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Investigation of Mechanical Properties of Polymer Matrix Composites Reinforced with Waste Iron Powder

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ABSTRACT

Recycling industrial waste plays a crucial role in sustainable environmental balance. Therefore, it is essential to effectively coordinate recycling and waste management, recovering materials like paper, plastic, and metal that are unsuitable for disposal. The investigation of mechanical properties of polymer matrix composites reinforced with waste iron powder can reveal significant enhancements in mechanical properties. Therefore, this study experimentally examines the tensile and flexural mechanical properties of polymer matrix composites reinforced with waste iron metal powder. Morphology investigations were carried out on the fractured tensile and flexural test specimens and comments were made on the results. For this purpose, the effect of reusability of iron powder additive as filler material on mechanical properties at four different iron powder/epoxy weight ratios (0, 2%, 4%, and 8%) was investigated. Subsequently, epoxy/iron powder homogeneous polymer matrix composite blends were cast into metal molds and test specimens were obtained. The results showed that the addition of 4 wt. % iron powder increased the tensile strength by 28%; however, it was concluded that the addition of iron powder negatively affected the flexural strength and modulus with concluding that this decrease in flexural test results was the result of the decrease in the interfacial adhesion strength between iron powder/epoxy.

Keywords: Iron powder, Recycling, Polymer matrix composite, Mechanical properties.

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Introduction

Polymer matrix composites (PMCs) have emerged as pivotal materials in modern engineering due to their exceptional strength-to-weight ratio, corrosion resistance, and versatility in applications ranging from aerospace to automotive industries [1-2]. These composites, typically composed of a polymer resin reinforced with fibers or particulate fillers, are continuously optimized to meet evolving industrial demands for lightweight, durable, and cost-effective materials [3-4]. However, the growing emphasis on sustainable manufacturing practices has prompted researchers to explore eco-friendly reinforcements derived from industrial byproducts, aligning material innovation with circular economy principles [5].

The incorporation of waste materials into PMCs offers a dual advantage: enhancing mechanical properties while addressing environmental challenges associated with waste disposal. Iron powder, a common byproduct of machining, grinding, and steel production, represents an underutilized resource with significant potential as a reinforcement phase [6]. Millions of tons of metallic waste are generated annually, often relegated to landfills, posing ecological risks. Recycling this waste into composite materials not only mitigates environmental harm but also adds value to an otherwise discarded resource [7-8]. Previous studies have demonstrated that metallic fillers, such as iron particles, can improve the stiffness, thermal conductivity, and wear resistance of polymers. However, the utilization of waste-derived iron powder—particularly its effects on the tensile, flexural, and impact properties of PMCs—remains underexplored, presenting a critical research gap. The development and application fields of composite materials are constantly expanding. Composite materials consist of matrix and reinforcement materials. Both the matrix and reinforcement materials possess distinct characteristic properties. Composite materials can be engineered to exhibit tailored properties based on specific needs and applications. As a result, they have become an integral part of numerous industrial applications such as construction, machinery manufacturing, sports, entertainment, automotive, aerospace, and more [9]. In composite materials, epoxy resins are widely employed as matrix materials due to their favorable mechanical, chemical, and electrical properties. As reinforcement materials, various options such as metal, ceramic, and polymer fillers can be utilized depending on the desired attributes. Particle-reinforced composites are created by uniformly dispersing a suitable powdered substance into the matrix material. These types of composites are not typically considered "high-performance" because they cannot achieve the strength and stiffness of fiber-reinforced composites, and thus, they are not utilized in advanced technological applications such as aircraft and spacecraft structures. However, these types of composites can be employed in various applications that do not necessitate high stiffness and strength [10]. Brito and Sánchez [11] fabricated epoxy matrix composite materials with varying percentages of Zn, Cu, and Al additives. The thermal behavior and fracture toughness of the produced materials were analyzed. Results from thermal analyses indicated that metal additives had a significant impact on the thermal stability of the investigated epoxy. The materials with additives exhibited a lower decomposition temperature compared to the additive-free materials. Experimental findings from mechanical testing revealed that the mechanical behavior was dependent on the type and content of the additive. Stabik et al. [12] produced epoxy composite materials reinforced with barium ferrite ($BaFe_{12}O_{19}$) and strontium ferrite ($SrFe_{12}O_{19}$). It was stated that it is feasible to manufacture materials with up to 30% additive content using the centrifugal casting method. It was observed that the additives enhanced the magnetic properties of the material. Adedayo and Onitiri [13] incorporated waste iron powder, obtained from iron ore beneficiation, into an epoxy matrix. They reported using iron powder with particle sizes of 150 µm and 300 µm, incorporating them into the matrix at varying volume percentages (ranging from 0 to 30% in 5% increments). They indicated that the curves obtained after tensile testing exhibited variations based on the additive ratios. Ramesh et al. [14] utilized slag, an industrial by-product, as a particulate filler material in epoxy matrix composites at different weight ratios (0%, 5%, 10%, 15%, 20%). They subjected the composite materials to various tests, including tensile, flexural, and impact tests. It was observed that the diverse components of slag enhanced certain mechanical properties. They highlighted that the produced composite material could be considered a viable lightweight engineering material. Devendra and Rangaswamy [15] conducted a study on the mechanical properties of E-glass fiber-reinforced epoxy composites filled with various filler materials. Composites filled with varying concentrations of fly ash, aluminum oxide (Al_2O_3), magnesium hydroxide ($Mg(OH)_2$), and hematite powder were fabricated using standard methods. The mechanical properties of the produced composites, including ultimate tensile strength, impact strength, and hardness, were examined. The test results demonstrated that composites filled with 10% by volume of Mg(OH)2 exhibited the highest ultimate tensile strength and hardness. It was noted that composites filled with fly ash displayed the highest impact strength. Onitiri and Akinlabi [16] experimentally investigated the effect of iron ore waste-filled epoxy and polypropylene composites on hardness and tensile strength, and compared the obtained results with calculations made with various theoretical models. It was found that the hardness of the materials increased with the contribution of iron ore waste. Pitchamuthu et al. [17] aimed to enrich both the mechanical and electrical properties of kevlar and glass fiber composites by adding iron (Fe) nanocomposites to epoxy resin. They stated that the additives improved the mechanical properties of the composites and reduced their weight. They stated that the additives improved the mechanical properties and reduced the weight of the composites. During the moisture absorption process, it was discovered that the mechanical behavior of the composite deteriorates and that there is a change in flexural properties closely corresponding to the percentage of moisture absorbed. Sideridis et al. [10] examined the influence of moisture absorption on the mechanical properties of particulate composite materials containing low percentages of iron powder. The changes in ultimate tensile strength, fracture strain, deflection, elastic modulus, and Poisson's ratio due to water absorption were investigated. Data related to pure epoxy were also included for comparison. All tests were performed at room temperature and according to ASTM standards. Density, hardness (Rockwell), tensile, flexural, and impact tests were performed, and the data were analyzed with statistical graphs to draw useful inferences. It was observed that the addition 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 showed a varying trend with respect to the cast iron content. Increasing the cast iron content showed significant improvements in tensile properties, hardness, impact strength, and density of the composites. Flexural strength was found to decrease at higher cast iron content. Bhavith et al. [9] prepared epoxy composites containing cast iron in different weight percentages using the casting technique. Cieślak et al. [18] created a composite material by adding powders obtained from waste cast iron chips to epoxy resin. They noted that epoxy resin is the most frequently chosen material for the matrix of polymer composites reinforced with metal powders. The epoxy composite was produced using the vacuum-assisted casting method. In the study, the morphological, mechanical, and corrosion properties of epoxy composites filled with gray cast iron powder, with a grain size below 75 µm and a mass content of 65% in the composite, were investigated. The composite cured at 130 °C for 90 minutes showed the best mechanical properties. It was observed that the sample cured at 130 °C for 90 minutes had the optimum effect with 28.35 MPa tensile strength, 55.4 MPa flexural strength, and 53.8 MPa compressive strength. It was noted that all the tested composites showed very. It has been noted that it exhibits good thermal resistance and has 2.5 times lower weight than gray cast iron and three times lower corrosion rate in tap water environment. Onitiri and Akinlabi [16] experimentally investigated the effect of iron ore waste-filled epoxy and polypropylene composites on hardness and tensile strength, and compared the obtained results.

