Research Article

Evaluating the Physical and Mechanical Properties of PET and Crumb Rubber Compounds for Tire Tread Applications

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Abstract

In the present study, two types of polymer materials are utilized: PET and crumb rubber. The PET material is used in the production of water bottles and crumb rubber (produced from recycled tires) for manufacturing the Tread part for passenger cars. The study utilizes a master batch compound prepared by the Babylon Tires Factory in Iraq to prepare laboratory final compounds using various experimental techniques. Extensive tests were conducted on rubber samples, including vulcanization process time (T90 and Ts2), specific gravity, hardness test, viscosity test, tensile strength test, torque test, abrasion test, and fatigue test. According to the test results, two compounds that confirmed to the company's standards were selected. Twelve samples of compounds are prepared and divided into two groups (A and B), each containing six compounds. In group (A), the amount of PET is stabilized with the rest of the additives added and the amount of crumb rubber. The group (B) amount of crumb rubber is stabilized with the rest of the other additions and the amount of PET. The test results of the compounds are compared with the standard specifications of Dunlop technology used in the rubber and tire industry. The results show that sample no. (2) From group (B) is the best sample for the abrasion value while maintaining the result of properties within the limits specified. The PET and crumb rubber amount should not exceed (1.3/2.5) pphr, in which the maximum tensile strength and hardness can be obtained with minimum cure characterization time. By tailoring PET-rubber ratios, the research enhances mechanical strength, thermal stability, and durability while promoting the recycling of plastic and rubber waste.

Keywords: Crumb rubber, Experimental tests, Mechanical properties, PET/rubber Composites, Tread part

1 Introduction

Pollution has emerged as a critical environmental issue, drawing increasing attention from governments across the globe since the mid-twentieth century. Recognized as one of the most urgent ecological challenges, its impact spans environmental, economic, and social domains. The situation worsened notably following the European Industrial Revolution, which was marked by rapid industrial growth fuelled by advancements in modern technology. In contemporary times, the diversification and complexity of industrial activities have intensified, giving rise to severe pollution that poses significant threats to the stability and health of the biosphere. The need has emerged to recycle industrial waste because this method contributes to waste disposal, as well as reducing production costs and the consumption of natural resources. In 2020, global plastic production exceeded 367 million tonnes. Efforts to reduce this volume have increasingly been linked to the principles of the circular economy, which emphasize reuse and recycling as key strategies to enhance the sustainability of materials at the end of their lifecycle. Researchers have aligned circular economy practices with sustainability assessments to support and evaluate the effectiveness of such approaches in managing plastic waste. Among widely used plastics, polyethylene terephthalate (PET) stands out for its mechanical strength, resilience, and ease of recycling, making it suitable for a broad range of industrial and consumer applications. It is commonly seen in everyday items like plastic bottles, clothing, and food containers. PET is a transparent material that is lightweight and resistant to impact due to its non-crystalline state. It is often used to manufacture bottles intended for water and non-alcoholic beverages [1]. It is used to manufacture bottles, food packaging, cosmetics, household appliances, mechanical engineering, safety belts, medical materials for agriculture, and thermoplastic applications [2]–[4]. Global production of PET exceeds 60%, and 30% of the worldwide output is used to manufacture synthetic textile fibers [5]. In 2016, the annual global production of polyethylene terephthalate (PET) was estimated to be around 56 million tonnes [6]. However, improper disposal of substantial quantities of PET waste can lead to significant environmental degradation.

In 2011, Nabil and his colleagues added polyethylene terephthalate to a natural rubber batch as a filler material. Their findings indicate that increasing the concentration of polyethylene terephthalate increases the crosslink density between the polymer chains and affects the vulcanization properties. This is because increasing the concentration leads to an increase in the maximum moment (MH), the ripening time (ts2), and the vulcanization time (t90). Also, the increase in the concentration of polyethylene terephthalate affects the mechanical properties of the batch, as it increases the tensile modulus and reduces the tensile strength, elongation at break, and fatigue life [7]. In Cazan *et al*. [8], mixed waste tire rubber with PET and high-density polyethylene and found that PET was essential in improving tensile properties and impact strength. Moreover, Razavizadeh and Jamshidi [9] studied the adhesion of nitrile rubber (NBR) to polyethylene terephthalate (PET), considering surface modification by methylene diphenyl di-isocyanate (MDI). In Rahimi *et al*. [10], a sustainable method was explored for recycling waste tire rubber and polyethylene terephthalate (PET) to develop eco-friendly concrete with enhanced resistance to sulfuric acid corrosion. Also, Leng *et al*., [11] examined chemically recycling waste PET and incorporating it into crumb rubber-modified asphalt. Due to its flexible, resilient, and resistant properties, rubber is indispensable across various industries, including automotive, construction, healthcare and medical, agriculture, sports, and leisure [12]–[14]. Recycled crumb rubber, derived from waste tires, is an effective filler that not only reduces waste but also contributes to the mechanical properties of rubber composites. Research indicates that the inclusion of recycled rubber can improve flexibility and impact resistance, making it suitable for various applications, including automotive and construction materials [15]–[17]. Composite materials are formed by combining two or more different constituents to produce a material that exhibits enhanced properties compared to those of the individual components. As much as possible, each component material should be combined to maximize its strengths, flexibility, durability, and lightness while minimizing its drawbacks. Composite materials have become essential in industries that demand high performance, weight reduction, and durability. Amid new technologies and manufacturing techniques, the applications of these materials continue to expand [18]–[20]. In rubber composites, rubber (usually elastomers like natural rubber, synthetic rubber, or thermoplastic elastomers) is combined with fibre, metals, ceramics, or fillers for reinforcement. By enhancing rubber's basic properties, such as flexibility, elasticity, and resilience, these composites enhance its performance. When rubber and reinforcing agents are combined, composite materials can achieve better properties, including strength, wear resistance, heat resistance, and weight reduction [21], [22].

During the life cycle assessment of an indoor PET/SBR carpet, Yasin *et al.*, [23] evaluated the effects of recycling binary polymer indoor carpets, incorporating a cradle-to-grave sustainability assessment and measuring microplastic atmospheric deposition over a defined usage period. In many PET/rubber composites, mixing polymeric fabric and rubber with reinforcement fillers significantly influences overall performance and durability [24]. Ameli *et al.*, [25] examined how anti-stripping agents, ground tire rubber, and PET affect the performance characteristics of binders and stone matrix asphalt mixtures. The findings indicated that incorporating these polymers improved binder elasticity, which in turn enhanced resistance to permanent deformation. It is evident from the above literature that studying the physical and mechanical properties of rubber composites is an important area of research in materials science and rubber composite engineering. Hybrid reinforcement materials typically combine two or more different types of reinforcement (e.g., carbon black, silica, aramid fibers, steel, or organic fibers) to improve the performance of rubber parts. Many researchers have reported the characteristics of using industrial waste fillers in polymers. These waste-based alternatives, such as crumb rubber and PET, are not only less expensive than traditional fillers but also significantly reduce the environmental impact. By choosing these fillers, we can satisfy the growing demand for fillers while being responsible and eco-conscious. In polymers or fibre reinforced polymers, these fillers enhance certain properties, reducing cost and improving performance. Unlike synthetic fillers, these fillers are composed of waste materials, which are either free or inexpensive [26], [27].

