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Fabrication and Characterization of Thermoplastic Elastomer from EPDM/Polypropylene Blend Filled with Waste Tire Rubber Powder as Impact Absorber for Vehicle Doors

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ABSTRACT
The increasing number of motor vehicles in Indonesia has led to a growing amount of waste tires, posing environmental concerns. This study investigated the use of waste tire rubber powder as a filler in EPDM/polypropylene-based thermoplastic elastomers (TPE) using PP-g-MA as a compatibilizer. The blends were vulcanized and hot-pressed at 185°C with waste tire powder contents of 5, 10, 20, 30, 40 phr. Mechanical properties were evaluated, while FTIR, SEM, and TGA analyses were conducted on the optimum composition. The optimum filler content was 20 phr, yielding tensile strengths of 10.9903 MPa before aging and 5.6893 MPa after aging, elongations at break of 23.76% and 16.67%, elastic moduli of 46.2554 MPa and 34.1289 MPa, and an impact strength of 12,906.220 J/m². The tensile strength met the SNI 06-1490-1989 requirement, although the elongation at break did not. FTIR indicated the formation of O–H groups due to oxidative degradation, SEM showed relatively homogeneous filler dispersion with slight agglomeration, and TGA revealed thermal decomposition at 411.38–533.60°C. These results demonstrate that waste tire powder is a promising filler for EPDM/PP-based TPE with good mechanical properties and thermal stability.

Keywords: Compatibilizer, EPDM Synthetic Rubber, Polypropylene, Thermoplastic Elastomer, Waste Tire Rubber Powder.

ABSTRAK
Peningkatan jumlah kendaraan bermotor di Indonesia menyebabkan bertambahnya limbah ban bekas yang berpotensi mencemari lingkungan. Penelitian ini bertujuan memanfaatkan serbuk ban bekas sebagai bahan pengisi termoplastik elastomer (TPE) berbasis paduan EPDM/polipropilena dengan PP-g-MA sebagai *compatibilizer*. Paduan divulkanisasi dan dicetak menggunakan *hot press* pada suhu 185°C dengan variasi kadar serbuk ban bekas 5,10,20,30, 40 phr. Karakterisasi meliputi pengujian sifat mekanik serta analisis FTIR, SEM, dan TGA pada komposisi optimum. Hasil menunjukkan komposisi optimum diperoleh pada 20 phr dengan kuat tarik 10,9903 MPa sebelum pengusangan dan 5,6893 MPa sesudah pengusangan, kemuluran 23,76% dan 16,67%, modulus elastisitas 46,2554 MPa dan 34,1289 MPa, serta nilai impak 12.906,220 J/m². Kuat tarik memenuhi SNI 06-1490-1989, meskipun kemuluran belum memenuhi standar minimum. FTIR mengindikasikan terbentuknya gugus O-H akibat degradasi oksidatif, SEM menunjukkan dispersi filler yang cukup homogen dengan sedikit aglomerasi, sedangkan TGA menunjukkan dekomposisi pada 411,38–533,60°C. Hasil penelitian menunjukkan bahwa serbuk ban bekas berpotensi sebagai bahan pengisi TPE EPDM/PP dengan sifat mekanik dan stabilitas termal yang baik.

Kata kunci: *Compatibilizer*, Karet Sintetis EPDM, Polipropilena, Serbuk Ban Bekas, Termoplastik Elastomer.

1. Introduction

The automotive industry in Indonesia has experienced significant growth in recent years. Based on data from the Central Statistics Agency and the Electronic Registration and Identification System of the Indonesian National Police's Traffic Corps, the number of active vehicles in Indonesia is projected to reach 172.94 million units by the end of 2025. This trend has driven an increasing demand for automotive components with superior

mechanical performance and high durability, including impact-absorbing components on vehicle doors known as weather strips [1].

On the other hand, this growth in motor vehicles has led to an increase in used tire waste, which has become an environmental problem. Vehicle tires made of vulcanized rubber are extremely difficult to break down naturally and can persist in the environment for hundreds of years. Currently, the reuse of used tires is generally carried out through a process of retreading, known as vulcanization. However, this process can typically only be performed 2-3 times, meaning it can only handle 2% of the total used tire waste generated [2].

One way to utilize scrap tires is to process them into rubber powder, which is used as a filler in polymer composites. Scrap tire powder can replace up to 30% of inorganic fillers in EPDM composites without compromising performance, and it can accelerate the vulcanization process and improve the material's mechanical properties [3]. The presence of natural rubber, synthetic rubber, carbon black, and reinforcing materials in tires also makes scrap tire powder a promising filler for polymer composites [4]. The weatherstripping on vehicle doors plays a critical role in maintaining cabin comfort. The material used for weatherstripping must combine high elasticity, weather resistance, good recovery after deformation, and long-term durability [5].

One of the materials used to manufacture weatherstrips is thermoplastic elastomer, which combines the high elasticity of traditional vulcanized rubber with the good processability and recyclability of thermoplastics. In four-wheeled vehicles, the use of thermoplastic elastomers contributes to reduced vehicle weight, improved fuel efficiency, energy savings, and easier material recycling [6]. One widely used type of thermoplastic elastomer is Ethylene Propylene Diene Monomer (EPDM). EPDM is a synthetic rubber widely used in the automotive industry because it offers good resistance to ozone, weather, and extreme temperatures due to its chemically stable saturated chain structure. In addition, the presence of diene monomers allows for the formation of cross-links that can improve the material's stability. However, EPDM still has weaknesses in terms of elasticity and crack resistance, so it needs to be combined with other materials to improve its performance [7].

Polypropylene (PP), as a thermoplastic widely used globally, offers advantages in terms of ease of processing, low cost, and good mechanical properties. However, pure PP tends to have poor impact resistance, especially at low temperatures, and limited elasticity for applications such as impact absorbers. Therefore, blending PP with elastomers such as EPDM has been shown to significantly improve the material's toughness, including impact strength and elongation at break. While the gradual addition of EPDM to the PP matrix does reduce yield strength and elastic modulus, this actually indicates an increase in flexibility and toughness due to the presence of the soft phase of EPDM in the blend [8]

Although the blend of EPDM and PP offers certain advantages, the two materials have significant differences in polarity, resulting in low compatibility and negatively affecting the material properties. To address this, it is necessary to add a compatibilizer. One compatibilizer used is polypropylene modified with maleic anhydride (MA-PP), which has been proven effective in enhancing interactions between components in the blend system [9]. Thus, the use of recycled tire powder as a filler in EPDM/PP blends has the potential to serve as an environmentally friendly alternative that can reduce solid waste while producing composite materials with good mechanical performance for automotive applications.

