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ORIGINAL RESEARCH

Enhancing the mechanical and thermal properties of ABS polymers through steel scale reinforcement: a sustainable approach to waste utilization

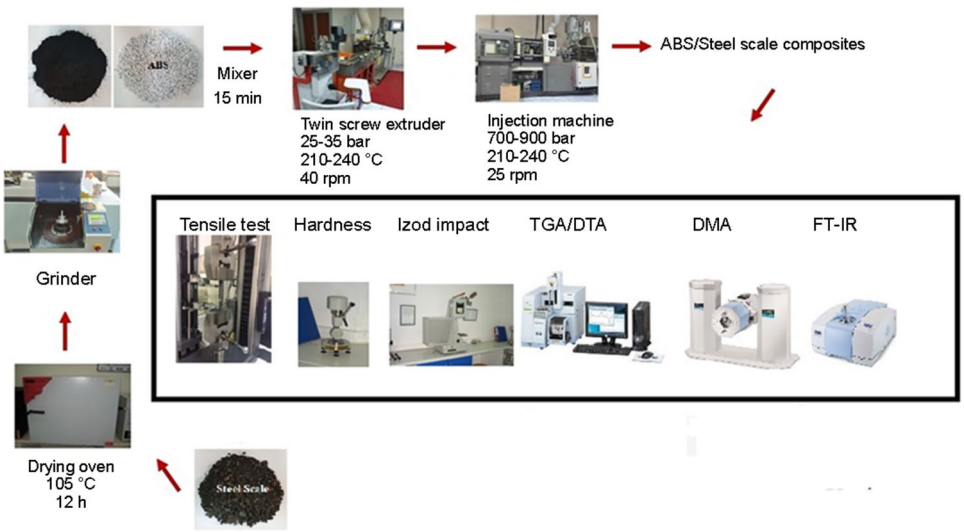
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Abstract

Steel scale, a byproduct of the iron and steel industry, primarily composed of iron oxide phases, is typically considered an industrial waste. This study investigates its potential use as a reinforcing filler in acrylonitrile–butadiene–styrene (ABS) polymer composites to enhance both mechanical and thermal properties while promoting sustainable material utilization. Composites were produced via melt blending ABS with varying steel scale contents (3%, 5%, 7% and 9% by wt), followed by injection molding. Mechanical properties were evaluated through tensile, hardness, and impact tests. In contrast, thermal and structural properties were analyzed using dynamic mechanical analysis (DMA), thermogravimetric analysis (TGA), Fourier transform infrared spectroscopy (FTIR), and scanning electron microscopy (SEM). Results showed that incorporating the steel scale increased both the modulus of elasticity and hardness. Notably, at 9% filler content, the modulus rose by 28.9% (from 968 to 1248 MPa), and hardness increased by 9.2% (from 63.1 to 68.9) compared to pure ABS. However, higher filler content led to slight decreases in tensile and break strength—tensile strength dropped by 14.2% (from 42.9 MPa to 36.8 MPa), and break strength by 7% (from 39.6 MPa to 36.8 MPa). Thermal analyses confirmed improved thermal stability of the composites, demonstrating the steel scale's effectiveness as a thermally resistant additive. These findings support the feasibility of recycling steel scale into polymer composites, presenting a sustainable alternative for reducing industrial waste. The developed composites show promise for applications in non-structural automotive parts, construction materials, and durable consumer products.

Graphical abstract



Extended author information available on the last page of the article

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Keywords Steel scale · Acrylonitrile–butadiene–styrene composites · Reinforcement · Mechanical properties · Thermal stability

Introduction

With the increasing global production capacity, the consumption of raw materials and energy in composite manufacturing continues to rise. Polymer composites offer numerous advantages, including high strength, corrosion resistance, hardness, and enhanced resistance to impact and abrasion, while also exhibiting a superior strength-to-weight ratio [1]. Due to these exceptional properties, polymer composites find extensive applications across various industries, including the aerospace and defense, construction, biomedical engineering, automotive, and marine sectors [2–4]. In recent years, industrialization has accelerated, significantly increasing pollution while simultaneously depleting raw material resources. Consequently, recycling waste materials and incorporating them into composite materials has become a major research focus. Recycling offers multiple advantages, such as waste minimization, material reuse, conservation of energy and raw materials, and cost reduction. The recycling of metals, glass, and plastics is particularly critical for fostering sustainability, as it not only mitigates waste accumulation but also contributes to the preservation of natural resources [5–7]. Among these benefits, cost reduction remains one of the most crucial factors driving the utilization of waste materials [8, 9].

During the cooling process of billets in foundries and rolling mills, an oxide layer comprising iron oxide phases such as wustite (FeO), magnetite (Fe_3O_4), and hematite (Fe_2O_3) forms on the metal surface due to high temperatures and an oxidizing environment. During rolling, this oxide layer fractures and is subsequently removed from the metal surface through high-pressure water cleaning, typically being treated as industrial waste and sold as scrap [10]. However, given its high iron content, the steel scale exhibits significant potential as a reinforcement material in polymer matrices, enhancing both mechanical strength and thermal properties. In this context, incorporating steel scale into polymer composites improves material performance and aligns with sustainability objectives by contributing to effective waste management. The reutilization of such waste materials facilitates more efficient resource utilization, promotes the development of environmentally friendly materials, and fosters the transition toward more sustainable industrial practices [11–13].