The research aims to study the physical and mechanical properties of the Tread compound of passenger car tires, such as hardness, viscosity, elongation, abrasion, and cure characteristics, after adding TPE and crumb rubber material in certain proportions as filler to the laboratory-prepared rubber batch. The potential impact of this study is significant, as the experimental results were analyzed to determine the optimal weight fraction that can be used to fabricate the Tread part of saloon car tires. While crumb rubber recycling and PET reinforcement have been studied separately, their combined effect on tire optimization has not been systematically explored. The main innovation of the study lies in integrating PET with crumb rubber to optimize tire compounds. This dual reinforcement approach not only improves tire performance (wear, hardness, adhesion) but also contributes to sustainability. It introduces a cost-effective, eco-friendly alternative to conventional tire formulations. The remainder of this paper is organized as follows: Section 2 describes the experimental work, including the materials used, the preparation of PET/rubber composite samples, and the mechanical testing procedures. Section 3 presents the results and discussion, including the mechanical properties test results. Finally, Section 4 concludes the paper with a summary of the key findings and suggestions for future work.

2 Materials and Methods

The study of tread compounds in passenger tires, especially those using hybrid reinforcements, holds significant promise for improving performance, durability, and sustainability. However, it faces challenges such as material complexity, variability, and the need for advanced testing and modeling. This section outlines the methodological approach employed in this study to investigate the characterization of physical and mechanical properties of Polyethylene Terephthalate (PET) composite samples reinforced with crumb rubber. The methodology, which encompasses both experimental and computational techniques, is designed to ensure a comprehensive and rigorous analysis of the composite materials. The flowchart in Figure 1 visually represents the methodological approach employed in this study. It outlines the sequential steps in the experimental and computational procedures, providing a clear understanding of the research process and reassuring the audience study's rigour.

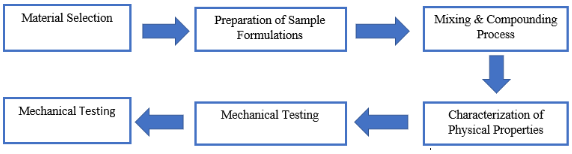

Figure 1: Flowchart methodological framework.

2.1 *Materials used*

This study used SBR 1502 (Styrene Butadiene Rubber, Reclaim, Zinc oxide (ZnO), Stearic acid, TMQ, 6PPD, Carbon black, Process oil, Sulphur, CBS, CTP-100, Polyethylene terephthalate (PET), and crumb rubber to fabricate rubber composite samples. Table 1 shows the details of the materials used. The experimental work has two sections. The first involves generating crumb rubber/PET composite samples by following the standard specification according to Dunlop technology. Second, the composite samples are characterized and tested under static and dynamic loads, and their mechanical properties are evaluated.

Table 1: The materials used physical properties.

Material	Specification	Supplier
ZnO	Purity =99.85%, size of particle =0.5-1μm, and surface area=3-5 m^2/gm	China
Cyclohexyl-Thio-Phthalimide (CTP-100)	Mass Density (1.44 g/cm3)	China
Carbon N660	Particle size (nm): 109, DBP: 90 (ml/100g), Surface area: 34 (m^2/g), Aggregate size:252 (nm)	Malaysia
PET	-	Iraq
SBR 1502	Working Temperature Range: -20°C to +70°C, Hardness (Shore A): 50° ± 5°, Abrasion Resistance: 125 mm^3, Elongation at Break: 300% – 900%, Density: 1.15 g/cm^3	Vietnam
Paraffinic Oil	Mass density 0.88 g/cm^3 at 20 °C), Viscosity:(8 cP)	Iraq
Rubber Antioxidant TMQ	-	Malaysia
Sulfur	-	Iraq
Benzothiazyl Disulfide MBTS	Melt Point: 172 °C, Moisture / Heat Loss, %: < 0.5, Ash, %: < 0.3, Specific Gravity: 1.5 Dispersibility: Good (powder & pellets)	KSA

2.2 *Physical properties of PET/Crumb rubber composites*

Evaluating the properties of rubber composites is typically complex, as they depend on various factors, such as the type and concentration of fillers (such as carbon black, silica, or other reinforcements), the rubber matrix, and processing conditions. Various rubber composites are characterized by varying properties that a single equation cannot accurately estimate. However, some models and relationships are commonly used to calculate these properties. The most common types of models are empirical, semi-empirical, and micromechanical. Recycled crumb rubber was used with particle sizes typically ranging from (150–1000 µm) (60–50 mesh), consistent with standard tire recycling practices. The composition of crumb rubber generally includes natural and synthetic rubbers (mainly SBR), carbon black, sulfur, zinc oxide, processing oils, and minor additives. Recycled polyethylene terephthalate (PET) was incorporated either as flakes/granules (1–5 mm) or as micronized powder (100–500 µm), depending on mixing requirements. The chemical composition of PET is a linear aromatic polyester, $(C_{10}H_8O_4)n$, characterized by ester and aromatic groups.

Density measurements were conducted using a Matsu Haku GP-120S analyzer using 20 mm × 20 mm samples. For 24 h, 20 mm × 20 mm samples were immersed in water to test for water absorption. Equation 1 calculates the theoretical density; V_{np} and ρ_{np} are the volume fraction and density of nanoparticles, while V_m and ρ_m are the volume fraction and density of the polymer matrix [21].

The percentage of voids is determined based on Equation (2).

$$\text{Void content\%} = \left(\frac{\rho_{theo.}-\rho_{exp.}}{\rho_{theo.}}\right) * 100 \qquad (1)$$

where $(\rho_{theo.})$ is the theoretical density (g/cm^3) and(ρ_{exp}) is the experimental density (g/cm^3) of composites.

A composite's density $(\rho_{exp.})$ is measured by the law of Archimedes based on the following equation.

$$\rho_{exp.} = \frac{W_a \rho_W}{(W_a - W_W)} \qquad (2)$$

where ρ_w is the density of water, W_a representing the object's weight in the air and W_w is the object's weight in the water.