Nevertheless, the incorporation of scrap or waste tire rubber into EPDM- and/or PP-based systems has been explored in earlier studies, though generally through matrix systems, filler types, and compatibilization strategies that differ from those adopted in the present work. In one case, waste EPDM rubber rather than tire powder was processed via ultrasonically aided twin-screw extrusion at a PP/EPDM ratio of 75:25, without the use of a PP-g-MA compatibilizer [10]. In another, waste tire powder was combined with a PP-g-MA compatibilizer, but within a commercial thermoplastic vulcanizate (Santoprene) matrix rather than an EPDM/PP blend formulated directly from raw rubber and polypropylene [11]. Elsewhere, a single PP matrix without an EPDM phase or compatibilizer was employed to examine the effect of tire powder particle size (12). Building on these findings, the present work specifically investigates a PP-g-MA-compatibilized EPDM/PP blend at a 70:30 ratio, reinforced with waste tire rubber powder at loadings of 5, 10, 20, 30, and 40 phr, and directed toward application as an impact-absorbing weatherstrip for vehicle doors a combination of system and application that has not previously been reported in the literature.

2. Research Methodology

2.1 Equipment

The equipment used in this study included an analytical balance, an oven, measuring cylinders, beakers, a motorized stirrer, thermometer, reflux apparatus, water pump, sieve shaker, aluminum foil, hot press, digital oil bath, D638-04 specimen molds, D256 specimen molds, Hung Ta-8041 impact testing, Shimadzu IR Prestige-21 FT-IR testing, Haida International tensile testing, Zeiss-Bruker EVO MA10 SEM, and Shimadzu DTG TGA.

2.2. Materials

Polypropylene, EPDM rubber, Benzoyl peroxide, Maleic anhydride, Paraffinic oil, Stearic acid, Sulfur, Dibenzothiazyl disulfide (MBTS), Zinc oxide, Xylene, Oil, Distilled water, Waste tire rubber powder was collected from PT Putra Arezda Purnama (PAP), located on Sisingamangaraja Road, KM 10, Medan Amplas.

2.3. Research Procedure

2.3.1 Preparation of Used Tire Powder

A total of 1,000 g of tire powder was cleaned and separated from textile and metallic components using a magnet, followed by sieving through a 100-mesh sieve. The powder was subsequently washed with distilled water to eliminate impurities. In the final stage, the sample was dried in an oven at 60 °C for 12 hours to remove residual moisture

2.3.2 Preparation of a Mixture of PP and Maleic Anhydride with the Addition of Benzoyl Peroxide

At this stage, 100 php PP was placed in a three-neck flask, and xylene solvent was added to the flask. A reflux apparatus was set up, and the mixture was heated using a digital oil bath until it reached a temperature of 170 °C. Next, 3 php of maleic anhydride was added to the mixture, which was then stirred for 15 minutes using a motorized stirrer to ensure the maleic anhydride is well dispersed. Once mixed, 2 php of benzoyl peroxide, acting as the reaction initiator, was added to the solution. The mixture was then refluxed for 90 minutes while being stirred using a motorized stirrer. Next, the mixture was poured into methanol. The resulting PP grafting precipitate was then dried to obtain PP-g-MA powder. It was subsequently characterized using FTIR spectroscopy to confirm the success of the grafting process through the identification of functional groups, and the degree of grafting was determined to assess the success rate of the grafting.

2.3.2.1 Determination of the Degree of Grafting of PP-g-MA

The degree of grafting was determined using a titration method. A total of 1 gram of PP-g-MA precipitate was refluxed with 100 mL of xylene until completely dissolved. After dissolution, 1 drop of water was added, and the mixture was refluxed again for 15 minutes. Next, 3 drops of phenolphthalein indicator were added to the solution, and it was titrated using 0.05 N KOH solution while hot. The titration was stopped when the solution turned rose red, indicating that the titration endpoint had been reached.

2.3.3 Preparation of EPDM/PP Rubber Composites with the Addition of Additives and waste tire rubber powder

At this stage, 30 phr of polypropylene was placed in a three-neck flask. It was then dissolved using xylene as the solvent. Next, a reflux setup was assembled, and the mixture was heated to 170 ℃ while being stirred with a motorized stirrer. At the same time, 70 phr of EPDM rubber was refluxed using xylene as the solvent at 170 ℃. Next, the mixture is refluxed at 170 °C and stirred using a motorized stirrer for 15 minutes. Then, 5 phr of PP-g-MA is added and stirred until homogeneous. Next, 5 phr of ground scrap tire filler is added and stirred until homogeneous. Then, 2 phr of paraffinic oil is added and stirred for 4 minutes. Next, 1.5 phr of stearic acid was added and stirred for 4 minutes. Then, 5 phr of ZnO was added and stirred for 4 minutes. After that, 1 phr of MBTS was added and stirred for 2 minutes. Finally, 1 phr of sulfur was added and stirred for 2 minutes. Next, the mixture was molded using a hot press with ASTM D638 and ASTM D256 molds at 185 ℃ for 20 minutes, then cooled to room temperature. The same procedure was performed to compare filler levels of 10, 20, 30, and 40 phr of recycled tire powder. The resulting composites were then characterized to determine their physical and mechanical properties.

2.3.4 Characterization of the Optimal EPDM/PP Compound with waste tire rubber powder

The optimal EPDM/PP blend with waste tire rubber powder was then analyzed using FTIR, SEM, and TGA.

2.4. Characterization of the Composite

2.4.1Tensile Strength Test

Tensile strength testing was conducted using an Autograph-type *Universal Testing Machine*, in accordance with the ASTM D638 standard. The test was performed at a pull speed of 50 mm/minute with a maximum load of 100 kgf. Prior to testing, the Torsee Electronic System was turned on and left active for approximately one hour to ensure stability. Next, the test specimens were clamped using the machine's grips. Afterward, parameters for stress and strain along with their units of measurement were adjusted. The testing process began by pressing the start button, and the machine would pull the specimen until failure (breakage) occurred. After the specimen broke, the load value and elongation (stroke) displayed by the machine were recorded. This procedure is repeated for each specimen. Based on the load and strain data obtained, the tensile strength and elongation of each sample are then calculated using the following Equations 1 and 2:

$$\sigma = \frac{F}{A_0} \quad (1)$$

Explanation:
σ = Stress (N/mm²)
F = Force (N)
A = Initial cross-sectional area (mm²)

$$\varepsilon = \frac{\Delta L}{L_0} \quad (2)$$

Explanation:
ε = Strain
ΔL = Increase in length (m)
Lo = Initial length (m)