This study investigates the mechanical behavior of polymer composites reinforced with waste iron powder, focusing on how varying filler concentrations influence key properties such as tensile strength, hardness, and fracture toughness. By integrating waste iron powder into epoxy matrix, the research evaluates microstructure-property relationships through scanning electron microscopy (SEM), tensile and flexural testing. The findings aim to establish optimal filler loadings that balance performance enhancements with processability, while assessing the feasibility of scaling this approach for industrial applications. The significance of this work lies in its contribution to sustainable material science, offering a pathway to transform industrial waste into high-performance composites. Such innovations could reduce reliance on virgin materials, lower production costs, and support industries like automotive manufacturing, where lightweight yet robust components are essential. By bridging the gap between waste valorization and composite technology, this research underscores the potential of circular economy strategies to drive advancements in material engineering.

Material and Method

Preparation of Iron Powder Added Samples

In the experiments, F-1564 epoxy and F3487 hardening chemical materials were used. The epoxy and resins used were supplied from FİBERMAK company in Turkey. Technical data of the resin and hardener used are given in Figure 1.

Figure 1. Chemical materials for production of composites

For the production of unfilled samples, the epoxy resin suitable for casting was mixed with the hardener at a resin/hardener ratio of 2:1 as specified in the catalog. For samples to be added with iron powder, epoxy resins were mixed with iron powder by weight at rates of 2%, 4% and 8% before adding hardener. The maximum particle size of the iron powder used in epoxy resin is 63 μm and it has 90% purity. SEM morphology of the pure iron powders have been illustrated in Figure 2. As can be seen in the Figure 2, the distribution of the diameters of iron powders in different sizes is found and the iron powders with small diameters are not very abundant. This means more epoxy-iron powder interface and better bond strength.