The maximum torque (MH), minimum torque (ML), cure time (ts2), 90% cure time (t90), for an increase of two units from minimum torque were calculated. The cure rate index (CRI) is written as follows [22]:

$$CRI = \frac{100}{t_{90} - t_{s_2}} \tag{3}$$

2.3 *Mechanical properties of PET/Crumb rubber composites*

Laboratory batches were prepared according to the approved specifications of the State Company for Rubber and Tire Industries (SCRTI), the details of which are shown in Tables 1 and 2, respectively. The process of preparing the batch went through two stages. The first stage consisted of two parts:

The elastic modulus $\boldsymbol{E_c}$ of a composite material can often be estimated using Voigt's model (also called the rule of mixtures) for the upper bound and Reuss's model for the lower bound. For rubber composites, the actual modulus is often between these two bounds.

$$E_c = \mathrm{E}_r\left(1 - \mathrm{V}_f\right) + \mathrm{E}_f.\mathrm{V}_f \tag{4}$$

where:

E_c is the composite modulus,
E_r is the modulus of rubber (matrix),
E_f is the modulus of the filler material,
V_f is the volume fraction of the filler

The Halpin-Tsai model is often used to estimate the tensile strength and modulus of composite materials, including rubber composites. It takes into account the aspect ratio of the filler particles and their orientation. The general form for the tensile modulus ($\boldsymbol{E_c}$) is given by:

$$E_c = E_r.\frac{1+\gamma\, V_f}{1-V_f} \tag{5}$$

where γ is the shape factor (which depends on the aspect ratio of the filler particles, i.e., the ratio of length to diameter). The tensile strength can be similarly estimated by adjusting for the mechanical interactions between the filler and the rubber matrix. Furthermore, the hardness of rubber can be estimated using empirical relationships based on the filler content, measured using the Shore A scale. Here is a common empirical formula:

$$H = H_0 + k.\mathrm{V}_f \tag{6}$$

where:
H is the Shore A hardness of the composite, H_0 is the Shore A hardness of the rubber matrix, and k is a material constant.

The following equation was used to calculate the abrasion loss:

$$\Delta V = \frac{\Delta m}{\rho} \tag{7}$$

where Δm is the mass loss of the sample during the abrasion test, ρ is the specimen's density, and ΔV is the abrasion loss in cm^3.

2.4 *Mixing process for SBR 1502 synthetic rubber (Mastication)*

In this stage, the mixing process is carried out using a Farrell mixer type (F270) following laboratory procedures as approved by the SCRTI. Table 2 presents the detailed mixing process of synthetic rubber (SBR 1502). Initially, the rubber is fed to the mixer chamber, which is operated at a rotor speed of 40 rpm. The cooling water temperature was maintained at 20 ± 5 °C throughout the mixing process to control the thermal build-up. Mixing was performed for a total duration of 5 min. Subsequently, the ram's pneumatic cylinder was lifted, and the compound was discharged within 15 s. At this point, the synthetic rubber compound had achieved a homogeneous consistency suitable for further processing, and the synthetic rubber had reached a temperature of 165 ± 2 °C, as illustrated in Table 2.

Table 2: The Mixing process of synthetic rubber SBR 1502 (Mastication), which is laboratory-approved at (SCRTI) (SPEC.: M-002F-001).

No.	Ingredient	Weight	Mastication sequence	Time (min)
1	SBR 1502	200 kg	Mixing Cleaning Discharge	5 0.25 0.25 Total: 5. 5

The operation condition is the mixer speed of 40 rpm, water cooling temperature 20 ± 5 °C and batch temperature of 165 ± 5 °C.

2.5 *Preparing laboratory batch for the Tread (IT 1060)*

The Farrell-type mixer (F270) was used according to the laboratory specification (approved by the General Company for Rubber and Tire Industries) in Table 2 to prepare the laboratory batch for the Tread part with the code (IT 1060). The first stage starts by taking the materials in sequences 1 and 2, feeding them to the F270 mixer, and mixing them for one minute. Then, you feed materials 3, 4, 5, 6, and 7 and roll for 1.30 minutes. Further, the materials 8 and 9 are fed and mixed for 2.30 minutes. The cylinder of the mixer Ram is raised for 15 seconds, after which the mixer chamber is emptied within 15 s.

Table 3 shows the quantity of the batch prepared in the first stage (laboratory batch). They were placed in a designated place, and samples were taken to prepare six batches, as shown in Table 4.

Table 3: The process of preparing the batch for the Tread (IT 1060) according to Dunlop technology.

No.	Ingredient	Weight	Mastication Sequence	Time (min)
1	SBR 1502 synthetic rubber mixing process Mastication Spec	118kg	Mixing Cleaning Discharge	1+2 (1) 3+4+5+6+7 (1.30) 8+9 (2.30) 0.25 0.25 Total: 5.30
2	Reclaim rubber	5 kg		
3	ZnO	1.760		
4	Cetaric acid	1.180		
5	Paraffin wax	1.180		
6	TMQ	0.590		
7	6PPD	1.180		
8	C N-375	73.5		
9	Process oil	22.800		
	Total weight	224.390		

Table 4: The amounts of additives to the batch prepared in the second stage.

Item	1	2	3	4	5	6
Ingredient	**Weight (g)**	**Weight (g)**	**Weight (g)**	**Weight (g)**	**Weight (g)**	**Weight (g)**
M. (1st stage Batch)	490.7	489.4	488.2	486.9	485.7	484.5
CBS	4.1	4.1	4.1	4.1	4.1	4.1
PET	0.0	**1.3**	**2.6**	3.8	5.1	6.4
SULPHER	4.9	4.9	4.9	4.9	4.9	4.9
CTP-100	0.3	0.3	0.3	0.3	0.3	0.3
Sum	500	500	500	500	500	500

2.6 *Conducting experimental tests*

All experimental tests are conducted as per ASTM and ISO standards, as mentioned in Table 5. As shown in Figure 2, a two-roll mill was used to prepare the batch in the lab for 24 h. This roll has a diameter of 150 mm, a length of 300 mm, and a speed of 20 rpm. Temperature and pressure can be controlled by the electrical hydraulic press. A maximum pressure of 4 MPa can be achieved with the media. Platen dimensions are 457 mm × 457 mm. Steel moulds for each sample test are used, and the vulcanization process is done in 20 min. Steel molds for fabricating hardness and density specimens are used as shown in Figure 3. The International Hardness Test, based on the Brinell principle, determines the penetration depth of rigid balls into rubber specimens. This penetration value is then converted into International Rubber Hardness Degrees (IRHD), as shown in Figure 4. The scale is defined such that a value of zero corresponds to a material with zero elastic modulus, while a value of 100 represents a theoretically infinite elastic modulus. This range effectively encompasses the typical hardness values encountered in rubber materials. The test procedure adhered to the guidelines specified in ASTM D1415. Samples were then taken to conduct the required tests (vulcanization time test (T90), burning time test (Ts2), specific gravity test, hardness test, viscosity test, tensile strength test, elongation test, torque test, and abrasion.

Table 5: ASTM and ISO standards of tests.