2.4.2 Impact Test

The impact test was conducted using the Charpy impact test method with a pendulum hammer at an initial angle of 160°. Rectangular specimens, each 60 mm long, were prepared in accordance with ASTM D256 and mounted on the test fixture with a distance of 40 mm between the supports. Before testing the sample, a blank test was performed to determine the energy lost due to external factors such as pendulum shaft friction and air resistance, as a correction to the total system energy. The hammer was then released to strike the specimen until it cracked or broke, and the absorbed energy was recorded via the needle indicator on the instrument's scale as a representation of the material's toughness against impact loads. The amount of energy used to break the specimen is calculated using the Equation 3:

$$E = W \times R \times g[\cos\beta - \cos\alpha] \quad (3)$$

Explanation:
E = Impact energy (J)
W = Weight of the hammer (kg)
R = Pendulum arm length (m)
β = Final angle of the pendulum
α = Initial angle of the pendulum

The impact value can be calculated using the following Equation 4:

$$HI = \frac{EI}{A_0} \quad (4)$$

Explanation:
HI = Impact value (J/m²)
E = Energy required to fracture the material (J)
A0 = Smallest cross-sectional area of the notch (m^2)

2.4.3 Aging Analysis

The aging test was conducted in accordance with SNI 06-1490-1989 by heating the specimens in an oven at a constant temperature of 70 °C for 7 consecutive days. After the heating process was completed, the specimens were removed from the oven and allowed to stand at room temperature until they reached a stable condition. Subsequently, a tensile strength test was conducted to determine changes in the mechanical properties, particularly elongation at break, following the aging treatment. The results were used to evaluate changes in the mechanical properties of the material after thermal aging and to assess its compliance with the requirements specified in SNI 06-1490-1989.

2.4.4 Morphological Analysis Using Scanning Electron Microscopy

Microscopic observations were conducted using Scanning Electron Microscopy (SEM). In the initial stage, the samples were coated with a mixture of gold and palladium in a vacuum chamber at a pressure of 0.2 Torr using a JFC1100-type ion sputter. After the coating process was complete, the sample was placed in a special chamber and exposed to an electron beam at a voltage of 10 kV. The interaction of the electrons with the sample surface triggered the emission of secondary electrons and reflections, which were then detected by a Scintillator detector. The received signal is amplified using an electronic circuit, forming an image on a Cathode Ray Tube (CRT) screen for approximately 4 minutes. Next, the sample which has been coated with a 400 Å-thick layer is inserted into the specimen chamber of the SEM for imaging. The magnification level of the resulting images can be adjusted as needed.

2.4.5 Thermal Analysis Using Thermogravimetric Analysis

Characterization analysis was performed using the thermogravimetric method with a Shimadzu DTG-type Thermogravimetric Analysis (TGA) instrument. The samples were tested by gradual heating, during which changes in sample mass were recorded as the temperature rose. These weight changes could be monitored directly through the resulting thermograms, allowing the decomposition peaks in the samples to be identified.

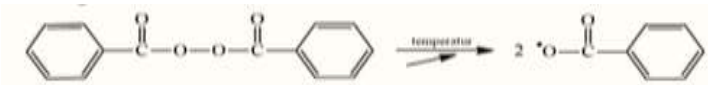
3. Results and Discussion

3.1 Reaction Mechanism

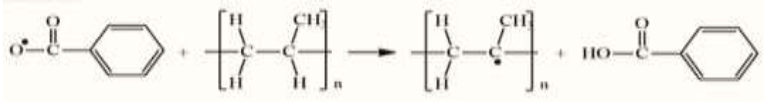
3.1.1 Reaction Mechanism for the Formation of PP-g-MA

Polypropylene is a long-chain polymer (macromolecule) formed through a polymerization process. In systems containing peroxide initiators, such as benzoyl peroxide (BPO), polypropylene can undergo degradation in the form of main-chain scission, particularly at high temperatures. The reaction mechanism for the formation of PP-g-MA is shown in Figure 1.

Peroxide Decomposition

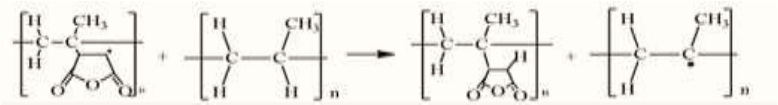


Initiation



Propagation

Chain Transfer



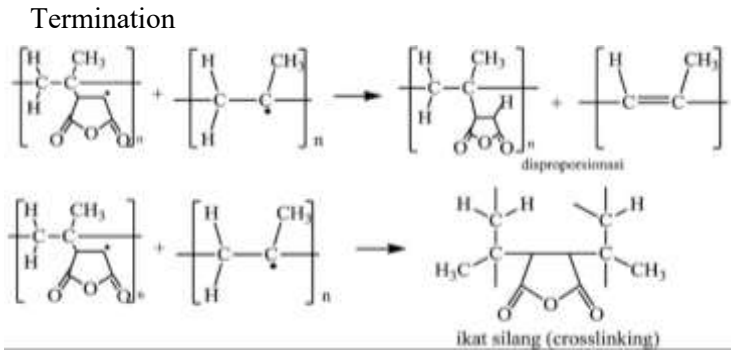


Figure 1. Reaction Mechanism for the Formation of PP-g-MA

In the initial stage of the reaction, BPO undergoes homolytic decomposition to produce a free radical (RO•). This radical then abstracts a hydrogen atom from the polypropylene main chain, forming a tertiary macromolecular radical (3P•). This degradation process aims to shorten the polymer chain and reduce the molecular weight of polypropylene, thereby increasing its reactivity toward maleic anhydride. Consequently, maleic anhydride can bond to the polymer's main chain and form a graft copolymer, namely PP-g-MA (10).

3.2 Reaction Mechanism of Adding Used waste tire rubber powder as a Filler

The interaction between polypropylene as the polymer matrix and recycled tire powder as the filler can affect the properties of the resulting composite. In this study, PP-g-MA was used as a compatibilizer to improve compatibility between the PP matrix and the waste tire rubber powder. The addition of PP-g-MA helped improve the dispersion of the filler within the polymer matrix and reduce particle agglomeration, thereby improving the interfacial bonding between the materials. The mechanism of interaction between PP-g-MA and waste tire rubber powder is shown in Figure 2.

