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Physical and Mechanical Properties: Effect of Substitution of EFB Filler on the Processing of Lump-Based Motorcycle Foot Pad Compounds

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A B S T R A C T

Lump is one of the processed rubber materials derived from latex of rubber trees and clusters of latex obtained from the Hevea Brasiliensis tree. Generally, lumps can be utilized as the basic material for component manufacturing. In the production of component products, additives such as filling materials, vulcanization agents, plasticizers, activators, antioxidants, and accelerators are required. This research utilizes EFB charcoal as a filling material in the production of rubber components to substitute carbon black, which will be used as a motorcycle footrest pad. The objective of this study is to analyze the characteristics of rubber components for motorcycle footrest pads with EFB filler as a filling material, and to obtain the best formulation in rubber component manufacturing that meets the hardness test parameters according to the Indonesian National Standard (SNI). The method used is a Completely Randomized Design (CRD) with one factor, namely the rubber component formula. This study consists of 5 treatments repeated 4 times, resulting in 20 experimental units. The results of the study showed that the physical and mechanical properties of each substitution treatment had the same characteristics with a reduction or decrease in test results for each test parameter carried out. However, based on the test results for each test parameter carried out, there were only 4 treatments that were still included in the SNI standard for hardness tests for step motors, namely F1 (0:60), F2(10:50), F3(20:40) and F4(30:30).. While the F5(40:20) treatment was still below the SNI standard. The best treatment was still obtained in the F2(10:50) treatment with a hardness value of 69.05 Shore A.

Contribution to Sustainable Development Goals (SDGs):
SDGs 8: Decent Work and Economic Growth
SDGs 9: Industry, Innovation and Infrastructure
SDGs 12: Responsible Consumption and Production
SDGs 13: Climate Action
SDGs 15: Life on Land

1. INTRODUCTION

1.1. Research Background

Rubber compound is a semi-finished material used in the production of rubber-based products, encompassing both natural and synthetic rubber [1]. In general, the rubber processing industry utilizes natural rubber in the form of SIR 3L, SIR 3WF, crumb rubber, RSS, or various rubber grades produced by large-scale rubber manufacturing facilities [2], [3]. The necessity of further processing field latex compels rubber smallholders to sell their fresh latex to rubber processing factories, a situation that ultimately results in price monopolization of rubber prices by the factory rubber [4].

In addition to these products, there exist alternative products that rubber smallholders can independently produce, namely lump and latex [5]. Lump is one of the processed forms of rubber,

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consisting of field latex and field latex coagulum obtained from the rubber tree (Hevea brasiliensis) [6]. Fresh lump is a processed rubber material that does not originate from field latex coagulum formed naturally within the collection cup [7]. Lump is generally utilized as a primary raw material for the production of rubber compounds, which are subsequently processed into various end products such as shoe soles, tires, seals, motorcycle footrests, and other applications [8].

To achieve the desired properties in rubber products, various additives are required, including fillers, vulcanizing agents, plasticizers, activators, antioxidants, and accelerators. Carbon Black (CB) is the most widely utilized filler in the rubber compound industry due to its broad availability and superior reinforcing capability [9]. However, CB is a non-renewable material and poses potential environmental hazards as a consequence of its production process. Therefore, alternative fillers to replace carbon black in rubber formulations need to be explored in order to mitigate environmental and health impacts.

Empty Fruit Bunches (EFB) of Oil Palm represent one of the most abundant agricultural by-products generated from the oil palm processing industry [10], [11]. EFB is a cellulosic material available in large quantities and possesses attractive properties such as toughness, weather resistance, and a unique chemical composition. Biochar derived from the pyrolysis of EFB has the potential to serve as an environmentally friendly alternative filler in rubber compound formulations [12].

The utilization of lump elastomer and EFB filler as raw materials in the rubber product processing industry is also highly relevant in supporting the enhancement of the Domestic Component Level (DCL) in accordance with Law No. 3 of 2014 on industrial affairs. Furthermore, the application of both local materials directly contributes to the implementation of the circular economy program by substituting synthetic CB filler with natural materials derived from industrial waste [13].

Based on the aforementioned background, this study aims to evaluate the use of EFB biochar as a partial substitute for Carbon Black in lump-based rubber compound formulations, with the intended final application of motorcycle footrests. The ratio of the CB/EFB filler hybrid filler system was varied to determine the optimal formulation that meets the standards for mechanical and curing properties of rubber compounds in accordance with international ASTM standards.

1.2. Literature Review

1.2.1. Rubber Compound and Lump Elastomer

Rubber compound is defined as raw rubber that has been blended with various additives, including fillers, process oils, accelerators, activators, and other constituents, to enhance the mechanical properties of rubber [14]. The formulation of rubber compounds plays a critical role in determining the final performance characteristics of rubber-based products, particularly in high-demand industrial applications such as automotive components, sealing systems, and vibration dampers [15]. The reinforcement process of rubber composites using lump elastomer in the automotive parts processing industry has conventionally relied on Carbon Black (CB) as the standard filler, owing to its well-documented ability to significantly improve tensile strength, and overall durability of the rubber matrix [16]. The dominance of CB as a reinforcing filler is attributed to its fine particle size, high surface area, and strong interfacial interaction with the elastomer chains, which collectively contribute to superior mechanical performance in the final vulcanized product [17]

The incorporation of fillers into the elastomer matrix improves the physical and rheological characteristics of composite rubber products; however, the use of natural fillers may result in a reduction in hardness and even processing failures if not combined appropriately [18]. Growing environmental concerns and the increasing cost of synthetic fillers have driven extensive research into the utilization of bio-based and agricultural waste-derived fillers as partial or complete substitutes for CB in rubber formulations [19]. Natural fillers such as silica derived from rice husk ash, calcium carbonate, and cellulose-based materials have demonstrated potential as alternative reinforcing agents, although their hydrophilic nature and poor compatibility with the non-polar rubber matrix often necessitate surface modification or the use of coupling agents to achieve adequate dispersion and interfacial bonding [20]. The optimization of filler loading, particle size distribution, and surface chemistry remains a fundamental challenge in the development of high performance natural filler reinforced rubber composites intended for automotive and industrial applications [21].

