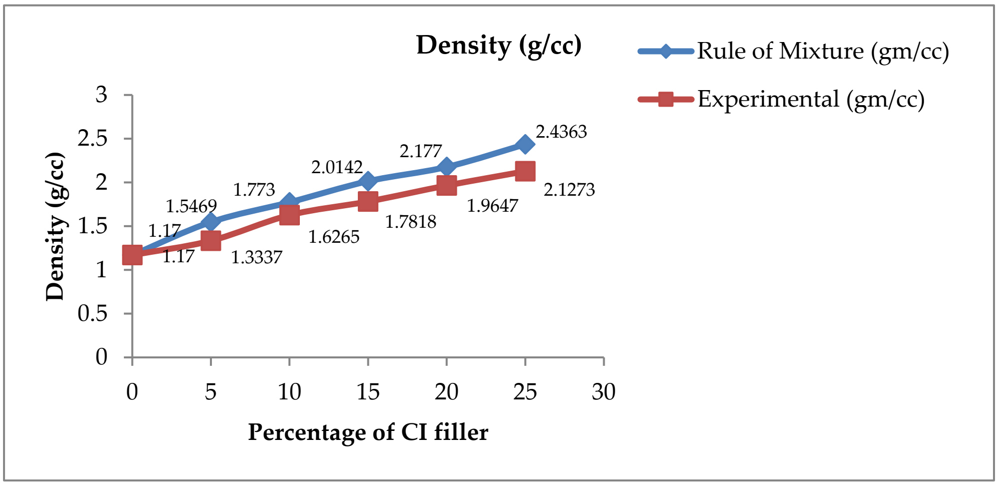

Figure 11. Effect of cast iron content on the density of neat epoxy.

The fatigue resistance, resistance to water penetration and weathering are lowered owing to the existence of voids in the composites. The void content is related to the composite quality and a composite of high quality must have fewer voids. The presence of voids in composites cannot be avoided, especially while using the hand layup method of specimen fabrication.

5.2. Hardness

The hardness of neat epoxy is found to be enhanced by adding a cast iron filler (Figure 12). This is due to the uniform distribution of the cast iron in the epoxy matrix. The hardness of the epoxy composites improved significantly as a consequence of the addition of cast iron. It is apparent that a CI filler content of 25% in an epoxy composite shows a higher hardness value, in the range of 3% to 11%, than the other composites; this is because a larger amount of cast iron filler has filled the gap and increased the compactness of the fiber and the matrix.

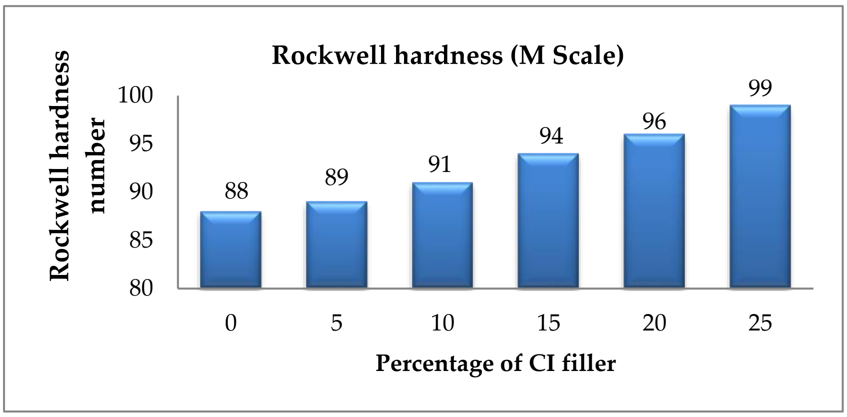

Figure 12. Effect of cast iron content on the hardness of neat epoxy.

5.3. Tensile Properties

Figure 13a depicts the changes in tensile strength observed in composite materials after the addition of a cast iron filler. It is clear that, as the percentage of cast iron filler increases, so does the tensile strength, which ranges from 7% to 24%. Notably, the composite with 25% of filler has a higher strength, owing to the major impact of the bonding force at the resin–filler interface.