The existing literature presents numerous studies on the remelting and reduction of scale, as well as its incorporation into natural aggregates, such as sand and gravel, which constitute the primary raw materials of concrete [14–16]. Additionally, various investigations have been conducted to explore alternative applications of steel scale in composite materials [17, 18]. For instance, Gok et al. [19] investigated the wear resistance and hardness of Clarofast-based composites reinforced with steel scale at different weight fractions (5–25% by wt). The materials were fabricated by hot pressing at 200 °C under a pressure of 500 N for 30 min, with a primary focus on dry sliding wear behavior. However, their study differs significantly from the present research in terms of polymer matrix selection, production method, and characterization focus. Similarly, Bayraktar et al. [20] incorporated iron flakes with varying particle sizes into LDPE at weight fractions ranging from 2.5 to 20% (by wt) using extrusion processing. Their study explored the influence of particle size and concentration on mechanical properties. The results demonstrated that as the iron scale concentration increased, elongation-at-break improved, whereas tensile strength remained relatively unaffected. Additionally, increasing the particle size enhanced both tensile strength and hardness, while elongation-at-break exhibited a decreasing trend. Notably, the highest hardness was recorded at an iron scale concentration of 20% (by wt).

Although the utilization of steel scale in various fields has been increasingly investigated, its application as a reinforcing filler in polymer-based composites remains relatively limited in the literature. In this study, the potential of incorporating steel scale conventionally considered industrial waste into an ABS polymer matrix at specific volume fractions (3, 5, 7 and 9% by volume) is explored without the use of any additional additives. The aim is to contribute to environmental sustainability and enhance material performance. Previous studies have primarily focused on different matrices, such as LDPE, with an emphasis on particle size or wear behavior under specific conditions. In contrast, this study provides a comprehensive evaluation of the effects of steel scale content on the mechanical (tensile, impact, and hardness), thermal (TGA and DMA), and microstructural (FTIR and SEM) properties of ABS-based composites. The results obtained from this study are systematically analyzed and discussed, offering valuable insights for future research and further advancements in composite material development. Accordingly, the present work addresses a significant gap in the literature and introduces an environmentally friendly approach to the valorization of industrial waste in composite material development.

Experimental

Materials

The steel scale was supplied by Asil Celik Co., a company based in Bursa, and its density was determined to be 5.0122 g/cm^3. The matrix material, ABS polymer (Starex SD-0150), was procured from Lotte Chemical Corporation. The ABS polymer exhibits a density of 1.03 g/cm^3, a tensile strength of 48 MPa, and a Vicat softening temperature of 98 °C.

Production of samples

The manufacturing and testing steps of the ABS/steel scale polymer composites are illustrated in Fig. 1. Given that water is extensively used in steel production processes for cooling, gas purification, descaling, and washing, the steel scale obtained from Asil Celik was subjected to a drying process to eliminate residual moisture. Specifically, it was dried at 105 °C for 12 h in a Yamato ADP-31 oven. Subsequently, the dried scale was ground into fine powder for 5 min using a Herzog ring mill equipped with a Siemens Simatic C7-621 control system. To determine the particle size distribution, sieve analysis was performed using a Retsch AS 200 analytical sieve shaker. The samples were vibrated for 15 min at a constant speed through a stack of sieves with mesh sizes of 180 µm, 90 µm, 63 µm, 53 µm, 45 µm and 38 µm. Subsequently, to ensure homogeneity, the solid components of the polymer composites were mixed for 15 min in a Patterson-brand mixer. The steel scale and ABS polymer were weighed according to the ratios specified in Table 1 and processed using the melt blending method in a Microsan co-rotating twin-screw extruder under temperatures ranging from 210 °C to 240 °C, a pressure of 25–35 bar, and a screw rotation speed of 40 rpm. Following extrusion, the polymer composites were cooled in water and subsequently granulated using a crusher. To remove any residual moisture from the production process, the granulated composites were dried in a vacuum oven at 105 °C for 12 h. Test specimens were then fabricated using an injection molding machine under an injection temperature of 210–240 °C, an injection pressure of 700–900 bar, and a screw rotation speed of 25 rpm. The selection of processing parameters such as temperature, pressure, and mixing time was based on similar studies in the literature that employed comparable ABS-based composite systems and processing techniques [21–23].