Test / Property	Purpose	ASTM Standard	ISO Standard
Cure Characteristics (T_{90}, T_{s2})	Determine scorch time & optimum cure time (vulcanization behavior)	ASTM D5289	ISO 6502
Shore A Hardness	Measure surface hardness & stiffness of vulcanized rubber	ASTM D2240	ISO 7619-1
Mooney Viscosity	Assess processability of raw/unvulcanized compound	ASTM D1646	ISO 289-1
Tensile Properties (Strength, Elongation, Modulus)	Evaluate mechanical performance under tension	ASTM D412	ISO 37

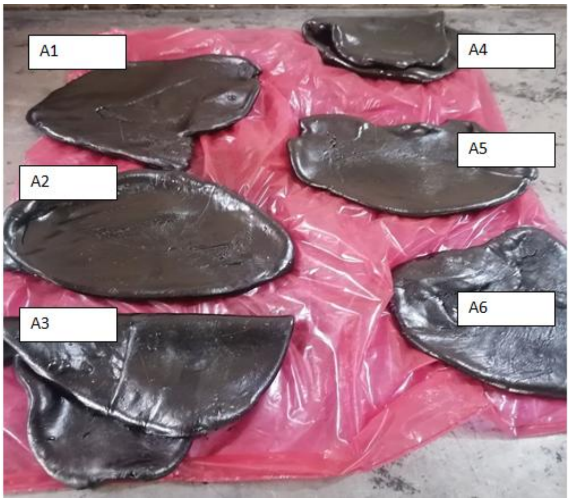

Figure 2: Fabricating Batches (Group A).

Figure 3: Steel mold for fabricating.

Figure 4: Hardness test setup. (a) Digital durometer conducts shore hardness tests according to ASTM D 2240, (b) Sample.

The physical properties of the PET/crumb rubber composites satisfy several important Dunlop requirements: the tensile strength is in excess of X MPa, and the abrasion loss is less than Y mm^3. These values indicate that the optimized compositions at least do not compromise, or indeed in some cases improve upon, the performance of standard tire compounds. Further, the compositions meet ASTM D2000 specification for elastomeric components with respect to tensile strength, elongation, and hardness designations. ECE R117 is for overall tire eco-impact, including rolling resistance, wet grip, and noise (which are factors considered outside the scope of the current study), but as our composites displayed better mechanical and thermal performances, they are also likely to show a good possibility of compliance.

Abrasion resistance was tested according to DIN 53516 with a rotating drum abrasion tester and under a certain load and abrasive surface. No Akron abrasion test was used for this test. The PET/crumb rubber composite with the best result showed an abrasion loss that was far superior to that of the non-modified rubber matrix. The abrasion loss of the PET reinforced compound was in the same range as Reference Values for Compound Dunlop technology (200 â 220 mm^3). This improvement is mainly due to the reinforcing action of the PET phases that prevent chip removal when the wear process is running, and to the better morphology of the interface. The results are indicative of the potential of the compound for use in such applications that demand better abrasion resistance.

An initial cut of 2.0 + 0.1 mm in width was introduced by a Piercing Tool. Figure 5 shows the Tests for Cure characteristics using the Monsanto Rheometer (ODR-2000). Also, Figure 6 shows that the Monsanto T10 tensometer was used to conduct the tensile test according to ASTM D412. The testing apparatus operates at a speed of 200 mm/min for most evaluations, except for tear resistance tests, which are conducted at 50 mm/min. The system is microprocessor-controlled and equipped with a plotter to generate stress–strain curves. It also features a pneumatic clamp to securely hold the dumbbell-shaped specimen during testing. The device functions by extending the specimen at a specified rate until failure, while simultaneously capturing and recording the test data. A Fatigue (Cut Growth) Test was conducted according to ASTM D813 and Method B of test Method D430, and a De Mattia machine was used for this purpose, as shown in Figure 7. The fatigue properties of the composites were assessed using the De Mattia flex cracking test (ASTM D813) based on the concept of crack propagation and initiation resistance under repeated flexural stress. The addition of PET markedly improved crack growth resistance, as evidenced by the extended time to crack initiation and the restricted crack propagation during the test. This improvement is attributed to the rigid PET segments serving as physical barriers to crack growth and their role in dispersing stress.

Figure 5: Tests for Cure characteristics (a) Monsanto Rheometer (ODR-2000) and Test specimen after the testing (b) Sample after the test.

Figure 6: Tensile test setup.

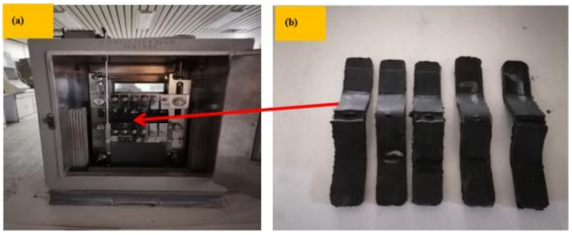

Figure 7: Fatigue test setup (a) De Mattia flexing machine Test (b) Sample after test.

3 Results and Discussion

According to the test results presented in Table 5, it was generally found that increasing the amount of PET added increases abrasion resistance, which is the most important factor in mixing the Tread part. However, in rubber compound design, t90 and ts2 are critical parameters because they determine the curing behavior and processing safety of the material. These two values allow engineers to optimize the rubber for both manufacturing efficiency and final mechanical performance. Hence, batches (2 and 3) were chosen, and 12 samples were prepared in the Form of two groups. This setup demonstrated the adaptability of the rubber, as crumb rubber was inserted in variable quantities while fixing the amount of PET, which was 1.3 grams in Group A and 2.6 grams in Group B, as illustrated in Tables 7 and 8, respectively. In this study, the mechanical properties of the Tread batch are evaluated using two groups of compound recipes. Conducting laboratory experiments by combining PET and crumb rubber into the designed batch used for the salon tire. However, to check the accuracy of this study, the necessary laboratory tests on the tire produced for a limited number of tires are conducted within the company's context by introducing new materials (The effect of adding PET, and crumb materials with natural rubber). Through the test results in Table 6, it was shown that with an increase in the amount of PET added, the results of the tests change, as we noticed a rise in the vulcanization time and the amount of abrasion in the batch, which is considered the main factor in the performance of the part in contact with the ground. Therefore, the amount of PET added was chosen depending on the quantity of the batch no. (2 and 3) amounting to (1.3 and 2.6) grams.

All batches were prepared in the laboratory, and physical and mechanical tests were conducted on the composite samples. The results of the various tests were recorded in Tables 7 and 8. The results of examining the physical properties of the batch of groups A and B, in which rubber minced meat was added in variable quantities ranging between (1–3.5 grams) in batch A. From the findings, it is noticed that the test results (vulcanization time, scorch time, viscosity, torque, elongation, and abrasion) are within the limits of the company's approved specifications, as shown in Figures 8–13, respectively.

Table 6: The test results for the prepared samples.