1.2.2. Carbon Black as a Conventional Filler

Carbon Black (CB) is one of the most extensively employed materials in the manufacture of rubber compounds and rubber products, owing to its wide availability and outstanding reinforcing capability (Sunali et al., 2022). The widespread use of CB is attributed to its thermal stability, electrical conductivity, and ability to enhance tensile strength and elastic modulus of rubber. Nevertheless, despite these advantages, CB is considered a non-renewable material and poses potential environmental hazards, as its production process generates significant carbon emissions (Sisanth et al., 2017).

1.2.3. Empty Fruit Bunch (EFB) of Oil Palm Biochar as an Alternative Filler

EFB constitute an abundantly available lignocellulosic waste material generated from the oil palm processing industry [22]. EFBOP possesses a chemical composition comprising cellulose, hemicellulose, and lignin, which can be converted into biochar through the pyrolysis process. EFB biochar has the capacity to function as an environmentally friendly alternative to CB filler in rubber compound formulations [23].

The particle size of fillers exerts a significant influence on the physical properties of rubber compounds. The smaller the particle size of the filler employed, the higher the resulting hardness, as smaller particles possess a greater surface area for interaction, thereby strengthening interparticle bonding and enhancing the mechanical properties of the material [24]. This principle serves as the scientific basis for utilizing EFB filler with controlled particle size as a substitute filler for CB within the elastomer matrix.

Prior research has demonstrated that EFB constitutes a filler and reinforcing agent whose characteristics differ from those of carbon black, yet it remains applicable in the manufacture of rubber vulcanizates [16]. The use of natural fillers such as EFB filler facilitates improved dispersion within the elastomer,

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enabling it to achieve reinforcement nearly as effective as that produced by carbon black at lower filler loadings [25].

1.2.4. Mechanical and Rheological Properties of Rubber Compounds

The evaluation of lump and EFB biochar utilization exerts an impact on changes in the mechanical properties of composite rubber. Among the mechanical properties most significantly affected are the reduction in tensile test values resulting from the use of EFB biochar [26], as well as changes in rheological parameters such as scorch time, optimum curing time, and curing rate [27]. Therefore, modifications in the preparation of EFB filler are essential to produce composite rubber compounds with mechanical properties that conform to quality standards.

The determination of the optimal ratio between CB and EFB filler as a hybrid filler system is critical in producing rubber compounds with an optimal combination of hardness, tensile strength and elongation at break. Properties of natural rubber filled with hybrid fillers have been widely compared, where the loading of the primary filler, carbon black (CB), is fixed while secondary fillers are varied to evaluate their combined reinforcing effects on the rubber matrix [28]. The growing environmental pollution caused by emissions generated during the CB processing has prompted researchers to synthesize naturally derived materials that can be used in conjunction with CB as a rubber filler. The carbon black used in rubber manufacturing is one of the causes of environmental pollution; notably, the production of one ton of CB generates approximately 2.4 tons of carbon dioxide, making the conversion of agricultural wastes such as EFB into reinforcing materials a key trend toward sustainability [29]. Among agricultural wastes, EFB fibres are particularly attractive as fillers and reinforcements in hybrid composites due to their abundance and favourable mechanical properties, and their incorporation into composite materials offers a viable solution to reduce environmental impact [30].

Although previous studies have extensively explored the use of natural fillers as substitutes for carbon black in rubber compounds, several research gaps remain to be addressed. First, the majority of prior studies have employed synthetic rubber or conventional natural rubber (RSS/SIR) as the base elastomer, whereas the potential of lump as a smallholder-based raw material elastomer has not been thoroughly investigated in the context of finished products such as motorcycle footrests.

Second, research on EFB biochar-based fillers applied to lump-based rubber compounds has generally examined only one or two aspects of mechanical properties, without integrating a comprehensive evaluation of both curing properties (rheology) and mechanical properties simultaneously. Third, the optimal ratio of Carbon Black to EFB fillers as a hybrid filler within a lump elastomer matrix for motorcycle footrest applications that meets ASTM standards has never been systematically determined. Fourth, studies examining the impact of varying CB/EFB hybrid filler ratios on the combined properties of hardness, tensile strength and elongation at break in lump-based motorcycle footrest products remain highly limited in the existing literature.

The novelty of this study lies in three principal aspects. First, this research represents the first systematic study to investigate the use of smallholder rubber lump as a base elastomer in combination with a hybrid filler system comprising Carbon Black and EFB filler (derived from pyrolysis) in rubber compound formulations intended for motorcycle footrest applications.

Second, this research comprehensively optimizes the CB/EFB hybrid filler ratio by simultaneously evaluating compound curing properties (scorch time, optimum curing time, and curing rate) and the mechanical properties of the final product (hardness, tensile strength and elongation at break) in accordance with ASTM standards, an approach that has not previously been conducted for lump-based elastomer systems.

Third, this research contributes to the development of value-added rubber products by integrating two categories of Indonesian local waste/materials, namely smallholder rubber lump and EFB waste from the oil palm industry, thereby directly supporting the implementation of circular economy principles and simultaneously enhancing the value of Domestic Component Level (DCL) in alignment with national industrial regulations.

1.3. Research Objectives

This research on the use of lump elastomer with Carbon Black and EFB fillers was conducted to evaluate the final properties of the elastomer based on international ASTM (American Society for Testing and Materials) standards, specifically with respect to the mechanical properties of tensile testing, and the curing acceleration level of the compound through rheological testing.

Based on the findings of previous research, the ratio of CB to EFBas a hybrid filler not only affects the mechanical and curing properties of the rubber compound, but also influences the properties of the final rubber product. Therefore, the objective of this research is to determine the most appropriate ratio of CB to EFB as a hybrid filler by varying the CB and EFB filler ratios and incorporating these hybrid fillers to produce motorcycle footrests as a rubber product. The curing properties of the rubber compound and the mechanical properties of the rubber product, including hardness, tensile strength, and elongation at break, were employed as the criteria to assess the quality of each formulation.