Table 1 Compositions of the ABS/steel scale composites

Groups	ABS (% by vol)	Steel scale (% by vol)	Steel scale (% by wt)
ABS	100	–	–
ABS/3S	97	3	13.08
ABS/5S	95	5	20.39
ABS/7S	93	7	26.81
ABS/9S	91	9	32.49

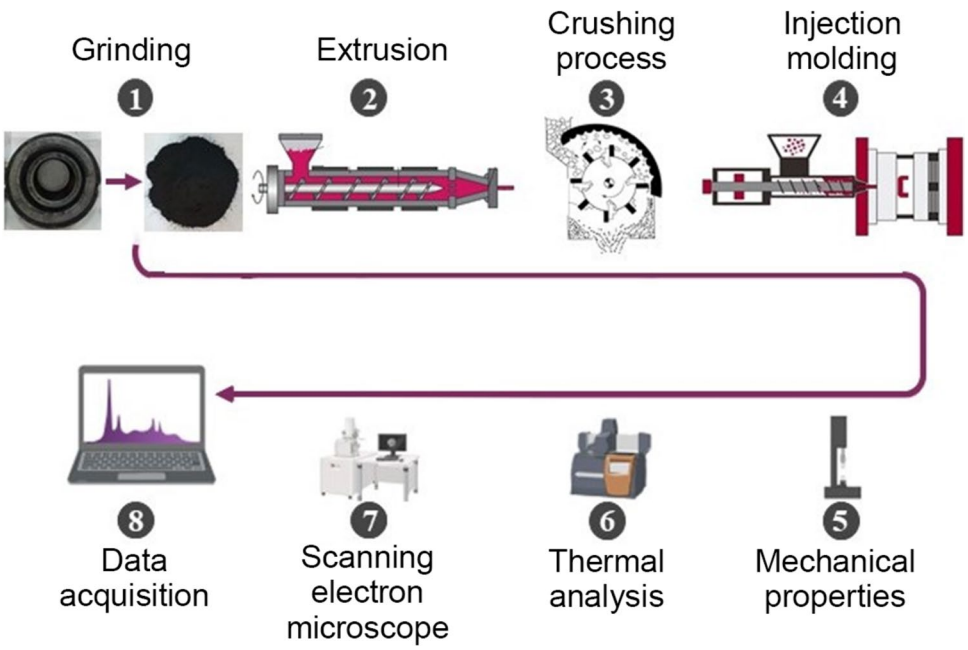


Fig. 1 Manufacturing and testing steps of ABS/steel scale polymer composites

Test procedure

The sieve analysis test was performed to determine the particle size distribution of the steel scale. The samples were subjected to vibration at a constant speed for 15 min using a Retsch AS 200 analytical sieve shaker, within a sieve assembly of various mesh sizes. Tensile tests were conducted by ASTM D638 standards using a Zwick Z010 universal testing machine equipped with a 10 kN load cell. The crosshead speed was set to 50 mm/min. The elasticity modulus, tensile strength, and elongation-at-break were determined. At least 6 specimens from each composition were tested, and the average values were recorded. The fracture behavior of polymer composites was assessed through a notched Izod impact test, following the ASTM D256 standard. The tests were carried out using a Zwick B5113 (Zwick, Ulm-Germany) impact testing device with a 5.4 kJ pendulum. The results were obtained by averaging 5 specimens for each group. The storage modulus (E') of the samples was analyzed using a Dynamic Mechanical Analyzer (Perkin Elmer, DMS 8000). The temperature was increased from 25 °C to 140 °C at a heating rate of 5 °C/min, with a frequency of 1 Hz. The tests were conducted in a single cantilever bending deformation mode. The hardness of the samples (Shore D) was measured following the ASTM D-1706-67 standard using a Zwick hardness tester, with 10 measurements recorded for each sample. To investigate the dispersion and microstructure of the steel scale within the ABS matrix, the samples were sputter-coated with a gold–palladium alloy layer approximately 20 Å thick before being subjected to SEM analysis. The SEM observations were performed using an FEI XL30 Sirion FEG Digital Electron Microscope at an accelerating voltage of 10 kV. TGA was carried out using a TG/DTA (Seiko Exstar, Japan) instrument. Approximately 5–10 mg of each sample was placed in a ceramic crucible and heated from 25 °C to 1020 °C at a rate of 10 °C/min. FTIR spectroscopy was performed in transmittance mode at room temperature, scanning the wavenumber range of 650–4000 cm^{-1}.

Results and discussion

The particle size distribution of the steel scale is depicted in Fig. 2, illustrating that the scale predominantly consists of particles smaller than 180 µm. The majority of the particles fall within the moderate size range of 45 µm to 90 µm, which is ideal for many polymer composite applications. A well-distributed particle size profile indicates that the steel scale is suitable for systems requiring specific gradation characteristics. The size distribution of the reinforcing particles plays a crucial role in determining the overall properties of the polymer composite. Smaller particles can provide more surface area for interaction with the matrix, thereby enhancing adhesion and mechanical strength. However, an optimal size range must be maintained to prevent issues such as agglomeration, which could lead to reduced performance. In the literature, several studies have investigated the impact of particle size distribution on the mechanical and thermal properties of polymer composites, finding that a uniform distribution can improve load transfer and overall material performance. Therefore, the steel scale's particle size distribution ensures consistent reinforcement and significantly contributes to the mechanical enhancement of the composites.