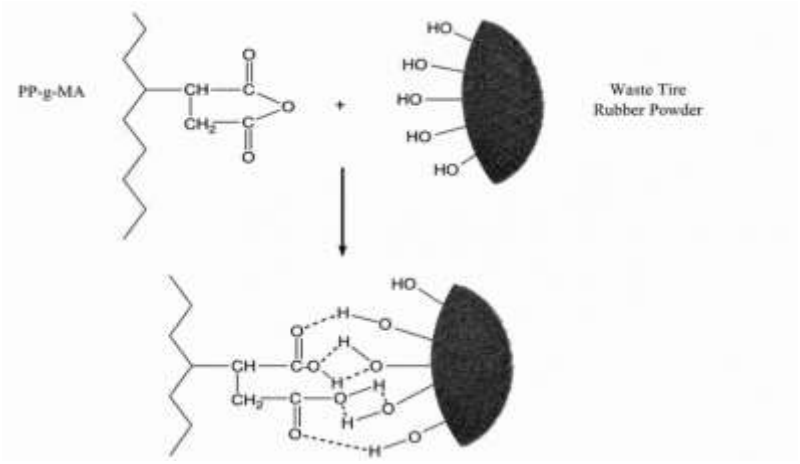


Figure 2. Interaction of PP-g-MA with waste tire rubber powder

The interaction of PP-g-MA as a compatibilizer in a system of PP and tire powder occurs through the maleic anhydride groups on the PP-g-MA interacting with the hydroxyl (-OH) groups present on the surface of the used waste tire rubber powder, while the PP chain segments of the PP-g-MA interact with the PP matrix. Thus, PP-g-MA acts as a bridge connecting the recycled tire powder to the PP matrix, thereby increasing the interfacial adhesion between the two and ensuring a more uniform dispersion of the tire powder particles within the matrix. Additionally, the presence of maleic anhydride groups increases the system's polarity and enhances compatibility between the PP phase and the recycled tire powder. This enhanced interfacial interaction contributes to the improvement of the composite's mechanical properties [11].

3.3 Reaction Mechanism of Sulfur Vulcanization in EPDM Rubber

The sulfur vulcanization process in EPDM/PP composites occurs through a series of chemical reactions that produce crosslinks between polymer chains. The formation of these crosslinks is influenced by the vulcanization system, which consists of sulfur, accelerators, activators, and other supporting materials. The reaction mechanism of sulfur vulcanization in EPDM is schematically presented in Figure 3.

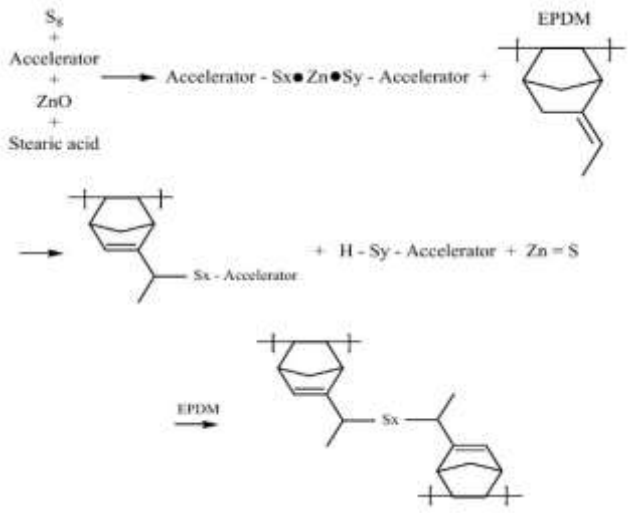


Figure 3. Reaction mechanism of sulfur vulcanization in EPDM

The sulfur vulcanization process of EPDM rubber begins with the formation of an active compound from a mixture of MBTS accelerator, ZnO, stearic acid, and sulfur (S_8). This active compound acts as a linker in the cross-linking reaction. The active compound then attacks the double bonds in the diene groups on the EPDM chains, causing the double bonds to open and allowing sulfur to attach to the polymer chains. The sulfur that has attached to one EPDM chain then reacts with other surrounding EPDM chains, forming cross-links in the form of sulfur bonds ($–S_x–$) that connect the polymer chains. It is these cross-links that make EPDM rubber stronger, more elastic, and more resistant to heat and pressure [12].

3.4 Determination of the PP-g-MA Grafting Degree

The degree of PP-g-MA grafting was determined by titration using a 0.05 N KOH solution with phenolphthalein as an indicator. This determination was performed to assess the success of maleic anhydride group grafting onto the polypropylene chain. The degree of grafting was calculated based on the following acid number (Equation 5 and 6):

For a volume of KOH used of 2.79 mL and a precipitate weight of 1 gram, then the following is obtained:

$$\text{Acid Number} = \frac{2.79 \times 0.05 \times 56.1}{1} = 7.83 \quad (5)$$

$$\text{Grafting Degree} = \frac{7.83 \times 98}{2 \text{ x } 56.1} = 6.84\% \quad (6)$$

The grafting degree of 6.84% indicates that maleic anhydride was successfully grafted onto the polypropylene chain via a free-radical mechanism initiated by peroxide, thereby enabling the formation of polar groups on the PP main chain. The success of this grafting process is supported by the FTIR characterization results in Table 4, which show the appearance of a new peak at a wavenumber of 1714.5 cm^{-1} corresponding to the carbonyl group (C=O) and a wavenumber of 1162.9 cm^{-1} corresponding to the vibration of the C–O group of maleic anhydride, indicating the formation of new functional groups that enhance the polar properties of polypropylene [10].

3.5 Analysis of Mechanical Properties

3.5.1 Tensile Strength Analysis

Tensile strength testing is conducted to measure a material's ability to withstand tensile loads until deformation or fracture occurs. In this study, tensile strength testing was performed on a mixture of EPDM and polypropylene with recycled tire powder added as a filler, and the test results were obtained. The results of the tensile strength testing are presented in Table 1.

Table 1. Results of mechanical property testing of EPDM/PP/waste tire rubber powder

No	EPDM:PP (Phr)	Waste Tire Rubber Powder (phr)	Tensile Strength (MPa)	Elongation at Break (%)	Elastic Modulus (MPa)
1	70:30	0	5.8964	12.02	49.0549
2	70:30	5	6.0009	12.25	48.9869
3	70:30	10	8.0267	24.4	32.8963
4	70:30	20	10.9903	23.76	46.2554
5	70:30	30	8.0411	20.68	38.8835
6	70:30	40	4.8472	10.22	47.4285

From Table 1 above, it can be seen that the EPDM/PP blend without the addition of scrap tire powder exhibits a tensile strength of 5.8964 MPa, an elongation of 12.02%, and a modulus of elasticity of 49.0549 MPa. After adding 5 phr of recycled tire powder, the tensile strength increased to 6.0009 MPa. A more significant increase occurred with the addition of 10 phr and reached an optimum value at 20 phr, namely 10.9903 MPa with an elongation of 23.76% and a modulus of elasticity of 46.2554 MPa.