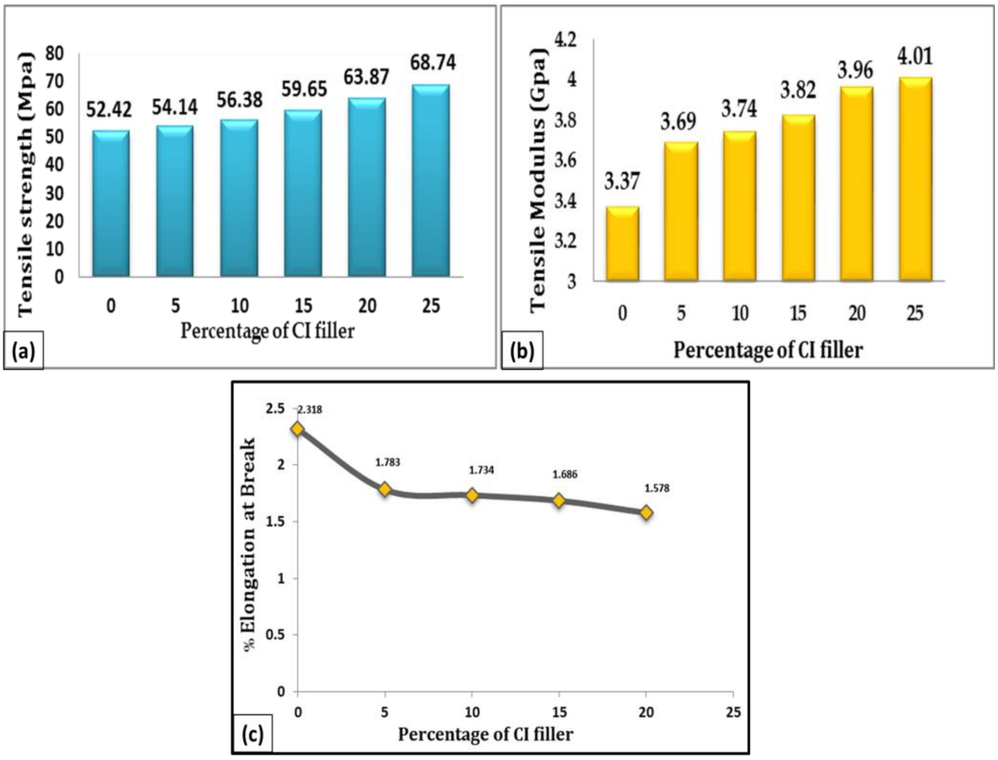

Figure 13. Effect of cast iron content on the (**a**) tensile strength, (**b**) tensile modulus and (**c**) elongation-at-break of epoxy composite.

The tensile performance of the composites increases in lockstep with the quantity of cast iron filler in the epoxy. This happens because the weight of the metallic filler displaces more air bubbles, effectively reducing their presence in the mixture. The increased density of the cast iron filler contributes significantly to this result by assisting in the elimination of air bubbles. Furthermore, the metal filler's irregular shape promotes a stronger bonding force at the material's resin–filler interface.

The tensile modulus (Figure 13b) data show that the composite containing 25% of cast iron filler has a significantly higher modulus than the other composites, with increases ranging from 2% to 15%. Conversely, (Figure 13c) as the quantity of cast iron filler in the composite increases, the elongation at the point of fracture decreases. The increased modulus detected in the epoxy composite with 25% of filler content denotes superior stiffness. This increase in the tensile modulus can be attributed to the existence of more rigid cast iron filler particles. It is positive that we detected that, as the filler content increases, there is a noticeable decrease in ductility in the composites, and elongation was also found to decrease with an increase in filler content at the interface [17].

5.4. Flexural Properties

The flexural test determines a material's ability to withstand a bending force applied at a right angle to its longitudinal axis (Figure 14a). Flexural strength was observed to reduce with an increase in cast iron content in the range of 5% to 30%. This can be ascribed to the fact that an increase in the cast iron filler content of an epoxy composite may alter the type of failure from ductile to brittle [18]. Furthermore, the cast iron content creates micro porosity in a small number of the composites. Pramod et al. [17] made similar observations.

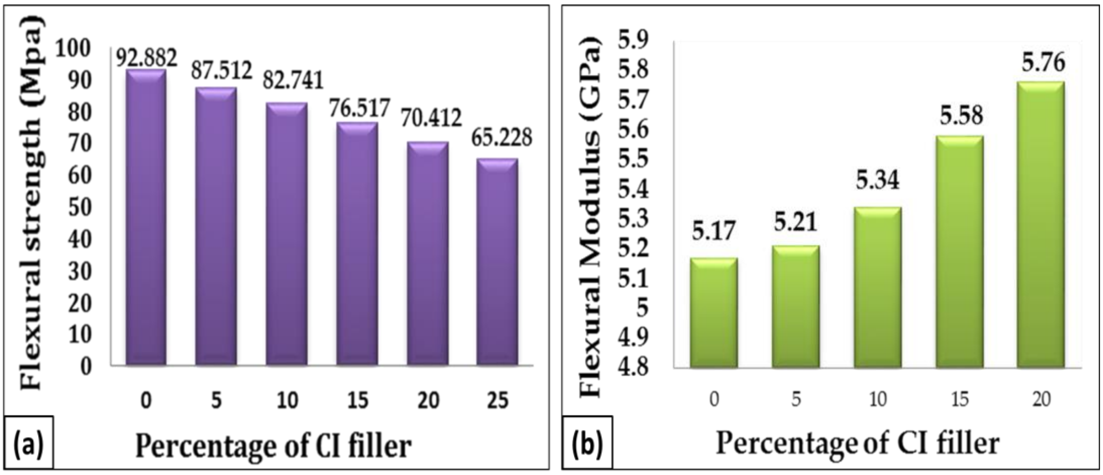

Figure 14. Effect of cast iron content on the (**a**) flexural strength and (**b**) flexural modulus of an epoxy composite.