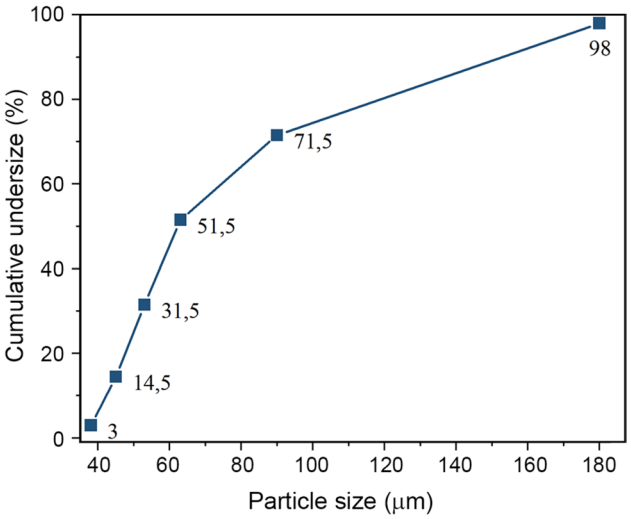


Fig. 2 Particle size distribution of steel scale powders: cumulative undersize values

Figure 3a illustrates the effect of steel scale concentration on the tensile and break strength of ABS-based polymer composites. A progressive decline in both tensile and break strength was observed with increasing steel scale content. The tensile strength of pure ABS was measured at 42.9 MPa, whereas for composites containing 3%, 5%, 7% and 9% steel scale, the values decreased to 39.7 MPa, 39.4 MPa, 38.3 MPa and 36.8 MPa, respectively. A similar trend was observed in break strength, where the initial value of 39.6 MPa for pure ABS gradually decreased to 38.7 MPa, 38.6 MPa, 38.1 MPa and 36.8 MPa for composites with 3%, 5%, 7% and 9% steel scale, respectively. This deterioration in mechanical performance is consistent with the findings of Tasdemir et al. [24], who investigated PS/iron powder composites and reported a comparable reduction in tensile strength with increasing iron powder content. The decline in mechanical properties can be attributed to the inadequate interfacial adhesion between the steel scale particles and the polymer matrix, which hinders effective stress transfer. Studies in the literature have consistently demonstrated that metallic reinforcements, including steel scale, contribute