2. MATERIALS AND METHODS

2.1. Materials and Equipment

This study employed a series of laboratory instruments that had been calibrated in accordance with standard procedures prior to use. The primary instruments included: (1) a two-roll open mill for elastomer mixing; (2) a hydraulic hot press for compound vulcanization; (3) an analytical balance with a precision of 0.001 g for material weighing; (4) a disk rheometer (Model HT-8756) for measuring vulcanization characteristics; (5) a Universal Testing Machine (UTM, Techcom) for tensile mechanical property testing; and (6) a Shore A durometer for hardness measurement of vulcanizates.

The materials used in this study consisted of primary raw materials and rubber compounding chemicals. The primary raw materials comprised rubber lump with a moisture content of approximately 15–20%, biochar derived from Oil Palm Empty Fruit Bunches (OPEFB) produced via pyrolysis at 300 mesh particle size, and industrial-grade Carbon Black N550. The rubber compounding chemicals included: zinc oxide (ZnO) as an activator; stearic acid as a co-activator; 2,2,4-trimethyl-1,2-dihydroquinoline (TMQ) as an antioxidant; tetramethylthiuram disulfide (TMTD) as an accelerator; 2-mercaptobenzothiazole

disulfide (MBTS) as a retarder; paraffin oil as a softener; and sulfur as a vulcanizing agent.

2.2. Methods

The research was conducted through two research stages, the first stage was the manufacture of filler from EFB to produce EFB charcoal and the second stage was the use of EFB filler as a substitute for the use of Carbon Black to make rubber compounds as raw materials for making motorcycle Foot Pad.

2.2.1. Manufacturing of EFB Filler

Empty Fruit Bunches (EFB) obtained from the palm oil processing plant of PTPN I Regional Bekri in Central Lampung were prepared through the following sequential steps. First, the raw material was washed repeatedly with boiling water to remove impurities and contaminants. The cleaned material was subsequently dried in an oven at 100 °C for 24 hours until a constant mass was achieved. The dried EFB material was then ground using a Hammer Mill and sieved through a 150-mesh screen to obtain a powder with a uniform particle size distribution.

Pyrolysis was conducted in a furnace using 150 g of EFB powder placed in a porcelain crucible. The process was carried out at three temperature variations 550 °C, 700 °C, and 800 °C under a constant nitrogen gas flow of 100 cm^3/min with a fixed heating rate of 10 °C/min. Upon reaching the target temperature, the nitrogen flow was terminated and replaced by a carbon dioxide flow for 60 minutes at the same flow rate. Three types of OPEFB activated carbon were produced through this procedure, designated as EFB 550, EFB 700, and EFB 800, corresponding to their respective activation temperatures. Following activation, the samples were cooled to room temperature under a nitrogen atmosphere and subsequently stored in a desiccator until further use.

2. Rubber Compound Manufacturing

Rubber compound preparation followed the basic formulation of Ginting et al. (2020), modified in accordance with the requirements of this study. Five formulation variants were prepared with varying ratios of EFB Filler to Carbon Black N550, as presented in Table 1. All materials were accurately weighed prior to mixing, which was performed using a laboratory open mill in accordance with ASTM D3184-89.

The sequence of material incorporation was established as follows. In the first stage, the rubber lump was masticated in the open mill for approximately 30 minutes until the elastomer attained a plastic condition with a smooth surface, thereby enhancing its capacity to absorb additive materials. In the second stage, ZnO and stearic acid were added as an activation system and mixed for 2–3 minutes. In the third stage, Carbon Black N550 and EFB Filler were added incrementally as fillers in accordance with the ratio specified for each formulation. In the fourth stage, the retarder (MBTS), accelerator (TMTD), antioxidant (TMQ), and paraffin oil were incorporated in succession. Finally, sulfur was added last to prevent premature prevulcanization. The homogenized compound was subsequently sheeted to a thickness of 6.00 ± 0.1 mm.

Table 1. Rubber compound formulations with varying ratios of EFB filler to Carbon Black N550

Ingredient	F1 (0:60)	F2 (10:50)	F3 (20:40)	F4 (30:30)	F5 (40:20)
Lump	100	100	100	100	100
EFB filler	**0**	**10**	**20**	**30**	**40**
CB N550	**60**	**50**	**40**	**30**	**20**
Stearic acid	2	2	2	2	2
ZnO	5	5	5	5	5
TMTD	0.5	0.5	0.5	0.5	0.5
MBTS	1.4	1.4	1.4	1.4	1.4
TMQ	2	2	2	2	2
Paraffin oil	4	4	4	4	4
Sulfur	2.5	2.5	2.5	2.5	2.5
Total	**167.4**	**167.4**	**167.4**	**167.4**	**167.4**

Note: all units are in phr = parts per hundred rubber; ratio indicates biochar EFB Filler : CB N550

2.3. Filler Characterization Elemental Composition

The elemental composition of the EFB Filler samples and Carbon Black was characterized using vario El Cube The elemental composition results are presented in Table 2.

Table 2. Elemental composition of EFB Filler and Carbon Black as determined by vario El cube

Sample	C (%)	O (%)	N (%)	Others (%)
EFB 550	65.55	13.85	0.25	20.35
EFB 700	70.55	11.08	0.14	18.23
EFB 800	75.26	8.23	0.11	16.4
Carbon Black	96.12	0.91	0.09	2.88