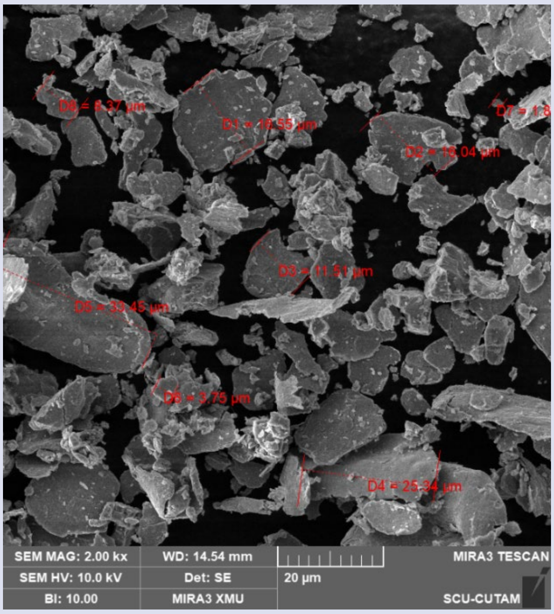
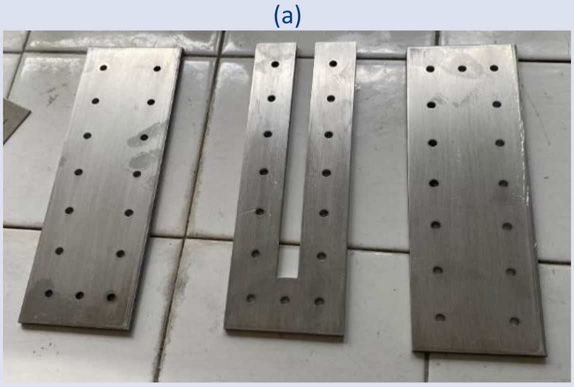


Figure 2. SEM figure of pure iron particles

After pouring the obtained mixture into the prepared molds, silicone oil was applied to the molds to prevent the mixture from sticking to the mold and to prevent the formation of permanent stains.

(a)



(b)

Figure 3. Molds prepared for mechanical tests. a) Mold parts manufactured for tensile test specimen, b) Mold parts manufactured for three-point flexural test specimen.

A mold made of aluminum plates was used in the casting of the prepared mixtures. 3 aluminum plates with a thickness of 4 mm, which will be placed at the bottom, middle and top for each mold, were cut by CNC laser cutting. A mold cavity was created by CNC laser cutting in the plate to be placed in the middle, according to the geometry of the sample to be produced. The geometry of the specimens to be tested for tensile testing is according to ASTM D638, and the geometry of the specimens to be tested for three-point flexural is according to ASTM D790 standard. 5 mm diameter screw holes were drilled in all plates with a column drill to be able to make screw connections. The manufactured mold parts are shown in Figure 3 for tensile and flexural test specimens.

To ensure good adhesion on the surfaces of the mold parts, a sanding process was carried out to obtain as smooth a surface as possible. A mold release spray was used to prevent the mixtures poured into the mold cavity from sticking to the mold parts. Then, the mold parts were assembled with M5 screws and nuts. The mixtures poured into the mold cavity were left to cure at room temperature for one day.

(a)

(b)

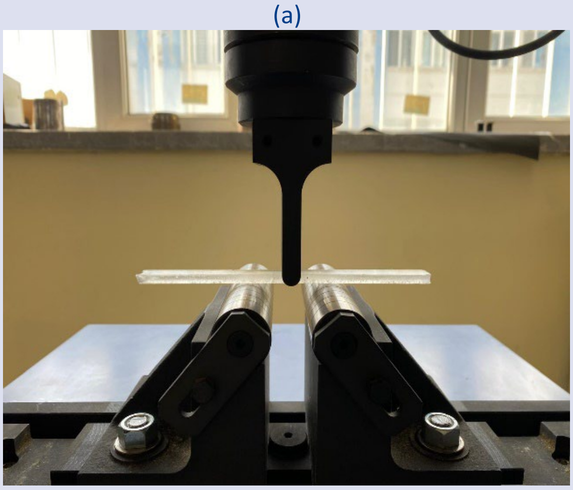
Figure 4. a) Applying vacuum sealant in the mold cavity, b) Applying glass putty to ensure the seal between the mold parts.

After curing, it was observed that some specimens had difficulty coming out of the mold cavity. For this reason, it was decided to make an improvement in the mold design. The middle plate, where the mold cavity is located, was cut vertically into two pieces on the cutting device. This ensured that the specimen could be removed from the mold more easily. In order to prevent the poured mixture from flowing, vacuum sealant was applied to the gap between them. Also, glass putty was used for general sealing (Figure 4).

Mechanical Testing

Tensile and three-point flexural tests were carried out on a Shimadzu AGX-250kN model universal tensile-compression testing machine to perform the mechanical tests of the produced metal powder-reinforced polymer matrix composites (Figure 5). The tests were carried out according to ASTM D638 for the tensile test and ASTM D790 for the three-point flexural test. The TRAPEZIUM program was used for performing the tests and transferring the data according to the relevant parameters. During the experiments, five tests were performed for each sample in each group and the average of the results obtained from these tests was used as the result.

(a)



(b)

Figure 5. Shimadzu brand AGX-250kN model universal tensilecompression testing machine. a) Performing the tensile test,b) Performing the three-point flexural test.

Results and Discussion

The graphs of the tensile test results of the waste iron powder-added specimens are given in Figure 6 in comparison with the specimens without additives. As can be understood from the results, it is seen that the addition of iron powder significantly increases the elongation at break. On the other hand, the strength values increased more significantly as the additive ratio increased. It is seen that the elongation at break decreases with increasing additive ratio. It was observed that the toughness of the material increased at all additive ratios.