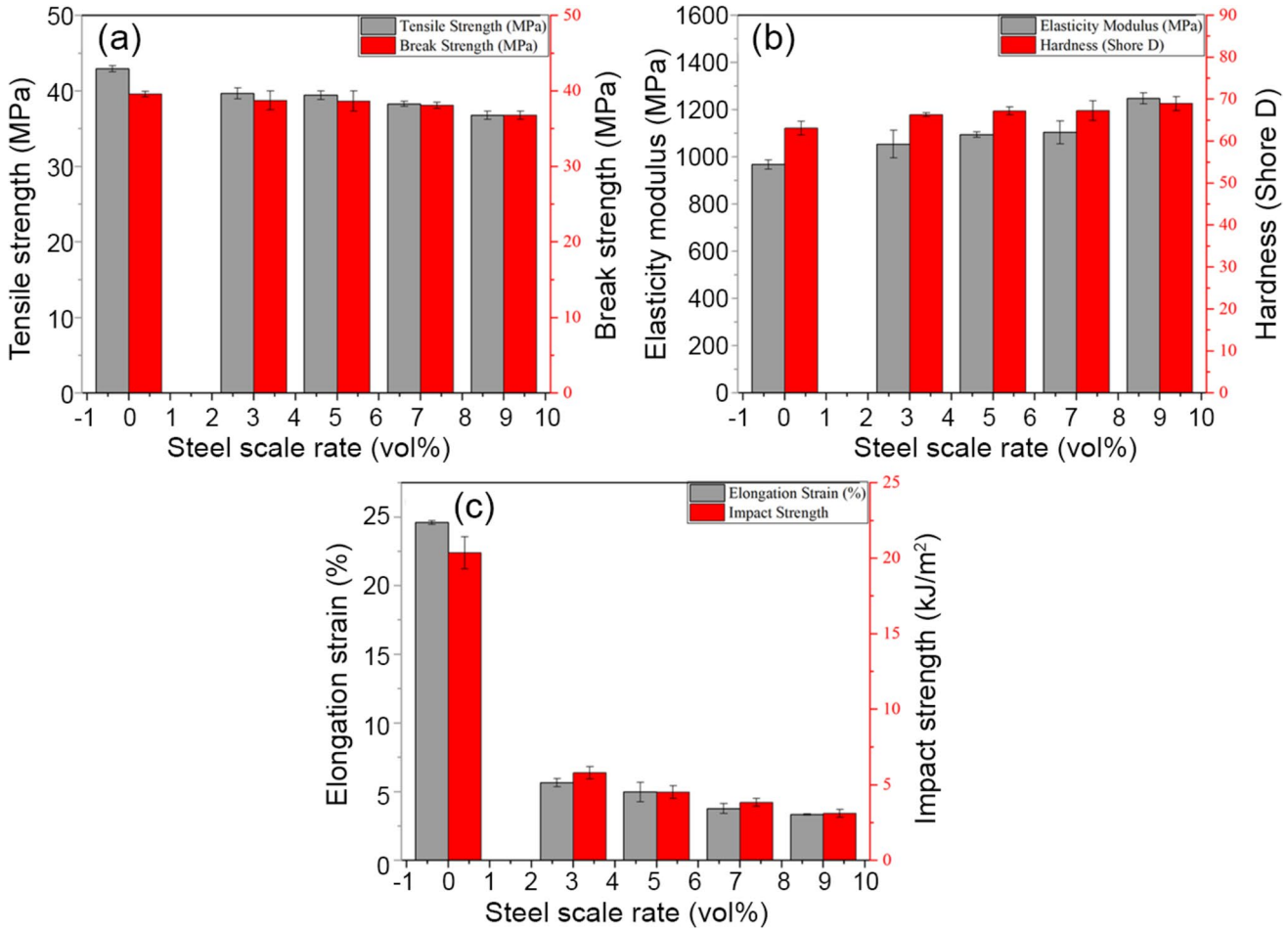


Fig. 3 Mechanical properties of ABS/steel scale polymer composites

minimally to load transfer within the polymer matrix, thereby compromising the overall mechanical integrity of the composite [25].

Figure 3b presents the impact strength and elongation-at-break of pure ABS and steel scale-reinforced composites, demonstrating a significant decline in both properties with increasing steel scale content. The impact strength of pure ABS was measured at 20.4 kJ/m^2, whereas for composites containing 3%, 5%, 7% and 9% steel scale, the values dropped drastically to 5.8 kJ/m^2, 4.5 kJ/m^2, 3.8 kJ/m^2 and 3.1 kJ/m^2, respectively. Similarly, a substantial decrease was observed in the elongation-at-break, which declined from 24.6% for pure ABS to 5.7%, 4.9%, 3.8% and 3.3% for composites with 3%, 5%, 7% and 9% steel scale, respectively. This pronounced reduction in impact strength and elongation can be primarily attributed to the weak interfacial adhesion between the steel scale particles and the polymer matrix, which inhibits the material's ability to absorb and dissipate impact energy efficiently. As the content of steel scale increases, the stress concentration points within the composite become more prominent, further exacerbating the brittle behavior of the material. Additionally, since steel scale exhibits lower elongation capacity compared to the polymer matrix, its presence restricts the overall ductility of the composite, leading to a significant decline in elongation-at-break. These findings align with previous studies in the literature, which have consistently reported similar trends in metal-reinforced polymer composites, emphasizing the critical role of interfacial bonding in determining mechanical performance.

Figure 3c illustrates the effect of steel scale reinforcement on the modulus of elasticity and hardness of ABS polymer composites. The results indicate that the incorporation of steel scale significantly enhances both properties. The modulus of elasticity for pure ABS was measured at 968 MPa, whereas composites containing 3%, 5%, 7% and 9% steel scale exhibited values of 1054 MPa, 1094 MPa, 1104 MPa and 1248 MPa, respectively. A similar increasing trend was observed in hardness values; while pure ABS had a hardness of 63.1, the hardness values for composites with 3%, 5%, 7% and 9% steel scale were recorded as 66.3, 67.2, 67.2 and 68.9, respectively. This improvement can be attributed to the

rigid nature of steel scale particles, which enhance the stiffness and durability of the polymer matrix, thereby increasing the overall rigidity of the composite. These findings align with the study conducted by Ozcan [26], which reported that the addition of scale particles to polymeric materials resulted in increased hardness and wear resistance. Similarly, Tasdemir et al. [27] observed a significant increase in the modulus of elasticity and hardness upon incorporating iron powder into HDPE, PP, and PS polymers. These consistent results highlight the beneficial role of metal-based reinforcements in enhancing the mechanical properties of polymer composites. Moreover, a study by Mindivan [28] demonstrated that adding graphene nanoplatelets (GnP) to polymer matrices effectively improves thermal conductivity and mechanical strength. The study reported that the exceptional strength and rigidity of GnP substantially enhanced the mechanical performance of polymer composites. Similarly, steel scale, as a metallic reinforcement, contributes to the increase in stiffness and hardness of polymer composites, further improving their overall mechanical performance. These findings underscore the crucial role of filler dispersion and interfacial bonding in determining the mechanical properties of composite materials.

Figure 4 presents the variation in mass percentage as a function of temperature under a nitrogen atmosphere, providing a detailed thermal degradation profile of the samples. The TGA results reveal that ABS undergoes substantial thermal decomposition within the temperature range of 380–560 °C, exhibiting a total mass loss of 96.04%. In contrast, the incorporation of steel scale into the ABS matrix significantly enhances its thermal resistance. The total mass losses observed for ABS/steel scale composites with volumetric additions of 3%, 5%, 7% and 9% are 85%, 77.07%, 72.25% and 68.22%, respectively. The progressive reduction in mass loss with increasing steel scale content highlights its role in improving the thermal stability of the composite, as evidenced by the TGA results. In the study by Güzel et al., it was stated that the incorporation of steel slag significantly enhanced the thermal stability of the polymer matrix used [25].