Figure 14b shows the flexural moduli of a neat epoxy and a filler content–epoxy composite. It is apparent that, as the filler content in the epoxy composite increases, the flexural modulus also increases in the range of 2% to 12%. This is due to an increase in the proportion of the hard and brittle phases in the cast iron filler in the epoxy matrix [19].

5.5. Impact Strength

The impact behavior and overall toughness of an epoxy polymer are directly related. The Izod impact test was conducted with pendulum-type impact loading to check the response of a standard composite specimen. The kinetic energy expended by the pendulum in breaking the test specimen was observed. The impact strength values are shown in Figure 15. The impact strength of neat epoxy is less than that of all other specimens. It is apparent that, as the cast iron filler content increases in an epoxy composite, the impact strength also increases in range of 7% to 23%. The epoxy composite with 25% cast iron content shows higher impact strength than the other composites. Cast iron particles dispersed well within the epoxy resin matrix, resulting in a strong interfacial connection. This strong interfacial bond between the fiber matrix and the iron filings contributed to the material's increased impact resistance, which is consistent with previous research [20–23].

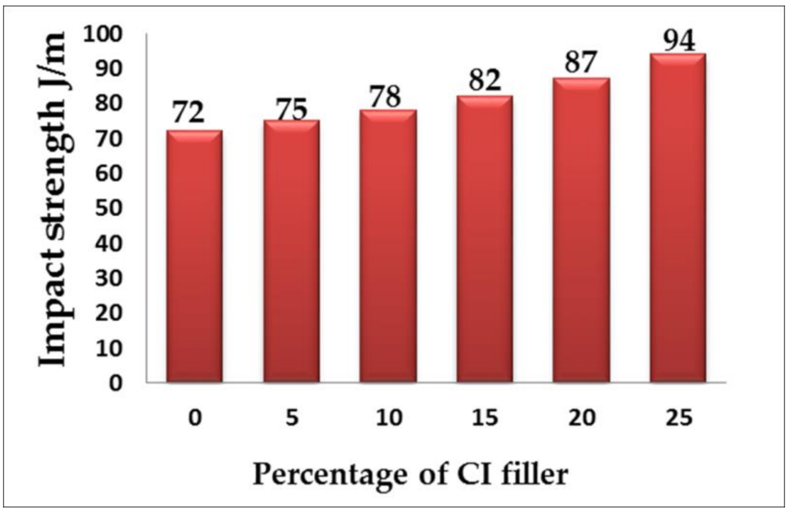

Figure 15. Effect of cast iron content on impact strength of neat epoxy.

6. Conclusions

This study was useful in determining the impact of incorporating cast iron filler into epoxy resin and examining its influence on material behavior. The proportion of cast iron and the mechanical behavior of the resulting epoxy composites were found to have a clear correlation. Cast iron, in particular, demonstrated its prowess as a filler material by significantly improving the density, hardness and tensile properties of epoxy resin composites. The addition of highly dense cast iron to pure epoxy resulted in an increase in the overall density of the epoxy composite. However, the occurrence of voids within the composites had a significant impact on selected mechanical properties and the composite's performance in its intended application. Due to voids within the composites, factors such as fatigue resistance, resistance to water ingress and resistance to weathering decreased. Furthermore, increasing the cast iron content was promoted to enhance the hardness of the epoxy composites. In particular, the addition of high-strength cast iron reinforcements aided in the creation of a network structure, increasing the overall hardness of the epoxy composites. Adding cast iron improved the tensile behavior of the epoxy composites significantly. Notably, the flexural modulus of pure epoxy was discovered to be the lowest, while it increased for other specimens containing various resin–filler combinations. It is worth noting that, in contrast, as the cast iron content increased, the flexural strength decreased. Furthermore, when related to all other specimens, the impact strength of neat epoxy was discovered to be inferior, with a noticeable improvement in impact strength with an upsurge in cast iron content. This study emphasizes the critical role that cast iron can play as a reinforcing and toughening agent in thermosetting resins like epoxy. From the above results it is apparent that the epoxy composite with 25% of cast iron filler has the potential to be used in light-load applications such as car door panels, table tops and in furniture.

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