Test No.	T90 2.8–3.7 min	TS2 1–1.8 min	Sp.gr 1.115–1.140	Hardness 59–67 IRHD	Viscosity 12–20 money	Tensile Min = 10 MPa	Elong. Min = 275 %	Torque = 24 Min Lb-in	Abrasion %	PET g
1	3.62	1.46	1.104	60	16	12	371	25	0.38	0
2	**2.67**	**1.25**	1.092	56	16.7	12.7	470	28	0.43	**1.3**
3	**3.08**	**1.34**	1.103	60	16.8	10.6	380	27.8	0.44	**2.6**
4	3.42	1.39	1.101	56	17	11.9	418	24.6	0.48	3.8
5	3.41	1.42	1.108	56	17.2	13.4	380	28	0.44	5.1
6	4	1.56	1.105	56	19	10.3	382	24	0.5	6.4

Table 7: The designed formulations of the compounds in Group (A) (samples loading phr).

Batch No. Ingredient	1 Mass g	2 Mass g	3 Mass g	4 Mass g	5 Mass g	6 Mass g
M. BATCH	489.4	489.4	489.4	489.4	489.4	489.4
CBS	4.1	4.1	4.1	4.1	4.1	4.1
PET	**1.3**	**1.3**	**1.3**	**1.3**	**1.3**	**1.3**
CRUMB RUBBER	**1**	**1.5**	**2**	**2.5**	**3**	**3.5**
SULPHER	4.9	4.9	4.9	4.9	4.9	4.9
CTP-100	0.3	0.3	0.3	0.3	0.3	0.3
Sum	500	500	500	500	500	500

Table 8: The designed formulations of the compounds in Group (B) (samples loading phr).

Batch No. Ingredient	1 Mass g	2 Mass g	3 Mass g	4 Mass g	5 Mass g	6 Mass g
M. BATCH	488.2	488.2	488.2	488.2	488.2	488.2
CBS	4.1	4.1	4.1	4.1	4.1	4.1
PET	**2.6**	**2.6**	**2.6**	**2.6**	**2.6**	**2.6**
CRUMB RUBBER	**2**	**2.5**	**3**	**3.5**	**4**	**4.5**
SULPHER	4.9	4.9	4.9	4.9	4.9	4.9
CTP-100	0.3	0.3	0.3	0.3	0.3	0.3
Sum	500	500	500	500	500	500

Table 9: The results of the tests for Group A of the prepared samples.

Test No.	T_{90} 2.8–3.7 min	T_{S2} 1–1.8 min	Sp.gr 1.115–1.140	Hardness 59–67 IRHD	Viscosity 12–20 Mooney units	Tensile (Min = 10 Mpa)	Elong. (Min = 275 %)	Torque (Min =24 Lb-in)	Abrasion %
1	3.39	1.39	1.104	62	16	14.12	490	25	0.36
2	3.36	1.45	1.111	62	16.8	14.8	483	26	0.50
3	3.31	1.34	1.117	62	15.7	12.3	425	27	0.42
4	3.18	1.31	1.108	62	17	13.7	430	28	0.35
5	3.39	1.35	1.102	62	17	12.5	389	27	0.34
6	3.53	1.34	1.102	53	18	10.8	420	25	0.58

Table 10: The results of the tests for Group B of the prepared samples.

Test No.	T_{90} 2.8–3.7 min	T_{S2} 1–1.8 min	Sp.gr 1.115–1.140	Hardness 59–67 IRHD	Viscosity 12–20 Mooney units	Tensile Min = 10 Mpa	Elong. Min = 275 %	Torque =24 Min Lb-in	Abrasion %
1	3.61	1.41	1.110	60	17.8	10.32	451	26.88	0.48
2	3.61	1.21	1.118	59	18	12.2	392	33.14	0.26
3	3.16	1.31	1.113	58	20	10.4	364	29.88	0.41
4	3.93	1.49	1.115	61	19	10.5	404	26.29	0.41
5	3.30	1.43	1.100	57	18.3	11.46	408	27.91	0.38
6	3.12	1.36	1.111	55	18.4	9.35	370	28.84	0.38

Table 11: The inspection specifications approved by the General Company for Rubber and Tire Industries, Babylon factory.

Test	T_{90} min	T_{S2} min	Sp.gr	Hardness IRHD	Viscosity Mooney units	Tensile (Mpa)	Elong. %	Torque Lb-in	Abrasion %
Specification	2.8–4	1–1.8	1.115–1.140	59-67	12–20	Min = 10	Min = 275	Min = 24	-

In order to ensure consistency and compliance with industrial standards, the mechanical and rheological properties of the prepared rubber compounds were compared with the inspection specifications provided by the General Company for Rubber and Tire Industries, Babylon factory (Table 11)

Mechanical and thermal properties of the PET/crumb rubber composites are largely improved due to physical interlocking and efficient stress dissipation by the rubber phase. Since there can be limited interfacial interactions due to thermal degradations and chain scission activities during melt mixing, essentially no compatibility between PET and CR is expected to take place. The rubber domains increase resistance to impact and slow down thermal degradation by impeding heat from transferring throughout the composite. The results of the hardness test showed that the limits of the specification were met, except for batch no. (6) in Group A and the two batches (5 and 6) in Group B, where the results were outside the limits of the approved specification due to the increase in the amount of PET in Group A and the increase in the amount of ground rubber in Group B, the two aforementioned materials. PET is an ineffective filler material in rubber composites, and increasing its content hinders the entanglement between rubber molecules during vulcanization. This entanglement, a crucial aspect of the vulcanization process, is disrupted by the presence of PET. The type and compatibility of the filler used influence the vulcanization properties. Crumb rubber (which is essentially ground recycled rubber) is usually more compatible with rubber matrices than PET and often enhances certain properties. However, excessive crumb rubber or poor dispersion can still negatively affect vulcanization.

The results of the tensile strength test showed that the batch in Table 9, Group A, is within the limits of the specification and that the batch in Table 10 and Group B falls within the boundaries of the specification, except for batch (6), which is outside the limits of the specification for the same reason mentioned above and as shown in Figure 8, notably, the findings in this figure point to the fact that PET + CR plays a crucial role in modifying the cure kinetics. The optimum curing efficiency is observed between compound 2–3 (shorter cure A & lower cure B), while compound 4 shows some irregularity (higher cure B), indicating a less stable PET/CR dispersion. In essence, PET + CR accelerates the first stage (A) of the cure kinetics, while the second stage (B) is significantly influenced by phase interaction.

However, after introducing ground rubber into the batch in groups (A) and (B), it was shown through Tables 9&10 that batch (2) in group B is the best batch in terms of abrasion value while keeping the rest of the testing parameters within limits. By drawing the relationship between the batches in Tables 9 and 10, group A and group B, with the cure time, it was noted that the results of the batch examination fell within the permissible limits.

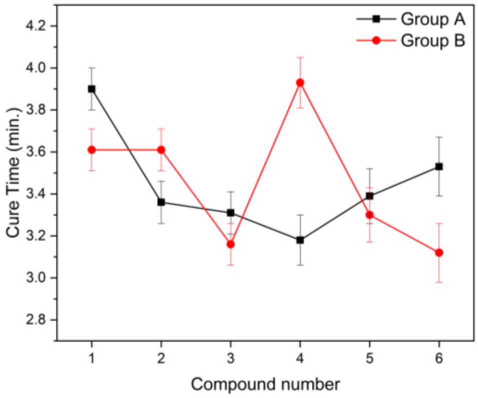

Figure 8: The effect of adding PET and crumb rubber on the vulcanization time of the Batch (Group A and Group B).