Figure 5 shows a decrease in the storage modulus for all samples as the temperature increases. Meanwhile, the storage modulus of the composites generally increases with the loading of steel scale. This finding indicates that adding steel scale can improve the composites' mechanical properties. Upon increasing temperature, the E' values of all composites decreased. The ABS/steel scale composite (91/9 by volume) had the highest storage modulus at 811 MPa. Compared to pure ABS, the ABS/steel scale composite (91/9 by volume) showed a 17% increase in E'. The ABS/steel scale composite (91/9 by volume) exhibited the highest storage modulus at 811 MPa, representing a 17% increase compared to pure ABS, which had an E' of 693 MPa. The reinforcement effect is attributed to the rigidity of iron oxide particles, which impede the mobility of polymer chains. The observed increase in storage modulus in the present study is consistent with the findings reported in the existing literature [8, 20]. The consistent rightward shift of about 2–3 °C at 9% (by volume) indicates that the addition of the steel scale has a substantial impact on restricting segmental mobility. This observation aligns with the results from TGA, which suggest an improvement in thermal resistance. As the filler fraction increases, thermally induced chain scission diminishes, as observed in TGA, while DMA shows an increase in the stiffness of the elastic network.

Figure 6 presents the microstructural images of pure ABS and ABS/steel scale polymer composites, respectively. Upon

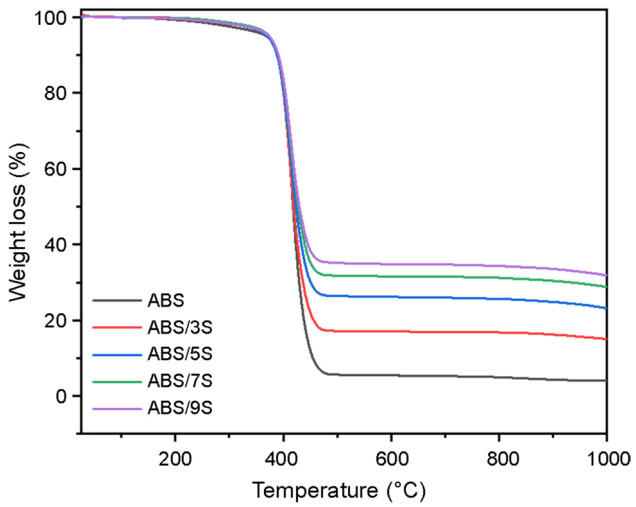


Fig. 4 TGA thermograms of ABS/steel scale polymer composites

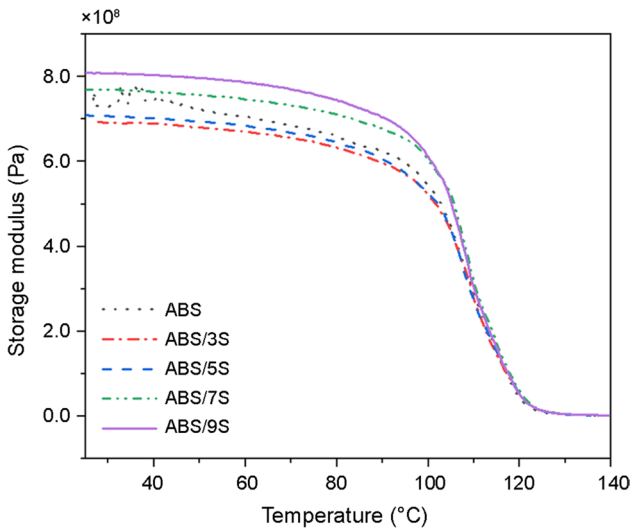


Fig. 5 Temperature dependence of storage modulus of ABS/steel scale polymer composites