Based on the elemental composition analysis conducted using the vario EL cube, the carbon content of EFB filler increased consistently with rising pyrolysis temperature, from 65.55% (EFB 550) to 70.55% (EFB 700), reaching its highest value of 75.26% at EFB 800, accompanied by a decline in oxygen content from 13.85% to 8.23% and a reduction in nitrogen content from 0.25% to 0.11%. This trend is consistent with the findings reported by Ribeiro and Brandalise [31], who demonstrated that pyrolysis produced at elevated temperatures exhibits higher fixed carbon content and lower volatile matter, resulting in superior mechanical properties compared to filler produced at lower temperatures. This observation is further supported by Tomczyk et al. [32], who established that high pyrolysis temperatures promote the formation of biochar with greater carbon content and porosity, albeit with reduced volatile matter. The decline in oxygen content observed in EFB 800 indicates more complete decomposition of polar functional groups (–OH, C=O), whereby increasing pyrolysis temperature correlates positively with elemental carbon content and negatively with oxygen, hydrogen, and volatile matter concentrations. Although the carbon content of EFB 800 (75.26%) remains considerably lower than that of commercial Carbon Black (96.12%), high-temperature biochar retains significant potential as a sustainable alternative to conventional fillers such as Carbon Black in the development of environmentally friendly materials derived from biomass waste. Consequently, EFB 800 was selected as the optimal filler, as it possesses the highest carbon content, the lowest oxygen and nitrogen concentrations, and the elemental composition profile most closely approximating that of Carbon Black among all EFB samples evaluated

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2.4. Characterization of Compound and Vulcanizate Properties

2.4.1. Vulcanization Characteristics

The cure characteristics of the rubber compounds were measured using a disk rheometer at 150 °C for 10 minutes, in accordance with ASTM D6204-15. Prior to testing, the instrument was conditioned until both the upper and lower platens reached stable operating temperatures. Circular specimens with a diameter of 30 ± 2 mm and a thickness of 6.00 mm were prepared from unvulcanized compound sheets. The parameters recorded during testing included: scorch time (TS2), optimum cure time (TC90), minimum torque (ML), and maximum torque (MH).

2.4.2. Tensile Mechanical Properties

Tensile property testing of the rubber vulcanizates was conducted using a Universal Testing Machine (UTM) equipped with a 10 kN load cell, in accordance with SNI ISO 37:2017. Type 1 dumbbell specimens were prepared from vulcanizate sheets with the following dimensions: minimum overall length of 115 mm, tab width of 25 mm, narrow section length of 33 mm, narrow section width of 6 mm, and radius of 14 mm. Testing was performed at a crosshead speed of 500 mm/min with a gauge length of 50 mm. The parameters recorded included tensile strength at break, elongation at break (Eb), modulus at 100% elongation (M100), and modulus at 300% elongation (M300). Five replicate specimens were tested for each formulation.

2.4.3. Hardness

Hardness testing of the vulcanizates was conducted using a Shore A durometer in accordance with ASTM D2240-15. Cylindrical specimens (diameter: 4 cm; thickness: 0.5 cm) were prepared from vulcanizate sheets. Testing was performed by pressing the indenter onto the specimen surface placed on a hard, flat surface, and the hardness value was recorded within 1 ± 0.1 seconds of indenter application. A minimum of five measurement points were taken on each specimen to obtain a representative mean value.

2.5. Statistical Analysis

Data on the physico-mechanical properties of the vulcanizates comprising hardness, tensile strength, and elongation at break as well as vulcanization characteristic data were statistically analyzed using one-way Analysis of Variance (ANOVA) at a significance level of $\alpha = 0.05$ (95% confidence level). When the ANOVA indicated significant differences among treatments, the analysis was continued with Duncan's Multiple Range Test (DMRT) to identify differences between treatment groups. All results are expressed as mean ± standard deviation. Statistical processing and analysis were performed using OriginPro 2024b (OriginLab Corporation, Northampton, MA, USA).

3. RESULT AND DISCUSSION

3.1. Vulcanization Characteristics of Rubber Compound

Rheological characterization of rubber compounds was performed to determine the vulcanization (curing) characteristics of the compounds, which are directly associated with the processability of the compounds into finished rubber products. Rheological testing using a Moving Die Rheometer (MDR) generated critical parameters including minimum torque (ML), maximum torque (MH), optimum cure time (TC_{90}), and scorch time (TS_2). These parameters are critically important in the production of finished rubber goods, as they determine the process conditions during the hot press stage. For compounds with greater thickness, a longer vulcanization time is required to allow heat to penetrate uniformly throughout the compound, whereas thinner compounds generally require shorter vulcanization times for production efficiency [33]. Based on the analysis of variance, the filler formula exerted a significant effect on the minimum torque (ML), TS_2, and TC_{90} values; however, the maximum torque (MH) showed no statistically significant differences among treatments. The complete rheological test results of the rubber compounds are presented in Table 3.

Table 3. Vulcanization Characteristics of Rubber Compound Measured by Moving Die Rheometer (MDR)

Comparison of EFB Filler and Carbon Black	Minimum Torque (kg/cm)	Maximum Torque (kg/cm)	TS_2 (minute)	TC_{90} (minute)
F1 (0:60)	7.95c	11.49a	11.20b	12.34b
F2 (10:50)	7.69bc	10.85a	10.49ab	11.35ab
F3 (20:40)	7.34ab	10.26a	8.91a	9.89a
F4 (30:30)	6.91a	9.59a	8.84a	9.63a
F5 (40:20)	7.19ab	9.39a	8.84a	9.46a

Note: Values followed by the same letter are not significantly different, while values followed by different letters are significantly different based on the DMRT test at a 95% confidence level (α = 5%).

3.1.1. Minimum Torque (ML)

Minimum torque (ML) is a rheological parameter that reflects the viscosity of the rubber compound before vulcanization proceeds significantly. A lower ML value indicates that the compound has lower viscosity, making it easier to process and shape. Based on the test results presented in Table 3, the minimum torque values of the rubber compound exhibited a decreasing trend as the proportion of EFB filler increased, with values of 7.95, 7.69, 7.34, and 6.91 kg/cm for EFB filler:CB ratios of 0:60, 10:50, 20:40, and 30:30, respectively. A slight increase was observed in formula F5 at a ratio of 40:20, reaching 7.19 kg/cm.