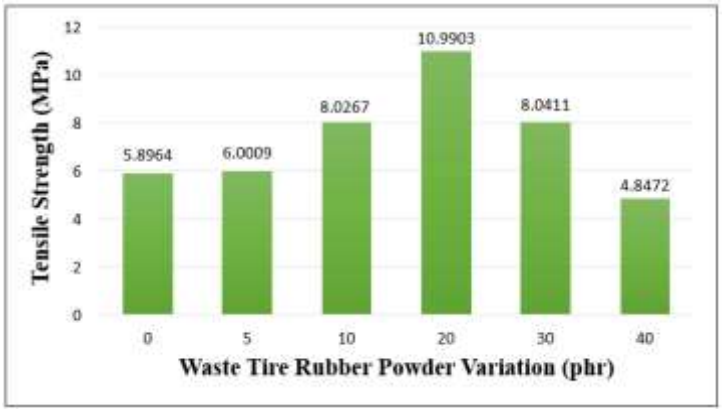


Figure 4. Bar Chart of Tensile Strength (MPa) before Aging

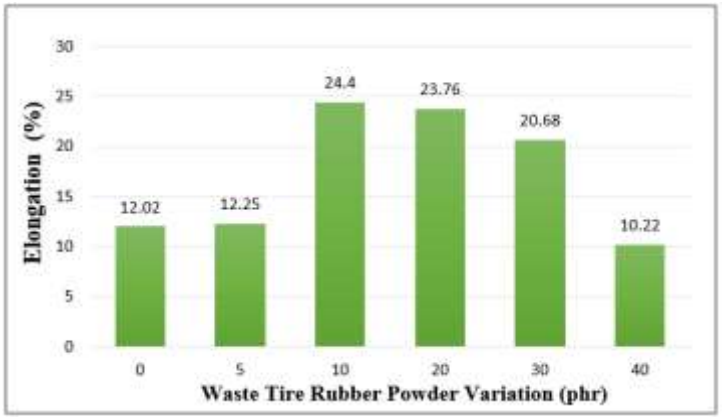


Figure 5. Bar Chart of Elongation (%) Before Aging

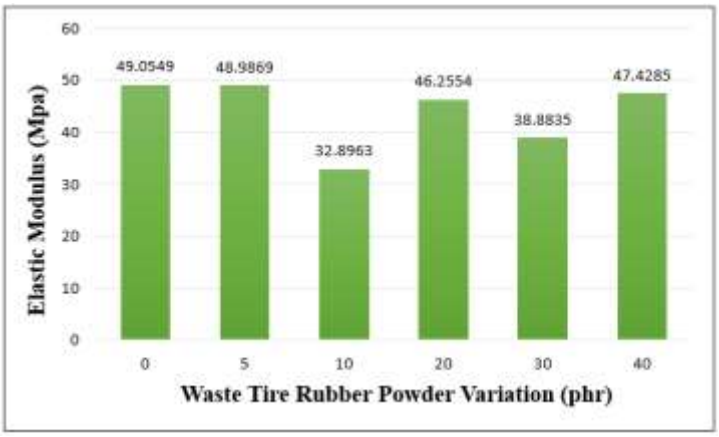


Figure 6. Bar Chart of Elastic Modulus (MPa) before Aging

Based on the bar charts in Figures 4, 5, and 6, the addition of recycled tire powder to the EPDM/PP blend showed a trend of increasing tensile strength up to a composition of 20 phr, the optimal condition, with a value of 10.9903 MPa, which meets the tensile strength requirement of SNI 06-1490-1989. This improvement is attributed to the recycled tire powder, derived from vulcanized rubber, possessing stable cross-links that act as a reinforcing agent, supported by the role of PP-g-MA as a compatibilizer that improves interfacial adhesion between EPDM, polypropylene, and the filler, resulting in more uniform particle distribution. However, at 30 phr and 40 phr, tensile strength decreases due to excessive particle agglomeration, resulting in non-homogeneous distribution and the formation of weak interfacial bonds, which hinder load transfer and reduce tensile strength [13]. In terms of elongation, the value obtained at 20 phr (23.76%) does not meet the standard's minimum requirement of 200% specified in SNI 06-1490-1989.

3.5.2 Aging Analysis

Aging tests are conducted to assess the extent to which a material's mechanical properties specifically tensile strength and elongation deteriorate as a result of the aging process over a specific period of time. This process is essential for determining the material's resistance to environmental conditions such as heat and oxidation, which can accelerate the degradation of the polymer structure. The simulated aging in this test is intended to represent the material's long-term service conditions in an accelerated manner, thereby providing insight into the material's service life and stability in actual applications. Changes in the tensile strength and elongation values before and after aging can also serve as indicators for evaluating the effectiveness of the filler composition in maintaining the material's mechanical properties against the effects of thermal and oxidative degradation. The tensile test results obtained after the aging process are shown in Table 2.

Table 2. Results of mechanical property testing of EPDM/PP/waste tire rubber powder blends after aging

No	EPDM:PP (Phr)	Waste Tire Rubber Powder (phr)	Tensile Strength (MPa)	Elongation at Break (%)	Elastic Modulus (MPa)
1	70:30	0	3.1612	7.826	40.4245
2	70:30	5	4.8627	10.38	46.8468
3	70:30	10	5.2917	10.65	49.6873
4	70:30	20	5.6893	16.67	34.1289
5	70:30	30	5.1674	10.78	47.9351
6	70:30	40	2.945	12.24	24.0604

Table 2 shows that all samples exhibited a decrease in tensile strength; specifically, the EPDM/PP blend without added scrap tire powder showed a decrease in tensile strength to 3.1612 MPa, an elongation value of 7.826%, and a modulus of elasticity of 40.4245 MPa. Meanwhile, the compound with 20 phr of recycled tire

powder showed a decrease in tensile strength to 5.6893 MPa, an elongation value of 16.67%, and a modulus of elasticity of 34.1289 MPa.