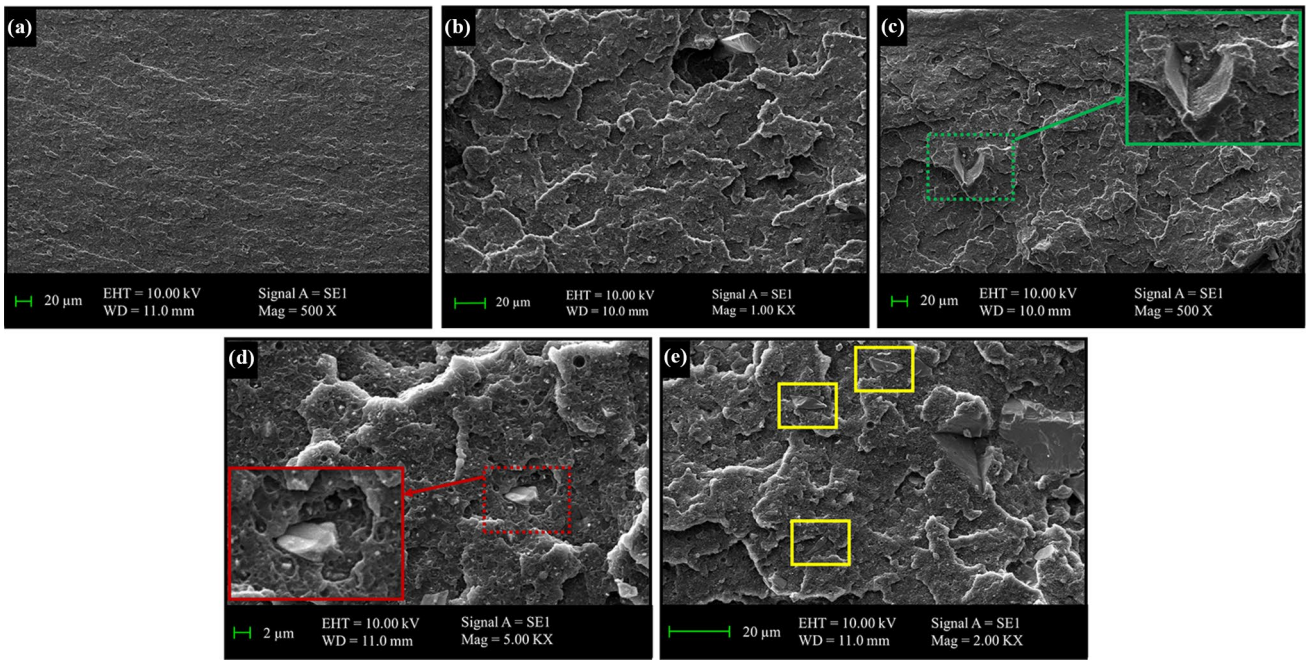


Fig. 6 SEM images of ABS/steel scale polymer composites: **a** ABS, **b** ABS/3S, **c** ABS/5S, **d** ABS/7S, and **e** ABS/9S

examining the microstructure of pure ABS, a smooth fracture surface is observed, indicating a homogeneous structure. The images of the polymer composites at different magnifications provide insight into the particle distribution. The green area shown in Fig. 6c highlights voids created by the separation of the steel scale from the polymer matrix, suggesting weak adhesion between the two phases. This poor interfacial bonding between ABS and steel scale indicates that the particles do not integrate well within the polymer matrix. With an increase in steel scale content, more voids and cavities are observed. This likely creates potential sites for crack initiation, leading to localized stress concentration, which could explain the reduction in mechanical strength due to particle addition [29]. The morphology of steel scale particles plays a crucial role in their dispersion and interaction with the polymer matrix. Powder metallurgy techniques produce powders with various shapes, including spherical, irregular, flaky, and angular geometries. Previous studies by Ozcan and Gok et al. have shown that ground steel scale particles exhibit a flaky structure with rough surfaces and sharp edges, as confirmed by SEM analysis [19, 26]. Similarly, in the current study, the embedded steel scale particles display an angular morphology with distinct edges, as seen in the magnified view of the red area in Fig. 6d. The presence of such irregularly shaped particles within the ABS matrix can contribute to stress concentration points, negatively impacting the mechanical properties of the composite. Additionally, in Fig. 6e, the steel scale particles in the yellow-marked regions exhibit a non-homogeneous distribution, further supporting the observed reduction in mechanical performance. The increased steel scale content results in more voids and cavities, which act as potential crack initiation sites. The SEM images confirm that the non-uniform dispersion of steel scale particles, combined with their weak interfacial adhesion to the polymer matrix, adversely affects the mechanical behavior of the composite [30, 31].

Figure 7 shows FTIR spectra of ABS material and its variations blended with steel scale at volume percentages of 3%, 5%, 7% and 9%. From the analysis, it was concluded that the composite was composed of ABS and Steel Scale.