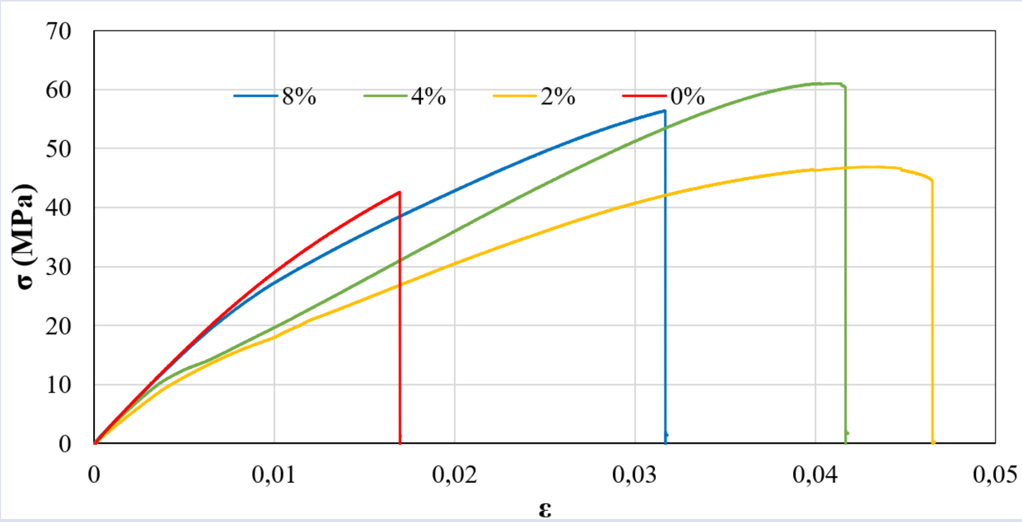


Figure 6. Tensile test results of waste iron powder-added composites.

In Figure 7, the failure mechanisms of the broken parts after the tensile test are shown. As can be understood from here, brittle fracture was observed in both unadded and added specimens. It is seen that a sudden fracture occurs in the fractured region without any necking. As the loading on the material increases, it is observed that the material fails without entering the plastic region, and this property decreases as the amount of waste iron powder added increases, thus ensuring the less brittle material. It was observed that matrix fracture in the specimens without additives was higher than those with additives. This has led to the conclusion that the added iron powder particles bond well with the epoxy, thereby increasing the load .

transfer in the matrix resin under tensile load.

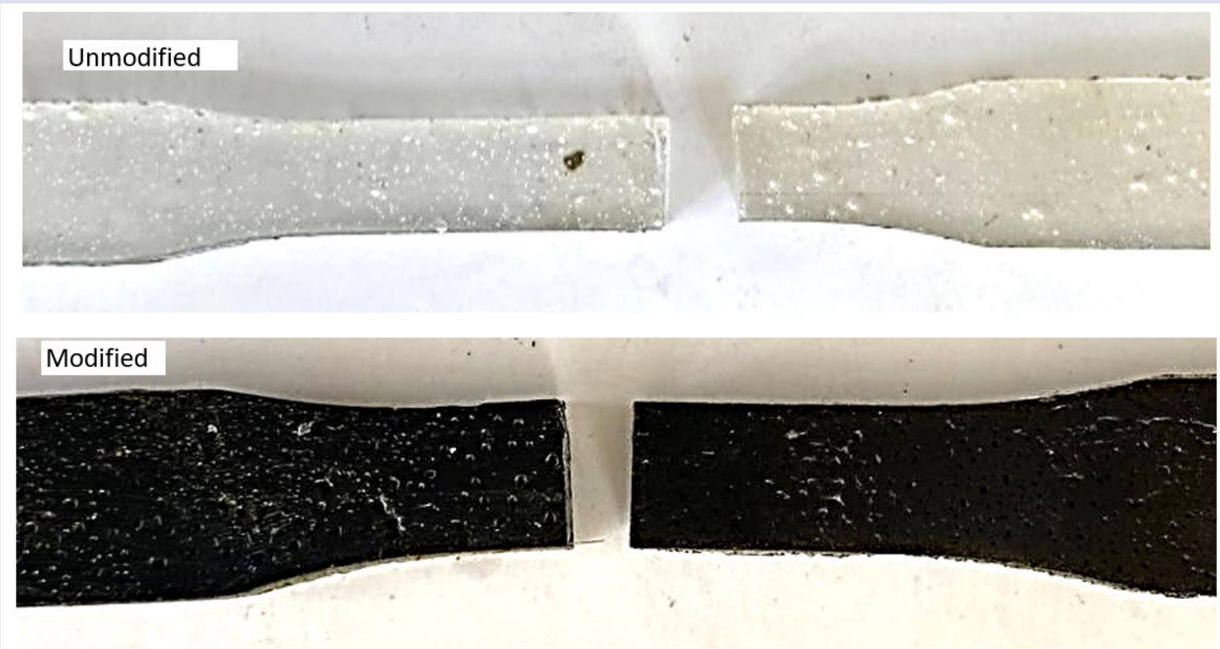
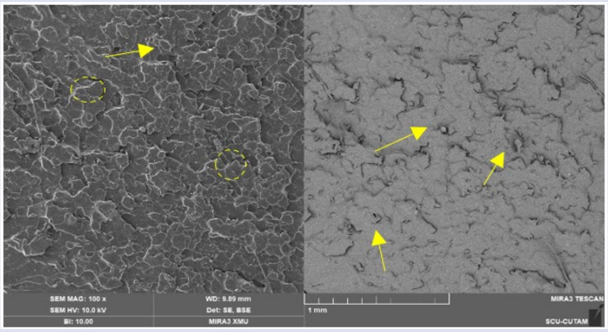


Figure 7. Fracture mechanisms after tensile test.