This decrease in minimum torque is attributed to differences in the physicochemical characteristics between carbon black and EFB filler as fillers. Carbon black is an active filler with very fine particle structure in the range of 8–100 nm, extremely high specific surface area, and strong affinity for the elastomer matrix. These unique characteristics enable carbon black to significantly increase the torque modulus of rubber compounds [34]. In contrast, EFB filler, as a bio-filler, has much larger particle sizes

of approximately 74 μm [8], resulting in weaker interactions with the natural rubber polymer chains compared to carbon black.

Partial or complete substitution of carbon black with biomass-based bio-fillers leads to reduced viscosity and modulus in rubber blends. This finding is consistent with the study by Hait et al. [35], who reported that the torque modulus increment was greater in compounds using carbon black compared to those using biomass charcoal as a filler. Torque modulus serves as an indicator of crosslink density and polymer chain entanglement, reflecting the extent of crosslink formation resulting from vulcanization [36]. Research conducted by Cui et al [37]. further confirmed that the number of crosslinks formed through sulfur-based vulcanization reactions significantly influences the torque modulus of natural rubber elastomers.

A recent comprehensive review by Karunanayake et al. [34] on EFB as an alternative to carbon black in rubber composites confirmed that biochar derived from biomass waste has considerable potential as a partial replacement for carbon black. Although the resulting mechanical properties do not fully match those of carbon black, optimization of particle size and surface modification of biochar can enhance its compatibility with the natural rubber matrix. Furthermore, the study by Abd El-Aziz et al. [38] demonstrated that replacing carbon black with biochar from agricultural wastes such as rice straw, date palm leaf fibers, and common reed yielded competitive rheological characteristics in EPDM rubber composites.

3.1.2. Maximum Torque (MH)

Maximum torque (MH) marks the completion of crosslink formation during rubber vulcanization and characterizes the endpoint of the hardening process at a given time and temperature. The MH value reflects the crosslink density formed between the elastomer and the filler through sulfur vulcanization reactions. Based on Table 3, formula F1 (0:60), in which all filler consisted of carbon black, exhibited the highest MH value of 11.49 kg/cm, while formula F5 (40:20) showed the lowest MH value of 9.39 kg/cm. Although a decreasing trend in MH values was observed with increasing EFB filler content, the analysis of variance indicated that these differences were not statistically significant across all treatments.

These results are consistent with the findings of Abd El-Aziz et al. [38], who stated that maximum torque is an indicator of the number of structural units forming crosslinks between the elastomer and the filler. Carbon black, owing to its unique structural characteristics including an exceptionally high surface area and its ability to absorb polymer chains around its particles (occluded rubber) enables the formation of more abundant and stronger crosslinks. This mechanism is known as the Payne effect, in which the filler–filler network and filler–rubber interactions collectively contribute to the improvement of mechanical properties in the vulcanizate [39].

Notably, although MH values declined with increasing EFB filler content, the reduction was not statistically significant. This suggests that EFB filler still contributes to crosslink formation, albeit with lower efficiency compared to carbon black. Research by Cui et al. [37] confirmed that carbon-based bio-fillers continue to participate in the vulcanization network through both physical and chemical interactions with natural rubber polymer chains, although with lower intensity compared to conventional carbon black.

3.1.3. Optimum Cure Time (TC90)

Optimum cure time (TC_{90}) is the duration required to complete 90% of the crosslink formation between sulfur and rubber from the onset of heating. This parameter is used as a reference for determining the vulcanization time and temperature during the hot-press stage in the production of finished rubber goods [40]. Based on the data presented in Table 3, formula F1 (0:60) exhibited the highest tc90 value of 12.34 minutes, while formula F5 (40:20) showed the lowest tc90 value of 9.46 minutes. Statistical analysis revealed that formula F1 was not significantly different from F2 but differed significantly from all other treatments.

The decrease in ts90 values with increasing EFB filler content is associated with differences in the carbon abstraction mechanism between EFB filler and carbon black in relation to the elastomer. In carbon black, the preferred site for carbon radical abstraction is the tertiary macro-carbon radical, thereby reducing the likelihood of chain scission and prolonging the crosslink formation process. In EFB filler, polymer chain scission occurs more readily, yielding polymer chains with lower molecular weight, which accelerates the vulcanization process [41], [42].

In addition, EFB filler contains various active functional groups, including carboxyl, carbonyl, and nitro groups [43]. These polar functional groups can interact with the vulcanizing agents (sulfur and TMTD accelerator), potentially accelerating the initiation of vulcanization reactions while simultaneously consuming part of the accelerator in the blend. This explanation is supported by the study of Cui et al. [37], which reported that biochar can adsorb curing agents, thereby altering the kinetics of vulcanization reactions. This finding was further confirmed by Pereira Negri et al. [8], who emphasized the importance of balancing a shorter TC_{90} for large-scale production efficiency with a longer TC_{90} for better process control during molding.

In general, the time required for rubber crosslink formation is influenced by several factors, including sulfur concentration, temperature, the type and quantity of accelerators, and the interaction between the filler and the elastomer matrix [44], [45]. In the context of this study, the mechanism governing the acceleration of crosslink formation was influenced by the TMTD accelerator and its interaction with EFB filler as a substitute filler for carbon black.

3.1.4. Scorch Time (TS2)

Scorch time (TS_2) refers to the safe processing window of the rubber compound before premature vulcanization (prevulcanization) or early hardening occurs. A higher TS_2 value indicates a longer period during which the compound can be processed in its plastic state, thereby providing a safer timeframe for processing and molding [46]. Based on the test results in Table 3, formula F1 (0:60) exhibited the highest TS_2 value of 11.20 minutes, which was statistically significantly different from formulas F3, F4, and F5. The lowest TS_2 values were observed in formulas F4 and F5, each recording 8.84 minutes.

The decrease in TS_2 values with increasing EFB filler content is related to the surface reactivity of biochar toward vulcanizing agents. The polar functional groups on the surface of EFB filler interact with the TMTD accelerator, thereby lowering the activation energy for the initiation of vulcanization reactions and accelerating the onset of prevulcanization. This is supported by the findings of da Rocha et al. [17], who noted that higher torque

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values are associated with greater crosslink formation, requiring more energy to process the compound and consequently extending the cure time. Scorch time also represents the initial stage of rubber vulcanization and serves as an indicator of processing safety.