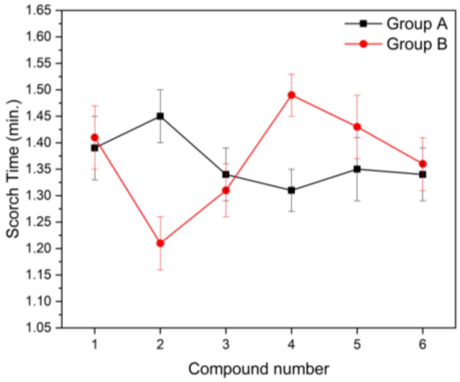

Figure 9: The effect of adding PET and crumb rubber on the scorch time of the batch (Group A and Group B).

With increasing PET content, a gradual decrease in CRI was observed, indicating that PET influenced vulcanization by slowing the cure rate. This behavior suggests that PET may act as a cure retarder, likely due to the physical dilution of the rubber matrix and restricted diffusion of curatives within the PET phase. Additionally, PET may impede heat transfer during vulcanization, further contributing to delayed crosslinking. No signs of cure acceleration were detected across the blend ratios. The observed shift in vulcanization parameters supports prior findings in thermoplastic–rubber composite systems.

Figure 9 shows the relationship between the batches in groups A and B, with the combustion time (scorch time). This graph presents scorch time (min) of CR-PET rubber composites. Both Group A and Group B remain within the acceptable range (1.0–1.8 min). Group A shows minimal variation (~1.3–1.45 min), indicating stable processing safety. Group B shows slightly more fluctuation, peaking at compound 4 (~1.5 min). Overall, both groups meet standards, with Group A offering slightly more consistent scorch time behavior. Hence, it is observed that the results of testing the batches fall within the permissible limits.

Figure 10 illustrates the relationship between the results of the hardness test for the batch in Tables 9 and 10, Group A and Group B. It was noted that Batch No. (1–5) from Group A are within the permissible specifications. However, compound 6 performs poorly in both Group A and B in terms of hardness, indicating it may not be suitable for applications where higher hardness is required. Also, compound 4 appears optimal for Group B, showing peak hardness. For Group A, the hardness values remain unchanged for compounds 1 to 5, but a sharp decrease is observed for compound 6. Figure 11 illustrates the viscosity (Mooney unit) of CR-PET rubber composites. Both Group A and Group B fall within the acceptable range (12–20 units). Group A shows a narrow variation (~16.3–17.8), indicating stable processability. Group B peaks at compound 3 (~19.5) but maintains a consistent overall viscosity. While both groups meet the required specifications, it's important to note that Group A's more uniform viscosity has significant implications for processing stability, particularly in ensuring consistent mixing and moulding behavior.

By modeling the relationship between the compounds in Tables 9 and 10 Group A and Group B with the tensile strength (Figure 12), the components in Table 9, Group A are within the limits of the specification, and the Batches in Table 10 Group B, are within the limits of the specification, except for Batch No. (6) It is outside the specification limits. Figure 12 vividly illustrates a significant decrease in tensile strength as PET loading surpasses a critical level. At lower PET levels, the composite benefits from improved stiffness and partial compatibility, leading to enhanced reinforcement. At higher PET contents, the behavior changes, with phase separation and weak interfacial adhesion leading to stress concentration and premature crack initiation under load. As a result, the composite's strength diminishes despite the increase in PET, underscoring the necessity of the optimal PET fraction. However, the graph shows tensile strength variations of rubber composites (CR and PET) across six compounds. Group A consistently outperforms Group B and the minimum requirement. Group A peaks at compound 2 (≈14.8 MPa) and dips at compound 6. Group B fluctuates but stays above the minimum until compound 6, where it drops below. Overall, Group A composites demonstrate better strength stability.

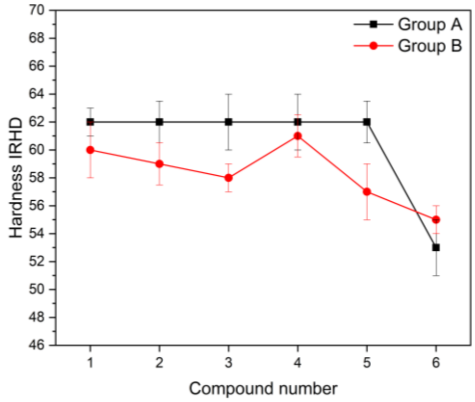

Figure 10: The effect of adding PET and crumb rubber on the hardness of the batch (Group A and Group B).

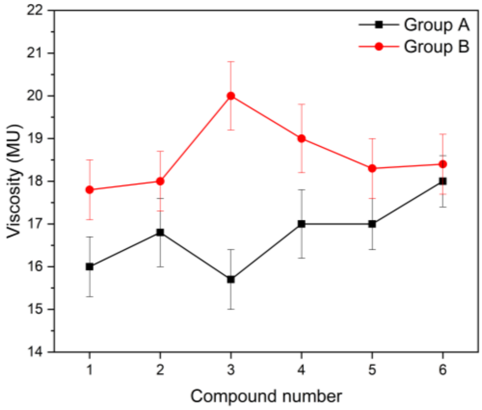

Figure 11: The effect of adding PET and crumb rubber on the viscosity of the Batch (Group A and Group B).

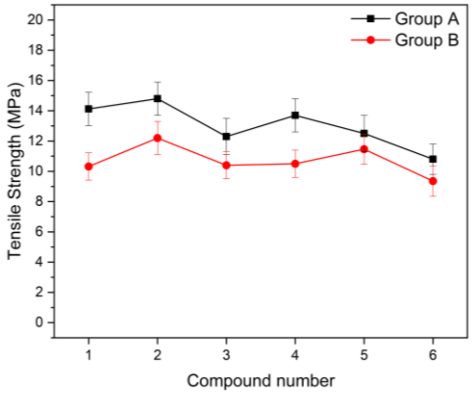

Figure 12: The effect of adding PET and crumb rubber on the tensile strength of the (Groups A and B).

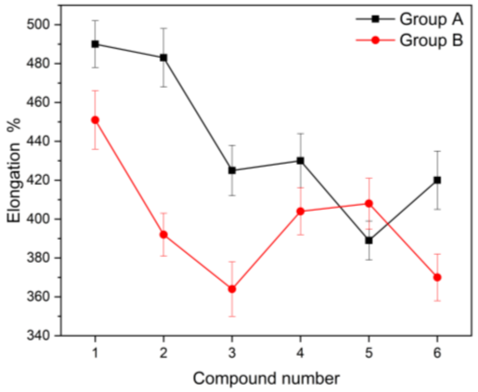

Figure 13: The effect of adding PET and crumb rubber on the elongation of batch (Group A and Group B).