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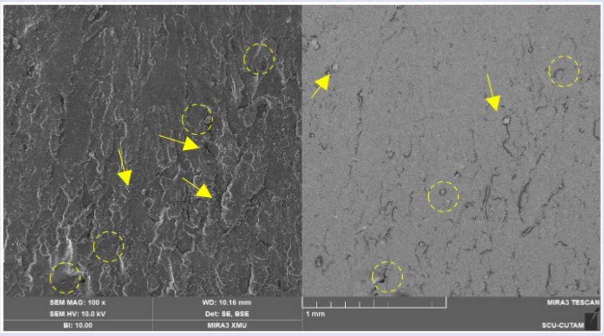

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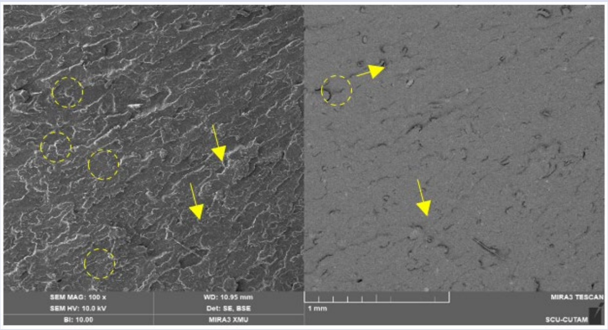

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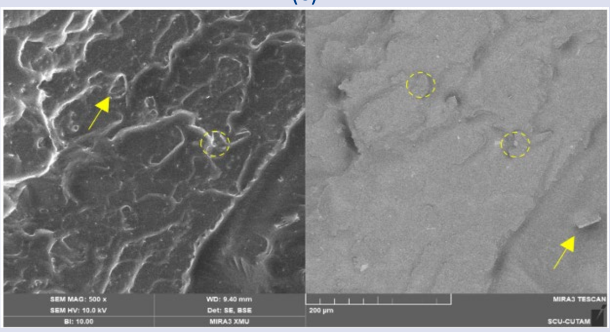


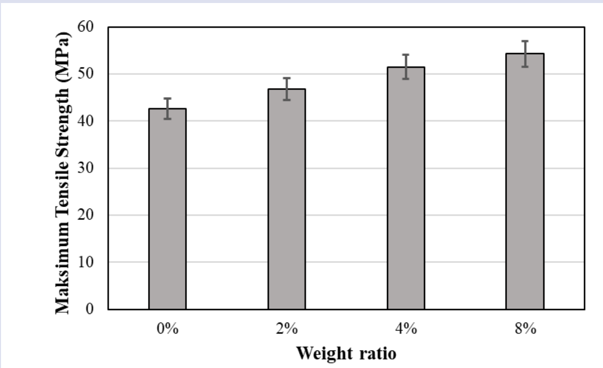
(d)

Figure 8. SEM photographs of the fractured tensile test samples. (a) Without additives, (b) 2 wt.%, (c) 4 wt.%, (d) 8 wt.%

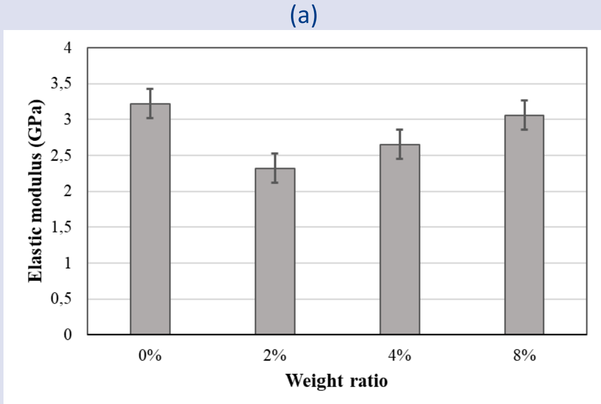
The data obtained are comparatively presented in Table 1 and Figure 7. SEM photographs were taken from the fracture side of the tensile test specimens and adhesion strength and particle distributions and morphology analysis were performed at the iron powder-epoxy interface around the fracture area (Figure 8). Also, the maximum values of the tensile tests are given in Figure 9. The results showed that the maximum tensile strength increased depending on the contribution ratio, while the elastic modulus first decreased and increased with the increase in the contribution ratios. However, it remained lower than the uncompounded sample in all contribution ratios. Elongation at break first increased significantly and then decreased. The elongation at break value was higher than the uncompounded sample in all contribution ratios. The increase in elastic modulus was the highest in composites with 8% by weight iron powder, resulting in 28% higher tensile strength compared to uncompounded ones. This increase revealed an important result in terms of using waste iron powder-added composites as fillers to increase the tensile strength of the recoveries. However, there was a decrease in the elastic modulus first and then an increase after 2%, and the maximum value was reached when the weight ratio was 8%. This result revealed that the elastic property of the material varies and the addition of iron powder makes a negative contribution in terms of increasing the elastic property.