A recent study by Butuc et al. [42] confirmed that the silica naturally present in biochar ash contributes to the acceleration of vulcanization through silica–accelerator interactions, which can reduce scorch time. Nevertheless, all formulas in this study still exhibited TS_2 values above 8 minutes, which remains within the acceptable range for the production of conventional finished rubber goods.

3.2. Physical and Mechanical Properties of Rubber Composites

Testing of the physical and mechanical properties of the rubber composites was conducted to evaluate their conformity with applicable quality standards. The parameters assessed included hardness, elongation at break, and tensile strength. The results of the physical and mechanical property tests are presented in Table 4.

Table 4. Physical and Mechanical Properties of Rubber Composites Measured by Durometer and Universal Tensile Strength Tester

Comparison of EFB filler and Carbon Black	Hardness Test (Shore A)	Elongation Break (%)	Tensile Strength (MPa)
F1 (0:60)	70.30c	612.50d	20.54d
F2 (10:50)	69.05c	600.00c	17.16c
F3 (20:40)	68.65bc	572.50bc	15.95bc
F4 (30:30)	65.85ab	565.00b	15.81ab
F5 (40:20)	64.65a	518.75a	14.61d

Note : Numbers followed by the same letter indicate no significant difference, and numbers followed by different letters indicate a significant difference in the BNT test at a 95% confidence level (a = 5%).

3.2.1. Hardness

Hardness is one of the critical parameters in determining the quality of finished rubber products. Based on the analysis of variance, the filler formula had a significant effect on the hardness of the rubber composites. The test results in Table 4 indicate that a higher carbon black proportion in the formula corresponds to a higher hardness value of the vulcanized rubber. The highest hardness value was obtained in formula F1 (0:60) at 70.30 Shore A, while the lowest was observed in formula F5 (40:20) at 64.65 Shore A.

The higher hardness values in formulas with greater carbon black content are attributed to the unique characteristics of carbon black as an active filler. According to Dwivedi et al. [47], carbon black possesses highly specific properties that allow it to function optimally as a rubber composite filler, including very fine particle size (8 -100 nm), polarity compatible with nonpolar elastomers, and strong affinity for the natural rubber matrix. The strong interaction between carbon black and natural rubber polymer chains creates a dense filler elastomer network, increases crosslink density, and ultimately enhances the hardness of the vulcanizate.

In contrast, EFB filler as a bio-filler presents several limitations that contribute to reduced hardness. First, the much larger particle size of EFB filler (approximately 74 μm) compared to carbon black induces local stress concentration within the polymer matrix, which may diminish composite hardness [8]. Second, EFB filler is a polar material due to the presence of polar functional groups such as carboxyl, carbonyl, and NO_2 groups on its surface, while natural rubber is a nonpolar material [48]. This polarity mismatch results in incompatibility between the EFB filler and the natural rubber polymer matrix, thereby reducing the efficiency of load transfer from the matrix to the filler.

The study by Ferreira et al. [49] reported similar findings, demonstrating that the use of bio-fillers leads to a decrease in rubber hardness, and confirming that a higher carbon black content in rubber products yields higher hardness values. These findings were further corroborated by a recent study from Karunanayake et al. [34], which concluded that biochar from various biomass sources consistently produces lower hardness values compared to carbon black at equivalent dosages, owing to fundamental differences in surface properties and particle morphology.

Nevertheless, this study demonstrated promising results, as formulas F1 through F4 still met the requirements of the Indonesian National Standard (SNI 06-7032:2004) for motorcycle footrest pads, which specifies a minimum hardness of 65 Shore A. Only formula F5 (40:20), with a hardness value of 64.65 Shore A, failed to meet this standard. This indicates that the substitution of EFB filler for carbon black at up to a 30:30 ratio can still yield rubber products that comply with quality standards. These findings align with research on oil palm trunk biochar (OPTB), which reported improvements in hardness and modulus at certain biochar concentrations, even though tensile strength and elongation at break declined.

From the perspective of filler classification, the differing effects of carbon black and EFB filler on hardness can be explained by the distinction between active and inactive fillers. Active fillers such as carbon black are capable of increasing hardness and reinforcing rubber products due to their strong interaction with the polymer matrix. In contrast, inactive fillers such as EFB filler can only increase the volume of the rubber product without making a significant contribution to hardness improvement. The morphology of EFB filler including its larger particle size, porosity, and surface characteristics that differ from carbon black results in suboptimal dispersion and homogeneity within the natural rubber polymer matrix. However, Fan et al. [50] cautioned that the addition of filler to improve hardness has an optimum level, and excessive addition may actually reduce hardness due to filler particle agglomeration.

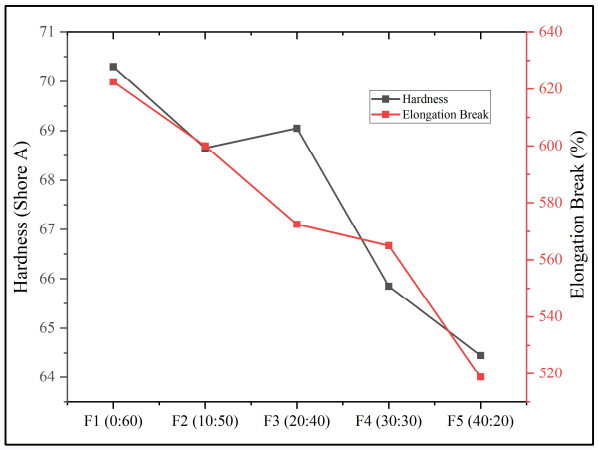

Figure 1. The comparison of hardness and elongation break in OPEFB substitution treatment

The tensile test shows how much force the compound rubber can withstand before the compound breaks. Based on the observation results, it was found that the Formula 1 composition showed the greatest tensile strength of 209.50 kg/cm2 and the longest elongation% of 612.50%. This shows that the ratio of the addition of Carbon Black filler has a perfect breaking stress level when compared to the substitution of the addition of EFB filler. Thus, the addition of EFB filler will have an impact on decreasing the breaking stress force and reducing the percentage of breaking elongation.