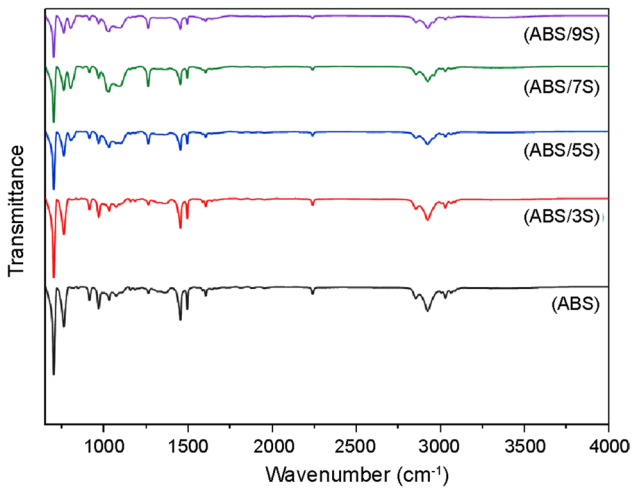


Fig. 7 FTIR spectra of ABS/steel scale polymer composites

The data obtained from the pure ABS curve indicates that it has a standard structure, which aligns with the FTIR profiles found in the literature for this material [32, 33]. The presence of steel scale introduces characteristic peaks of iron oxide (Fe–O) at around 570–580 cm^{-1} and 460–470 cm^{-1}, which become more intense as the steel scale content increases. The connections between 3200 and 3000 cm^{-1} and 3000–2800 cm^{-1} correspond to the (-CH-) aromatic and aliphatic bonds, while the bond at 2237 cm^{-1} represents acrylonitrile (C≡N). The fact that these bands remained distinct in all composite groups indicates that the chemical structure of the polymer remained intact. The region between 810 and 698 cm^{-1} indicates the presence of the aromatic ring of styrene, and the bonds (–C = C–) of butadiene are detected between 1130 and 980 cm^{-1}. Upon investigation of the composite material, it was observed that the interaction of ABS and steel scale decreased peak intensity between 2800 and 3200 cm^{-1}. A broad and increasingly intense band became visible as more steel scale was added to the ABS between 1000 and 1200 cm^{-1}. Additionally, FTIR analysis revealed that the addition of steel scale did not result in the formation of any new peaks indicative of a new functional group. The observed peak intensity reductions within the 2800–3200 cm^{-1} spectral region, coupled with the enhancement of bands between 1000 and 1200 cm^{-1}, are indicative of increased physical interactions and suggest alterations in molecular interactions, reflecting possible physical interactions rather than chemical modifications.

Conclusion

Polymer composites have gained considerable attention due to their ability to combine the advantages of organic polymers and inorganic reinforcements, offering enhanced mechanical, thermal, and structural properties. The use of waste materials, such as steel scale, in polymer matrices not only promotes sustainability by reducing waste but also improves the performance of composite materials for various industrial applications. This study examines the impact of incorporating steel scale, a byproduct from the iron and steel industry, as a reinforcing additive in ABS polymer composites, focusing on its effects on mechanical and thermal properties. In the impact strength test, it was observed that the impact strength decreased with increasing steel scale content. This decline is attributed to the low affinity between the matrix and the reinforcement, which reduces the load-bearing capacity of the composites, leading to sudden fractures. The weak bonding between the ABS matrix and steel scale particles, primarily due to van der Waals forces, contributes to the reduction in impact strength. On the other hand, steel scale, being more rigid than polymers, increased the hardness of the ABS matrix. Tensile testing showed an increase in the elastic modulus of the composites with the addition of scale particles. However, SEM analysis revealed poor adhesion between the matrix and the scale at higher concentrations and a heterogeneous particle distribution that adversely affected tensile strength. This poor compatibility can be attributed to the lack of chemical interactions at the interface, possibly due to the inert surface chemistry of the steel scale. The absence of functional groups or surface treatments on the filler likely hinders interfacial bonding. Additionally, the observed non-homogeneous dispersion suggests that simple mechanical mixing may not be sufficient for achieving optimal particle distribution. Insufficient grinding time during scale preparation may have led to the formation of larger or irregular particles, which could have contributed to poor dispersion within the matrix and negatively affected interfacial interactions. Therefore, improving interfacial bonding between the polymer and the reinforcement may be achieved either by using a compatibilizer or by increasing the grinding duration to obtain an optimal particle size distribution. Thermogravimetric analysis showed improved thermal stability of the composites, indicating that the steel scale contributed to enhanced resistance to high temperatures. The reduction in mass loss is attributed to the higher thermal stability of the steel scale compared to pure ABS, which acts as a barrier to heat propagation. DMA confirmed an increase in the storage modulus, suggesting improved stiffness. Steel scale inhibits thermal degradation by acting as a thermal barrier and reducing chain mobility, which also explains the increased stiffness observed in both DMA and elastic modulus measurements. In short, increasing the scale content in ABS enhances thermal stability and stiffness but reduces ductility, tensile strength, and impact resistance. The rigid steel particles restrict polymer chain mobility, making the composite more resistant to deformation and elevated temperatures. FTIR observations highlight physical interactions at the interface rather than chemical reactions. The FTIR analysis confirms that there's a "mechanically interlocked-chemically inert" interface present. This means that the steel scale particles are effectively combined within the structure and affect the vibrational properties without interfering with the ABS backbone. This finding aligns with the improvements in thermal stability and stiffness observed through TGA and DMA testing. It also helps explain why there are impact strength losses, which can be attributed to the weak chemical bonding at the interface. These results suggest that ABS composites reinforced with steel scale may have valuable applications in high-temperature environments, particularly where increased rigidity and thermal stability are desired. This study addresses a gap in the literature and advances the development of environmentally friendly ABS-based composite materials. The findings also contribute to the development of the circular economy and waste recovery. Future research should focus on enhancing

mechanical performance by optimizing interfacial adhesion through surface modification techniques or the use of compatibilizers. Additionally, exploring hybrid reinforcement with steel scale and other fillers might lead to composites with better thermal and mechanical properties.

Data availability All data generated or analyzed during this study are included in this published article.

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