Table 1. Average values obtained from tensile test data

Sample	Maximum Tensile Strength (MPa)	Modulus of Elasticity (GPa)	Elongation at Break (%)
0%	42.590	3.219	1.696
2%	46.852	2.321	4.324
4%	51.479	2.655	3.257
8%	54.252	3.061	2.878



(a)



(b)

Figure 9. Distribution of tensile test results. a) Maximum tensile stress, b) Elastic modulus.

The data obtained from the three-point flexural tests applied to the waste iron powder-added composites are shown in Figure 11. In addition, the maximum flexural strength and flexural modulus results with the obtained data are comparatively given in Table 2 and Figure 12. As can be understood from the results, it can be said that the elongation at break decreased with the increase in the iron powder contribution ratio, and in the sample with 8% contribution by weight, the toughness of the material and the maximum strength values were significantly lower than the uncompounded sample. Considering the area under the curve, it can be said that the fracture toughness of the material decreases significantly with the increase in the contribution ratio. This reveals that the material becomes more brittle and less resistant to flexural. In addition, it was observed that the elastic modulus did not increase or decrease significantly, this result revealed that the added iron powder contribution disrupts the load-carrying capacity and structure of the material. The decrease in the flexural strength values of the produced polymer matrix composites revealed that the deterioration at the epoxy-iron particle interface negatively affected the strength values. When looking at the morphology of the tensile test specimens (Figure 8), it was observed that the cracks on the surface of the specimens without particle additives were prominent and wavy. This can be explained by the brittle structure of epoxy. It was observed that when the iron powder particle addition increased in weight ratio, the wavy structure on the level was less and the epoxy-iron powder wound surface provided a good fit. This can be explained by the fact that an increase in the wt% of iron powder in the results resulted in better tensile strength performance of the specimens. In this case, it is concluded that iron powder with epoxy in the specimen subjected to shrinkage increases the resistance to load bearing and increases the tensile strength by showing homogeneous distribution of iron powders. It was understood that the elastic modulus was low in composites with 2% additives and that the material loosened, whereas the tensile strength of the material increased.

Similarly, Erdoğan et.al. [19] found that a 5% addition of iron scale resulted in the highest tensile strength, while higher amounts decreased the tensile strength compared to pure PP. In addition, the hardness of the composites increased from 58 to 64 Shore-D with increasing iron scale content, indicating improved mechanical performance and wear resistance of the reinforced composites. Abdelhaleem et al. [20] investigated the mechanical properties of recycled polypropylene (RPP) reinforced with 10%, 20% and 30% recycled iron powder (RIP). The tensile strength increased from 21 N/mm² for virgin RPP to 27.72 N/mm² (32% increase) with 30% IP. The Elastic modulus also improved significantly, reaching 566.30 MPa (46.09% increase) at 30% IP. Hardness increased from 71 to 76 Shore D, demonstrating improved mechanical performance with the addition of iron powder. Taşdemir ve Gülsoy [21] investigated the mechanical properties of metal-polymer matrix composites using iron powder as a filler, focusing on high density polyethylene (HDPE), polypropylene (PP) and polystyrene (PS). It examines the effects of varying amounts (5, 10 and 15 vol%) of iron powder on properties such as yield strength, tensile strength, elongation, Izod impact strength and hardness. The results indicate that iron powder has a negative effect on yield and tensile strength, but a positive effect on elastic modulus and hardness.