3.2.2. Elongation at Break

Elongation at break is a measure of the elastic capacity of a rubber composite to stretch before fracture or rupture occurs. A high elongation at break value reflects good flexibility and elasticity of the rubber composite. Based on the data in Table 4, elongation at break values demonstrated a consistent decreasing trend with increasing EFB filler proportion: 612.50%, 600.00%, 572.50%, 565.00%, and 518.75% for formulas F1, F2, F3, F4, and F5, respectively. Statistical analysis indicated that all consecutive treatment pairs were significantly different from one another.

The decrease in elongation at break is closely associated with the reduction in crosslink density within the rubber composite. The crosslink formation process involves carbon–sulfur bonds present in the filler, which incorporate sulfur atoms into the polyisoprene chain, the TMTD accelerator, and hydrogen bonds between phospholipid proteins at the initiation and termination ends of the rubber chain [51]. The addition of bio-fillers into the rubber compound reduces crosslink density, as filler rubber interactions alter the rubber molecular chains and diminish sulfur vulcanization efficiency; furthermore, these interactions do not prevent solvent penetration into the rubber compound [37].

From a materials mechanics perspective, the decrease in elongation at break with increasing EFB filler content is consistent with reduced flexibility of the polymer network resulting from the incompatibility between the polar filler and the nonpolar matrix. The large particle size of EFB filler creates local defects within the polymer matrix that act as crack initiation sites when the composite is subjected to tensile load. This is confirmed by research on Natural Rubber Composites using hydrothermally carbonized hardwood waste biomass, which reported that biochar with large particle fractions in the range of 10 -100 µm can cause local stress concentrations, ultimately leading to fracture in the rubber composite [37].

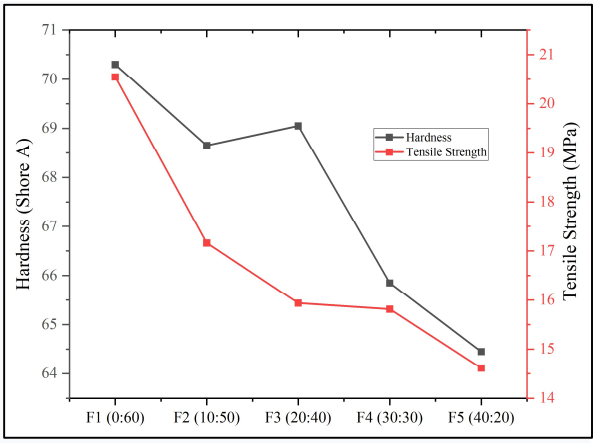

Figure 2. The comparison of hardness and tensile strength in EFB filler substitution treatment

The comparison of hardness to the mechanical properties of Tensile strength and Elongation at break proves that the more EFB filler substitution is added, the value of the resulting test variable will also decrease. The decrease in the value of the hardness variable is directly proportional to the change in Tensile Strength and Elongation at Break. This shows that the process of cross-linking with each addition of EFB filler substitution is decreasing. Cross-linking includes carbon-sulfur bonds present in the filler and involving sulfur atoms in the polyisoprene chain and the TMTD accelerator as well as hydrogen bonds between phospholipid proteins at the initiation and termination ends of the rubber chain

3.2.3. Tensile Strength

Tensile strength is a parameter that indicates the maximum force that a rubber composite can withstand per unit cross-sectional area before fracture occurs. Based on the test results in Table 4, formula F1 (0:60) exhibited the highest tensile strength of 20.54 MPa, while formula F5 (40:20) showed the lowest value of 14.61 MPa. A consistent decreasing trend was observed as the proportion of EFB filler in the formula increased.

This significant decrease in tensile strength reflects the superiority of carbon black as a reinforcing filler compared to EFB filler. The reinforcement mechanism of carbon black in natural rubber involves several aspects: (1) the formation of chemical bonds between active groups on the carbon black surface and the polymer chains; (2) physical immobilization of rubber layers on the surface of carbon black particles (bound rubber); and (3) the filler–filler network, which contributes to efficient load distribution [52]. These mechanisms cannot be fully replicated by EFB filler due to fundamental differences in particle morphology and surface properties.

The study by Ferreira et al. [53] confirmed these findings, stating that fillers with higher carbon black content provide better reinforcement compared to those with lower carbon black content, as carbon itself is an excellent reinforcing filler. Hayeemassae et al. [54] also reported that the presence of vulcanizing agents affects the crosslink formation behavior of composites during the curing reaction, whereby scorch time (Ts2) and optimum crosslink formation time (TS90) tend to decrease

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with increasing vulcanizing agent loading, which consequently reduces elongation at break and tensile strength.

A recent study by Karunanayake et al. [34] demonstrated that modified biochar or biochar produced at higher carbonization temperatures can yield tensile strength values approaching those of carbon black. Research using sawdust-derived activated carbon (SAC400) carbonized at 400°C achieved a tensile strength of 13.40 MPa in NR composites, approaching the values produced by composites containing carbon black. This indicates that optimization of the carbonization process for EFB filler has the potential to improve the tensile strength performance of EFB based rubber composites.

Although the tensile strength values of formulas containing EFB filler are lower than those with carbon black, the tensile strength values of formulas F2 through F4 remain within an acceptable range for motorcycle footrest pad applications. The use of EFB filler as a substitute filler should be complemented by particle size optimization through more intensive milling, surface modification to improve compatibility with the natural rubber matrix, or the addition of a compatibilizer to enhance interfacial bonding between the filler and the polymer matrix.

3.2.4. Correlation Among Mechanical Property Parameters

Correlation analysis among the tested variables revealed that increasing the proportion of EFB filler consistently reduced all measured mechanical properties, namely hardness, elongation at break, and tensile strength. The decrease in hardness values was directly proportional to the changes in tensile strength and elongation at break. This strong positive correlation indicates that the crosslink formation process undergoes a systematic decline with each incremental substitution of EFB filler.