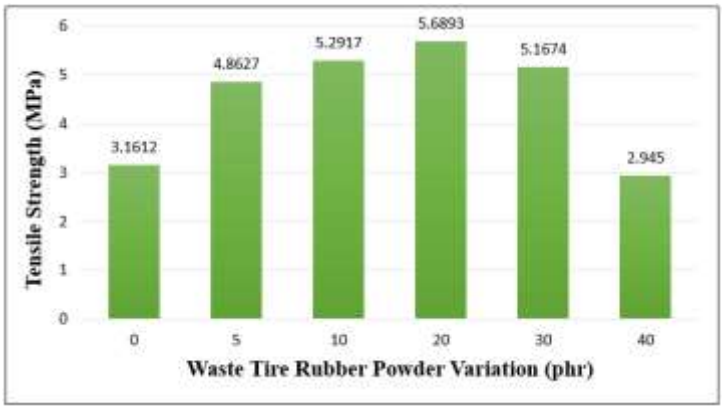


Figure 7 Bar Chart of Tensile Strength (MPa) after Aging

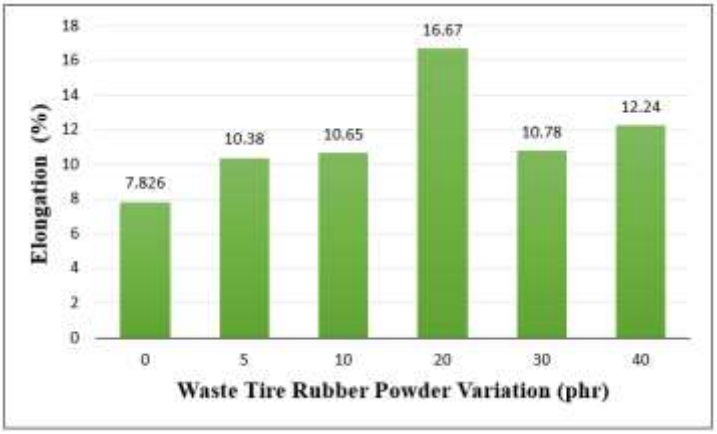


Figure 8. Bar Chart of Elongation (%) after Aging

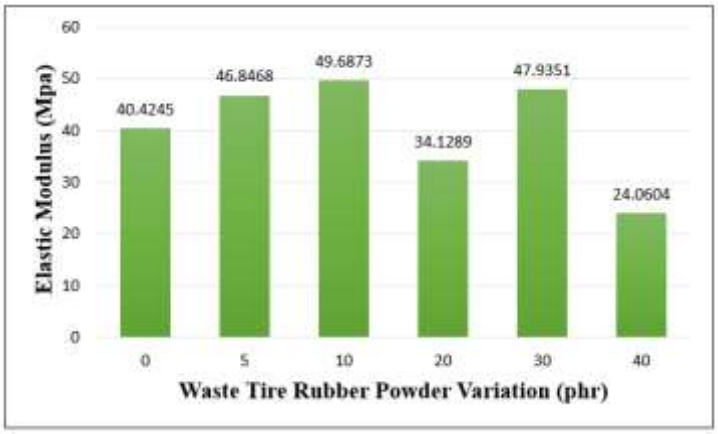


Figure 9. Bar Chart of Elastic Modulus (MPa) after Aging

Based on the test results in Figures 7, 8, and 9, the aging process reduces the mechanical properties of the material, as indicated by changes in tensile strength and elongation values, due to the oxidative degradation of the rubber caused by exposure to oxygen, heat, ultraviolet light, and ozone during the aging process. During aging, free radicals in the polymer matrix react with oxygen, triggering simultaneous chain scission and post-crosslinking; chain scission dominates in the early stages and is followed by continued crosslinking as the aging period extends, causing the rubber material to become harder and more brittle [14].

3.5.3 Impact Strength Analysis

Impact strength testing was conducted to evaluate a material's ability to absorb energy until cracking or failure occurs due to an impact load, while also illustrating the material's level of impact resistance. The testing

was performed on EPDM/PP blends with added scrap tire powder in various compositions, with the results presented in Table 3.

Table 3. EPDM/PP/ Waste Tire Rubber Powder Impact Strength Test Results

No	EPDM : PP (Phr)	Waste Tire Rubber Powder (phr)	Impact Strength (J/m²)
1	70:30	0	7,940.889
2	70:30	5	12,019.138
3	70:30	10	12,720.266
4	70:30	20	12,906.220
5	70:30	30	10,441.937
6	70:30	40	5,550.156

Table 3 shows that the EPDM/PP blend without the addition of scrap tire powder has an impact strength of 7,940.889 J/m². With the addition of filler, the impact strength value increased gradually until it reached its highest value at 20 phr, which was 12,906.220 J/m². This indicates that the presence of recycled tire powder can improve the material's toughness by aiding in the absorption and distribution of impact energy within the matrix. However, beyond that composition, the impact strength decreases with the addition of 30 phr and 40 phr of recycled tire powder, to 10,441.937 J/m² and 5,550.156 J/m², respectively. The impact strength test graph for the EPDM/PP blend with added tire powder filler is shown in Figure 10.

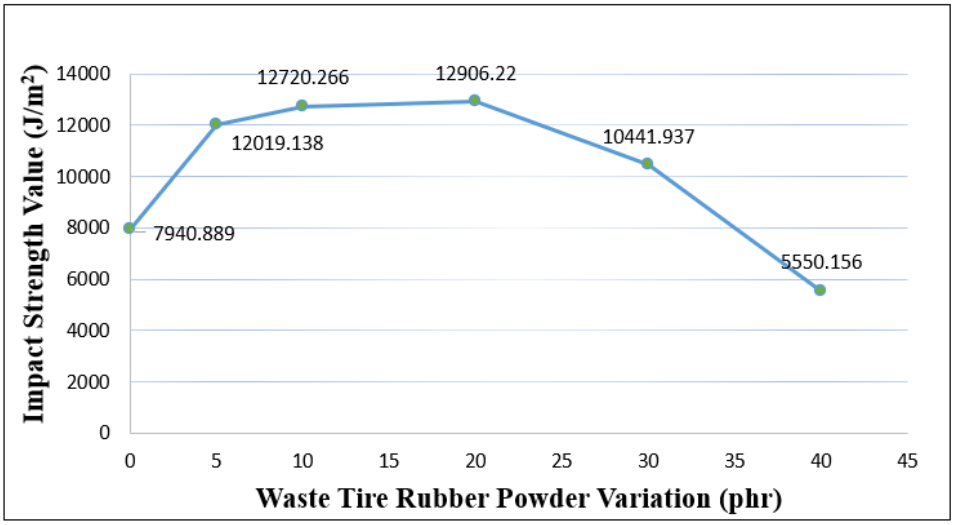


Figure 10. Impact Strength Graph

Based on Figure 10, the impact strength reached a maximum value of 12,906.220 J/m² at 20 phr, then decreased to 10,441.937 J/m² at 30 phr, and further decreased to 5,550.156 J/m² at 40 phr. This decrease is caused by the agglomeration of used tire powder particles due to an excess of filler, resulting in an uneven distribution, creating stress concentration points, and reducing interphase adhesion. The addition of excess filler also reduces the material's elasticity, making it more brittle due to reduced plastic deformation, thereby decreasing its ability to absorb impact energy [15].