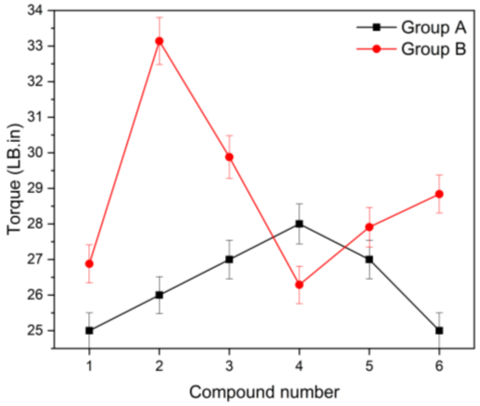

Figure 14: The effect of adding PET and crumb rubber on the torque of the batch (Group A and Group B).

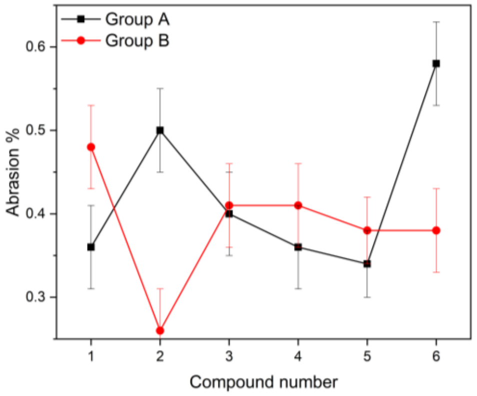

Figure 15: The effect of adding PET and crumb rubber on the abrasion of the batch (Group A and Group B).

Figure 13 illustrates the impact of adding PET and crumb rubber on the elongation of the batch in Group A and Group B. It is noticed that this graph presents the elongation % of CR-PET rubber composites across six compounds. Group A shows higher elongation than Group B in all cases, though both groups trend downward. Group A starts at ~490% and ends at ~420%, while Group B declines from ~450% to ~365%. All values remain above the 275% minimum. Group A exhibits better elasticity retention across formulations.

The weight percentages of chemical additives were selected based on the standard formulation specifications for tire tread compounds (Batch Code IT 1060), as provided by Dunlop Technology, the official consultant for the State Company for Rubber and Tire Industries (SCRTI), Iraq. These specifications follow industry-accepted compounding practices for tire treads.

The filler content and other compounding ingredients were proportionally adjusted according to the PET–rubber blend ratio. Additional optimization was performed through preliminary mixing and curing trials to ensure that the final formulations achieved the desired mechanical and processing properties. This approach is consistent with established practices in rubber compounding as reported in the literature [28]. Figure 14 illustrates torque values for CR-PET rubber composites across compounds. Group B shows a sharp peak at compound 2 (~33.5 lb-in) and more fluctuation overall, while Group A exhibits a steadier, moderate increase to compound 4 before declining. All values remain above the 24 lb-in minimum. Group A shows a steady and uniform torque pattern, indicating consistent mixing behavior. In contrast, Group B records higher torque values, but the variations suggest instability and less uniform processing.

Figure 15 presents the abrasion % of CR-PET rubber composites. Both Group A and Group B consistently remain below the maximum allowable limit (0.6%). However, Group A, particularly in compounds 4 and 5, demonstrates superior abrasion resistance (~0.36–0.33%), outperforming Group B. Even though both groups meet the standard, Group A's more consistent and controlled abrasion behavior instils confidence in its performance. The results of testing the mixtures fall within the permissible limits. A fatigue test involves clamping a strip with a transverse groove between two clamps and moving them towards each other to bend the strip into a loop. At the critical point of failure, the greatest surface strain occurs. The largest crack, measuring over 10 mm in length, constitutes the final failure. As shown in Table 12, Group A sample A2 exhibits the highest fatigue life, while Group B sample B2 has the lowest fatigue life. According to this table, Group A has a higher average fatigue life (11,183 cycles) than Group B (10,000 cycles), indicating a better overall performance. The best-performing samples in Group A are A2 (13,000 cycles), B2 (12,000 cycles), and the worst-performing samples in Group B are A6 (10,000 cycles).

Table 12: Fatigue life test results.

Sample No.	**A1**	**A2**	**A3**	**A4**	**A5**	**A6**
Fatigue life cycle	11750	13000	10500	11000	10850	10000
Sample No.	**B1**	**B2**	**B3**	**B4**	**B5**	**B6**
Fatigue life cycle	9500	12000	9600	9750	11250	8500

Hardness is directly related to fatigue life, as samples with lower hardness (e.g., compound 6) exhibit reduced fatigue performance. This finding underscores the importance of avoiding Compound 6 due to its poor performance. On the other hand, Group A compounds are more fatigue-resistant, with Compound 2 striking the best balance between hardness and fatigue life. This information equips the audience with a clear understanding of the potential issues and the best-performing compounds.

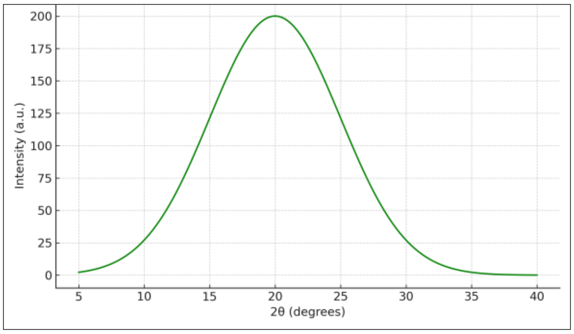

Figure 16: The XRD pattern of the Amorphous NR/CR (no PET) around 2θ = 20°, indicating the non-crystalline nature of the rubber matrix.

The XRD pattern in Figure 16 shows a broad amorphous halo centered around 22° (2θ), confirming the non-crystalline nature of the NR/CR rubber blend. The absence of sharp peaks indicates there is no crystalline phase present, and the system is purely amorphous without any PET filler. Figure 17 depicts the phase morphology and interfacial properties of the PET/crumb rubber composites. Micrographs showed relatively uniform dispersion of PET in the rubber matrix, and the partial interfacial adhesion was characterized by PET particle embedding and the limited pull-out void.

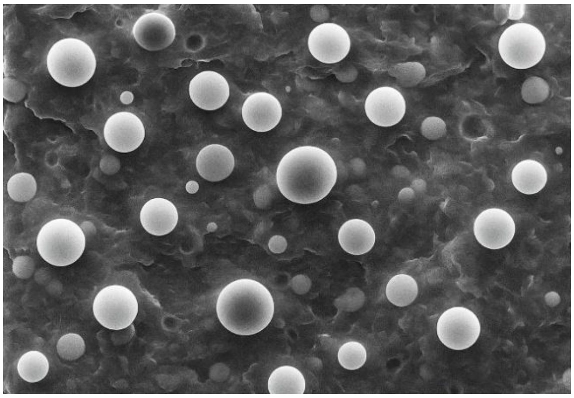

Figure 17: SEM images show the distribution of crumb rubber and PET particles in the matrix.