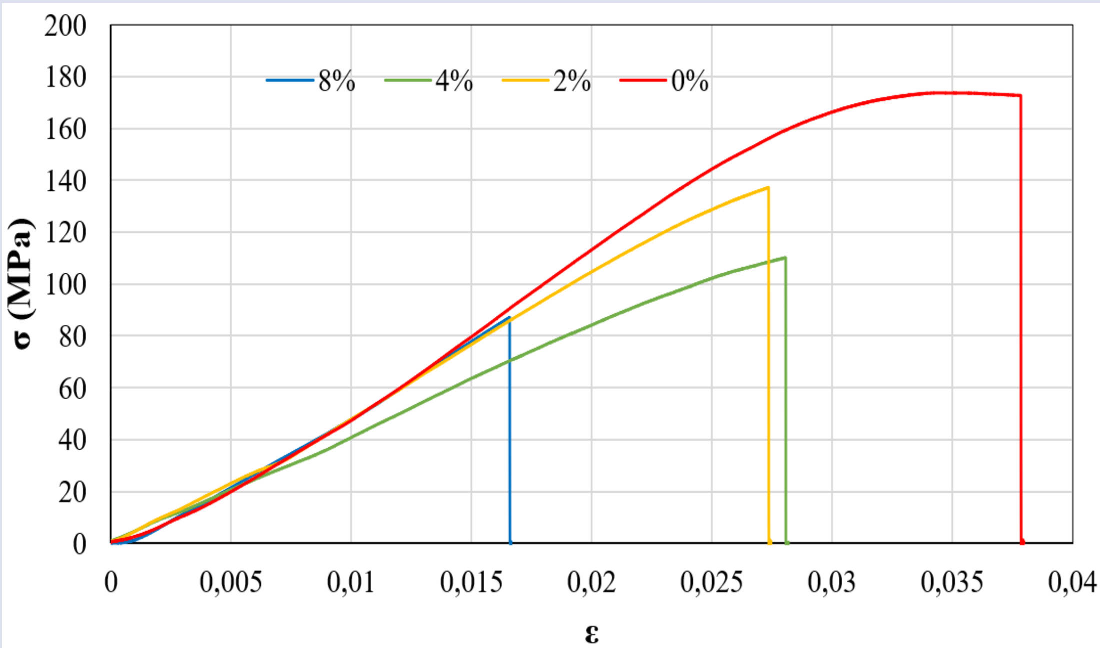


Figure 11. Flexural test results of polymer matrix composites with waste iron powder additive

Table 2. Average values obtained from three-point flexural test data

Sample	Maximum Flexural Strength (MPa)	Flexural Modulus (GPa)	Elongation at Break (%)
0%	153.104	4.20	3.785
2%	137.205	4.40	2.736
4%	110.101	3.91	2.806
8%	87.134	4.39	1.659

Figure 12 shows the distribution of iron powder addition according to the maximum tensile strength and flexural modulus values. As can be seen from the figure, although the addition of iron powder at a rate of 2% by weight has a limited positive contribution to the flexural modulus value, it has been revealed that the addition of more iron powder generally affects the structure of the material negatively.

It was concluded that the maximum flexural strength generally decreases gradually with the addition of iron powder, and that this deterioration is followed by a decrease in the load-carrying capacity of the material in terms of flexural with the decrease in the strength values of the bond at the epoxy-iron powder interface. Figure 13 shows the post-test damage mechanisms of the specimens subjected to the flexural test. As can be seen from the figure, the uncompounded specimens fractured brittlely, and matrix cracking increased depending on the amount of iron powder added.

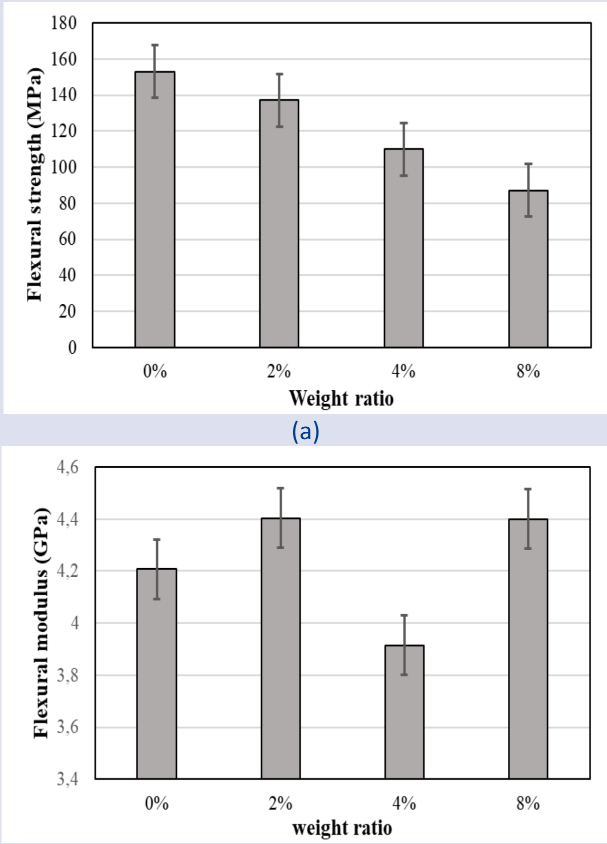


Figure 12. Distribution of flexural test results. a) Maximum flexural stress, b) Flexural modulus