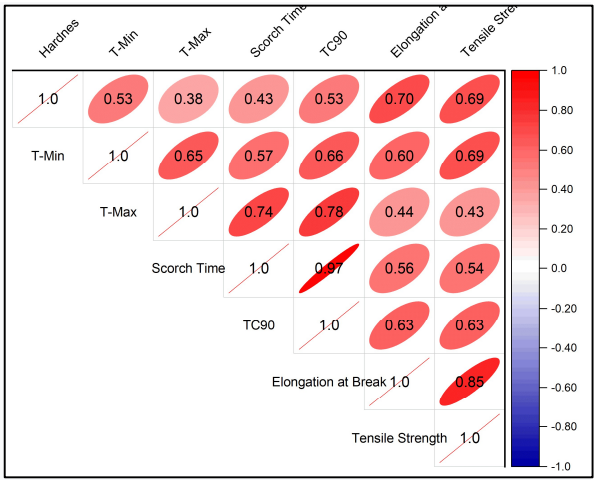

Figure 4. The comparison of hardness and tensile strength in OPEFB substitution treatment

The underlying mechanism for this correlation is that hardness, tensile strength, and elongation at break are all influenced by the crosslink density within the vulcanizate network. A reduction in crosslink density resulting from decreased filler–rubber interaction efficiency upon using EFB filler simultaneously reduces all three parameters. This finding is consistent with the research of Hayeemassae et al. [54], which stated that decreases in elongation at break, hardness, and tensile strength are caused by a reduction in crosslink formation reactions between carbon chains in the filler and the elastomer.

This consistent and correlated pattern of decline indirectly confirms the distinct reinforcement mechanisms of carbon black and EFB filler within the natural rubber matrix. Carbon black functions through an active reinforcement mechanism involving strong chemical and physical bonding with polymer chains, while EFB filler acts more as a passive filler, providing more limited mechanical contributions. Going forward, the development of surface modification methods for EFB filler such as chemical activation using KOH or H_3PO_4, or surface functionalization with silane coupling agents has the potential to improve interfacial interactions between EFB filler and the natural rubber matrix, thereby enhancing the overall mechanical properties of the composite [55].

3.3. Standard Compliance Evaluation and Practical Implications

Based on the test results for all parameters, the evaluation of compliance with the Indonesian National Standard (SNI 06-7032:2004) for motorcycle footrest pads indicates that formulas F1 (0:60), F2 (10:50), F3 (20:40), and F4 (30:30) still meet the minimum hardness requirement of 65 Shore A. Formula F5 (40:20), with a hardness value of 64.65 Shore A, does not fulfill this standard requirement. From an economic and sustainability perspective, formula F2 (10:50) with a hardness of 69.05 Shore A represents the best formula, as it offers the optimal balance between meeting product quality standards and utilizing OPEFB agro-industrial waste.

From a sustainability perspective, the utilization of EFB filler as a substitute for carbon black in rubber composites offers several significant advantages. First, OPEFB is the primary waste material of the palm oil industry and is available in extremely large quantities in Indonesia, with production reaching tens of millions of tons per year. The use of OPEFB as a feedstock for biochar contributes to the reduction of agro-industrial waste while generating value-added materials. Second, the production cost of biochar is considerably lower than that of carbon black; as of 2023, the average cost of biochar was approximately $131 per metric ton, well below the $1,198 to $2,085 per metric ton range for carbon black. Third, the substitution of petroleum-based carbon black with bio-fillers contributes to reducing the carbon footprint of the rubber industry.

To improve the performance of EFB filler-based rubber composites, several strategies can be considered based on a review of recent literature: (1) optimization of the OPEFB carbonization temperature, where higher temperatures yield biochar with a more ordered carbon structure and greater specific surface area; (2) milling and particle size classification to obtain finer particles that more closely approximate the size of carbon black; (3) surface modification of EFB filler using silane coupling agents or other chemical agents to improve compatibility with the nonpolar natural rubber matrix; and (4) optimization of the accelerator system to adjust the vulcanization characteristics of the compound to accommodate higher EFB filler content.

A recent study by Application of Sawdust Derived Activated Carbon demonstrated that biochar activated at 400°C can produce NR composites with hardness reaching 70 Shore A and tensile strength of 13.40 MPa, approaching the performance of carbon black. These findings confirm the considerable potential of

optimized EFB filler as a technically viable substitute for carbon black in finished rubber product applications, including motorcycle footrest pads.

4. CONCLUSION

The findings of this study support the potential utilization of Oil Palm Empty Fruit Bunch (OPEFB) charcoal as a natural filler substitute in rubber composites, partially replacing carbon black, which has traditionally served as the primary component in rubber formulations. OPEFB is sourced from palm oil industry waste, which is abundantly available in Indonesia; thus, its development holds strategic value from both economic and environmental perspectives.

The substitution of EFB filler for carbon black had a significant effect on all tested variables except maximum torque (MH). The physical and mechanical properties across all substitution treatments exhibited a consistent pattern, characterized by a decline in every measured parameter as the proportion of EFB filler increased. This reduction in parameter values is attributable to differences in the physicochemical characteristics of EFB filler and carbon black, including particle size, surface polarity, and affinity for the natural rubber elastomer matrix.

Based on the test results for each evaluated parameter, four formulas were found to comply with the Indonesian National Standard (SNI 06-7032:2004) for the hardness requirement of motorcycle footrest pads, namely F1 (0:60), F2 (10:50), F3 (20:40), and F4 (30:30). Formula F5 (40:20) remained below the Indonesian standard requirement. The overall best-performing formula was F2 (10:50), with a hardness value of 69.05 Shore A, which offers the optimal balance between meeting product quality standards and the substitution of agro-industrial waste-based filler.

Further research is recommended to focus on optimizing the particle size of EFB filler through advanced milling processes, surface modification of EFB filler to improve its compatibility with the natural rubber matrix, and exploration of combinations of EFB filler with other fillers such as silica to further enhance the mechanical properties of the resulting rubber composites.

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