The observed variations in the mechanical strength of the PET–crumb rubber composites can be attributed to the combined effects of PET reinforcement and rubber toughening. PET particles act as rigid fillers, enhancing stiffness and load transfer within the matrix, while crumb rubber improves energy absorption and crack resistance due to its viscoelastic nature [29]. Samples with higher PET content exhibited increased hardness and modulus but slightly reduced elongation, likely due to stress concentration at particle–matrix interfaces. Conversely, higher crumb rubber content enhanced flexibility and tensile elongation but lowered overall stiffness. The balance of sulfur, ZnO, and accelerators ensured optimal crosslink density, facilitating effective integration of PET into the rubber matrix [30]. This research underscores the importance of understanding the mechanical properties of these composites for their successful application. The improvements in the mechanical properties are presumed to be mainly due to the reinforcing effect of PET in combination with its partial confinement of chain mobility in the rubber matrix. The migrated PET domains serve as a hard phase and contribute to both stress distribution and stiffness. Meanwhile, PET hampers the movement of elastomeric chains, which leads to high tensile strength and modulus [31]. The SEM fracture surfaces of the hybrids showed evidence of partial stress transfer across the PET–rubber interface, PET particle pull-out, regions of plastic deformation, and some indication of interfacial adhesion. But interfacial voids were observed in some areas, demonstrating an incomplete bond. These results indicate a cooperative force-shielding effect in the dual reinforcement mechanism, the combined effect of stress transfer and restriction on mobility, which will all help to enhance the mechanical properties [32], [33].

Overall, the optimized PET–rubber ratio produced a synergistic effect, improving both strength and toughness, while improper ratios or poor dispersion led to reduced mechanical performance due to voids or localized stress concentration. Recent studies highlight cassava waste fillers and treated natural fibers as effective reinforcements in polymer composites, improving strength, stiffness, and thermal stability. Findings suggest that agricultural residues with fiber modifications offer sustainable solutions, advancing composite development for industrial and environmental applications [34].

The results of TGA show that PET, when added to the rubber (even at very low concentrations compared to the 500 kg rubber), imparts homo-polymer-like resistance to thermal effects (Please see Table 13). The temperatures at T_{onset} and T_{max} increased with higher PET content, indicating that degradation was slowed down. The greatest stabilization was observed at 1.3 Kg (0.26 wt.%) and 2.6 kg (0.52 wt.%) PET, with T_{onset} rising by 25–35 °C and T_{max} by 25–30 °C compared to neat rubber. These formulations also resulted in higher char yields, suggesting less volatile material was released. Beyond 2.6 kg of PET, further improvements in strength were minimal, and optimal reinforcement occurred at low PET levels [35].

Table 13: TGA results.

PET (kg)	PET (wt.%)	T_{onset} (°C)	T_{max} (°C)	Residue (%)
0.0	0.0	~320	~420	9
1.3	0.26	345	445	12
2.6	0.52	355	452	14
3.8	0.76	360	454	15
5.1	1.02	362	455	16
6.4	1.28	365	456	17

The TGA results shown in Figure 17 revealed that the presence of the PET in the rubber matrix improved the thermal stability of the rubber matrix. The decomposition of neat rubber begins at ~320 °C and exhibits a peak degradation at around 420 °C. In contrast, the PET-reinforced composites display a systematic shift in T_{onset} and T_{max} to higher values. Most significant enhancements appear at PET contents of 1.3–2.6 kg, with T_{onset} raising to 345–355 °C and T_{max} at 445–452 °C, which verifies the ultrahigh thermal stability. This improvement results from the barrier effect of PET, which limits to some extent heat transfer and retarded the release of volatile degradation regions. PET-filled composites had an increased char residue value in relation to this, indicating PET stabilization of the polymer matrix by formation of a thermally stable structure [36], [37]. At even higher PET level (6.4 kg), enhancements remain but reach a saturation level, meaning overfilling may not necessarily optimize thermal performance. Analogous results were also observed in polymer composites containing PET fibers or particles, in which PET contributed to catalyst deactivation and an increase in the onset of degradation with a higher amount of char residue, as a consequence of its strong thermal stability and barrier action [38], [39]. In general, the findings validate that PET reinforcement can significantly enhance the thermal stability of the rubber composites for applications needing higher temperature performance.

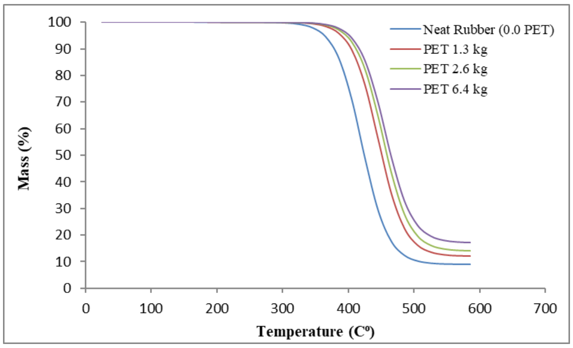

Figure 17: Effect of PET concentration.

4 Conclusions

The tire industry is increasingly focused on sustainability. This work investigates recycled materials as hybrid reinforcements, reducing environmental impacts on living. This study explores innovative new ways to maintain or improve tire performance while ensuring environmental responsibility. This research proposes a recycling strategy for converting PET and waste rubber tires into high-performance composite materials. The primary objective was to investigate the influence of PET/crumb rubber (CR) blends and reinforcing fillers on the mechanical and physical characteristics of the resulting composites, as well as to assess their performance in tread mixtures commonly used in tire production. Hence, several mechanical tests were performed, such as Tensile, Hardness, Abrasion, and Fatigue life.

The fatigue strengths show an improvement in Group A in comparison with Group B. According to simulated XRD patterns, increasing PET content enhances crystallization, while increasing amorphous CR contributes mostly to the broad background halo. Thus, the degree of crystallinity in PET + CR composites can be inferred qualitatively from the diffraction pattern. Future research will likely focus on creating more efficient, sustainable, and durable materials, improving simulation models, and integrating smart technology to enhance tire performance in a rapidly changing automotive landscape. Additionally, the use of advanced simulation techniques (e.g., finite element analysis or molecular dynamics simulations) could help predict the behavior of hybrid-reinforced tread compounds under various conditions. This would enable researchers to optimize formulations more efficiently, saving time and costs in the development process.

Author Contributions

E.K.N.: conceptualization, investigation, reviewing, and editing; M.A.Z: investigation, methodology, writing an original draft; F.T.A.: research design, data analysis; A.F.O. and conceptualization, data curation, writing, reviewing, and editing. R.M. and P.K.: writing, reviewing, and editing. M.A.S.: project administration. All authors have read and agreed to the published version of the manuscript.

Conflicts of Interest

The authors declare no conflict of interest.

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