Considering the combined trends of tensile strength, elongation at break, elastic modulus, and impact strength, the selection of 20 phr as the optimum filler loading was established by evaluating all four mechanical parameters rather than tensile strength alone. At 20 phr, the tensile strength reached the highest value among the investigated formulations (10.9903 MPa), while the impact strength also reached its highest value (12,906.220 J/m²). This indicates that the 20 phr formulation provided the most favorable balance between load-bearing capacity and energy-absorption capability among the compositions investigated. Although the elongation at break at 10 phr (24.40%) was slightly higher than that at 20 phr (23.76%), the tensile strength at 10 phr was considerably lower (8.0267 MPa), while its elastic modulus (32.8963 MPa) was also lower than that of the 20 phr formulation (46.2554 MPa). At higher filler contents, the simultaneous decrease in tensile strength, elongation at break, and impact strength at 30 and 40 phr indicates that excessive waste tire rubber

powder loading negatively affected the mechanical performance of the composite. Therefore, 20 phr was selected as the optimum formulation for further characterization by FTIR, SEM, and TGA.

3.5.4 Functional Group Analysis Using Fourier Transform Infrared (FTIR) Spectroscopy

FTIR analysis was conducted to identify the functional groups present in PP-g-MA and in the EPDM/PP blend with the addition of recycled tire powder at the optimal composition. In addition, the obtained FTIR spectra were compared with those of EPDM, PP, and EPDM/PP blends without the addition of filler. The absorption spectra of each FTIR sample are shown in Figure 11.

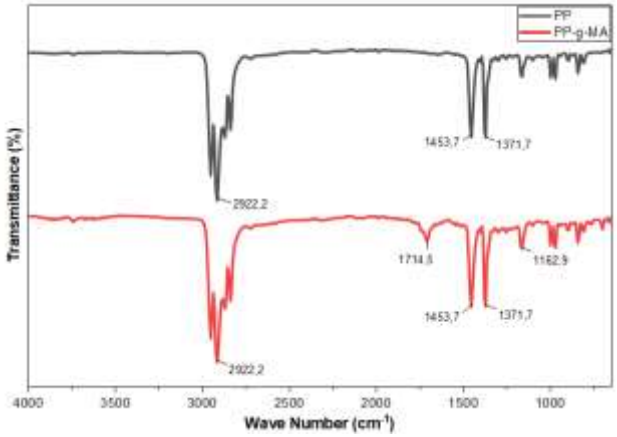


Figure 11. FTIR Absorption Spectra of PP and PP-g-MA

The appearance of a new absorption band at 1714.5 cm^{-1} in the PP-g-MA spectrum confirms the successful grafting of maleic anhydride onto the polypropylene chain. This band is attributed to the C=O stretching vibration of the carboxylic acid group formed as a result of the partial hydrolysis of the grafted maleic anhydride group. The characteristic PP bands at 2922.2, 1453.7, and 1371.7 cm^{-1} remained detectable without significant shifts, indicating that the main structure of polypropylene was preserved during the grafting process. The success of the grafting was also supported by a grafting degree of 6.84%, indicating the formation of PP-g-MA as an effective compatibilizer for improving compatibility and interfacial adhesion in EPDM/PP composites [16].

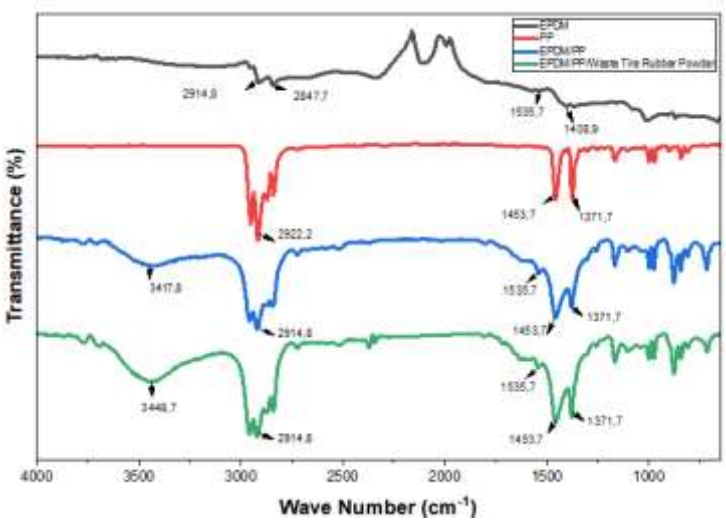


Figure 12. FTIR Absorption Spectra of EPDM, PP, EPDM/PP, and EPDM/PP/20 phr Waste Tire Rubber Powder

The FTIR spectra of all samples (EPDM, PP, and EPDM/PP blends) showed relatively similar absorption band patterns, with the appearance of characteristic polyolefin bands such as C–H stretching, CH_2, and CH_3 (1453.7 and 1371.7 cm^{-1}), as well as C=C/C–S at 1535.7 cm^{-1}, which indicates cross-linking with sulfur, suggesting that the basic structure of the polymer matrix did not change significantly as a result of blending EPDM and PP. In the composite without scrap tire powder (0 phr), an O–H band appears at 3417.8 cm^{-1} resulting from the reaction between stearic acid and ZnO during vulcanization (producing zinc stearate and water as byproducts), rather than from the nonpolar EPDM/PP structure, whereas in the composite with 20 phr of scrap tire powder, the intensity of the O–H band increased (3448.7 cm^{-1}) due to the surface oxidation of the scrap tire powder during aging and the mechanical grinding process; these –OH groups are stable and do not

disappear even after washing and drying, as these treatments only remove free water from the surface. The absence of new functional groups, aside from the shift in the O–H band, indicates that the addition of scrap tire powder to the EPDM/PP matrix is a physical *blending process* without the formation of new chemical bonds, since the scrap tire powder has been vulcanized, thus limiting its chemical reactivity [17].

3.5.5 Thermal Analysis Using Thermogravimetric Analysis (TGA)

TGA analysis was performed to evaluate the thermal stability of the EPDM/PP composite by observing changes in mass as the temperature increased over the range of 30–600°C at a rate of 40°C/minute in a nitrogen atmosphere. Based on Figures 13 and 14, both the EPDM/PP blend without filler and the blend with 20 phr of waste tire rubber powder exhibit a single decomposition stage characterized by a significant mass loss at a specific temperature range; the decomposition temperatures for each sample are presented in Table 3.4.