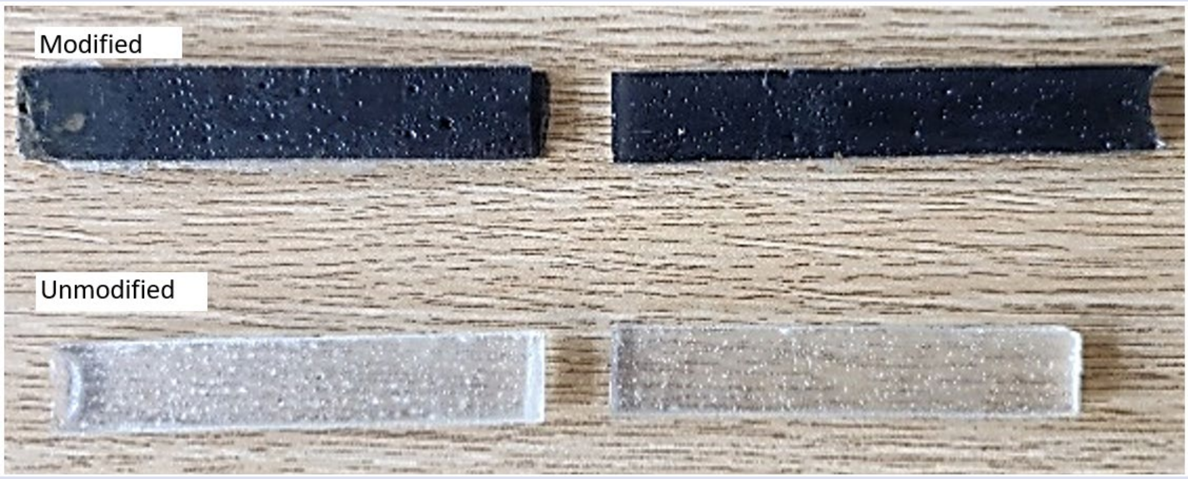
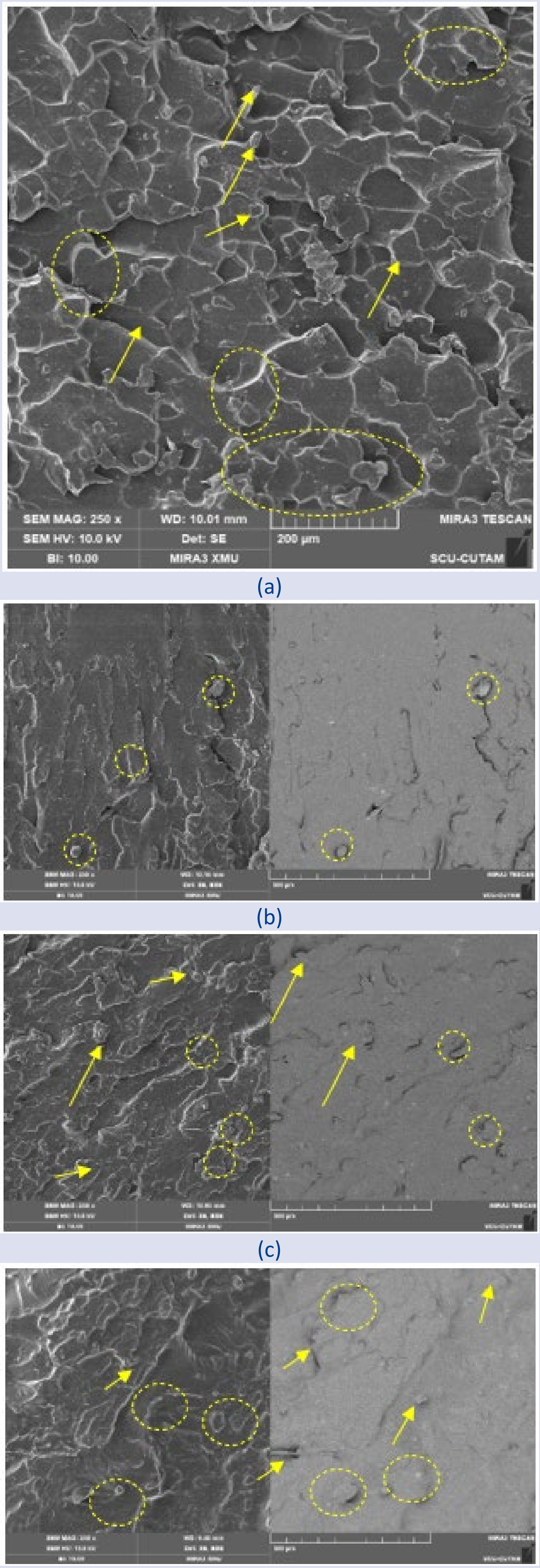


Figure 13. Fracture mechanisms after the flexural test.

Figure 14 shows SEM photographs of the modified and pure composites. It was concluded that the amount of additive ratios affects the strength and related properties of the material, and therefore, determining the optimum amount of additive according to the desired properties of the material where it will be used is important. In this context, it would be beneficial to determine the optimum amount of additive by conducting more experiments. In this study, it can be stated that the sample with 4% additive is the sample that exhibits optimum properties according to the tensile test results; and for flexural tests, the most suitable samples are the additive-free samples.



(a)

(b)

(c)

(d)

Figure 14. SEM photographs of the fractured flexural test samples. (a) Without additives, (b) 2 wt.%, (c) 4 wt.%, (d) 8 wt.%

As can be understood from Figure 14, it can be said that the fluctuations on the surface of the samples without additives are high and this is due to the brittle structure of the epoxy. However, it can be said that the addition of iron powder, such as the specimens in the tensile test, reduces these fluctuations and provides a better fit to the epoxy by providing a homogeneous distribution. However, it was observed that the flexural test results gradually decreased with the addition of iron powder. It is understood that the resistance of the materials to flexure is weakened by the stress intensity and damage progression at the iron powder-epoxy interface. Thus, it is concluded that iron powder has a negative effect on both the air voids in the material and the load transfer against flexural resistance.

Conclusion

Within the scope of this study, experimental calculations of the tensile and flexural strength behaviors of waste iron powder-added E-glass polymer matrix composites, and studies on the applicability of recycling iron powder as a filler material were carried out and reported. The obtained data showed that the addition of waste iron powder in terms of tensile strength; when added to epoxy at a rate of 4% by weight, it provided a 28% improvement in tensile strength compared to the additive-free ones; however, it showed a limited decrease in elastic modulus. The flexural test results revealed that the addition of iron powder negatively affected the flexural strength and modulus.

Conflicts of interest

There are no conflicts of interest in this work.

Ethical Approval Statement

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article. The authors also declared that this article is original, was prepared in accordance with international publication and research ethics, and ethical committee permission or any special permission is not required.

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