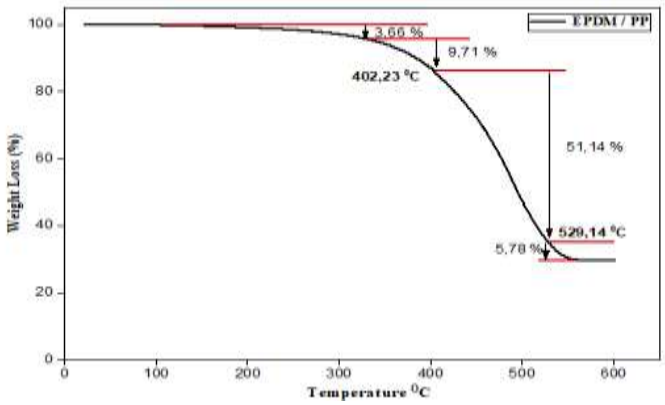


Figure 13. Thermogram of EPDM/PP

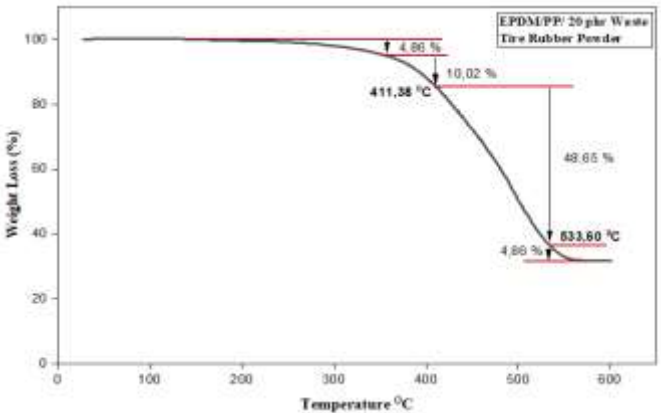


Figure 14. Thermogram of EPDM/PP/20 phr Waste Tire Rubber Powder

Table 4. Results of TGA Analysis of EPDM/PP and EPDM/PP/20 phr Waste Tire Rubber Powder

No	Sample	Decomposition		Weight loss (%)	Char residue (%)
		Onset (°C)	End set (°C)		
1	EPDM/PP	402.23°C	529.14°C	70.296 %	29.703 %
2	EPDM/PP/ Waste Tire Rubber Powder 20 phr	411.38°C	533.60°C	68.395%	31.605 %

Based on Table 4, the EPDM/PP blend decomposed at temperatures ranging from 402.23 to 529.14°C, with a weight loss of 70.296%, whereas the EPDM/PP blend with 20 phr of recycled tire powder decomposed at a higher temperature range of 411.38–533.60°C with a lower weight loss of 68.395%. The weight loss in EPDM/PP is caused by the release of trapped gas and water, the evaporation of volatile compounds due to PP chain scission, and the breakdown of the EPDM cross-linked network, which occurs gradually due to overlapping degradation zones [18]. The increase in onset temperature and char residue (31.605%) at 20 phr is associated with the composition of the scrap tire powder itself, which consists of a mixture of

natural/synthetic rubber, carbon black, and other residues [4]. Carbon black restricts the diffusion of volatile degradation products and promotes char formation, while the rubber fraction in the tire powder decomposes within a temperature range that overlaps with the EPDM/PP matrix, as shown by the single decomposition stage observed in the thermogram. This indicates that the improved thermal stability results from the combined contribution of the various components present in the waste tire rubber powder.

3.5.6 Morphological Analysis Using a Scanning Electron Microscope (SEM)

Scanning Electron Microscopy (SEM) analysis was performed to observe the surface morphology of the composite fracture and to evaluate the degree of homogeneity, phase dispersion, and the quality of the interfacial bonds formed between the material's constituent components. The SEM results are shown in Figure 15.

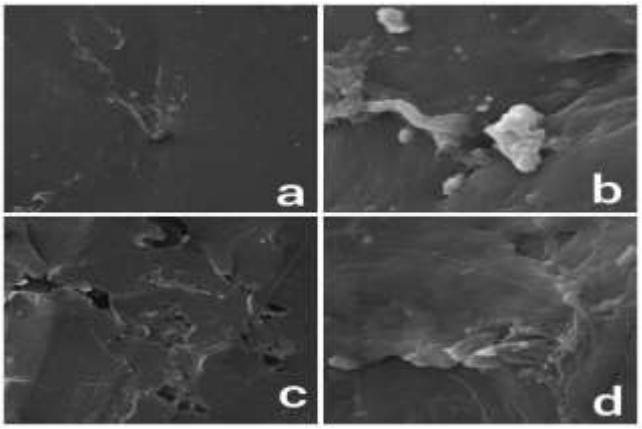


Figure 1. SEM images of EPDM/PP at 100x magnification (a) and 5,000x magnification (b); SEM images of EPDM/PP/20 phr waste tire rubber powder at 100x magnification (c) and 5,000x magnification (d)

The SEM images in Figures 15(a) and (b) show that the EPDM/PP composite without recycled tire powder has a smooth, even, and homogeneous fracture surface without agglomeration, voids, or significant cracks, indicating good mixing of EPDM and PP as well as a homogeneous phase distribution. The presence of PP-g-MA as a compatibilizer enhances interfacial adhesion between the two phases, thereby reducing phase separation, which contributes to the composite's ability to withstand plastic deformation before fracture [11].

In Figures 15(c) and (d), the composite with 20 phr of waste tire rubber powder exhibits a rougher surface, with the scrap tire powder particles dispersed and embedded in the matrix, indicating fairly good interfacial interaction, although small voids still exist due to the hydrophobic nature of the scrap tire powder, which prevents fully optimal compatibility. This interaction nevertheless allows for effective stress transfer and inhibits crack propagation, thereby enhancing the composite's ability to absorb impact energy and yielding high impact strength values [19].

4. Conclusion

Based on this study, it can be concluded that the optimal filler content of used waste tire rubber powder in the production of EPDM/PP blends is 20 phr. This blend yields tensile strengths of 10.9903 MPa (before) and 5.6893 MPa (after aging), elongation of 23.76% and 16.67%, and an impact strength of 12,906.220 J/m², with the tensile strength meeting the requirement of SNI 06-1490-1989, whereas the elongation at break did not meet the standard's minimum requirement. FTIR analysis results showed an increase in the intensity of the O-H group at 3,448.7 cm^{-1} due to the oxidative degradation of the scrap tire powder; SEM analysis revealed a relatively homogeneous morphology with fairly even dispersion of the filler material despite some agglomeration; and TGA analysis indicated decomposition in the temperature range of 411.38–533.60°C with a mass loss of 68.395% and a char residue of 31.605%.

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