QATAR UNIVERSITY

COLLEGE OF ENGINEERING

INVESTIGATING THE IMPACT AND MECHANICAL PROPERTIES OF RECLAIMED RUBBER AND SAWDUST COMPOSITE

BY

MOHAMMED S. A. MATAR

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COMMITTEE PAGE

The members of the Committee approve the Thesis of
Mohammed S. A. Matar defended on 28/11/2021.

Prof. Faris Tarlochan
Thesis/Dissertation Supervisor

Dr. Ioannis Chachladakis
Committee Member

Dr. MD Anwarul Hasan
Committee Member

Dr. Anand Kumar
Committee Member

Approved:

Khalid Kamal Naji, Dean, College of Engineering

ABSTRACT

MATAR, MOHAMMED, S. A. , Masters : January : 2022,

Masters of Science in Mechanical Engineering

Title: Investigating The Impact and Mechanical Properties of Reclaimed Rubber and Sawdust Composite

Supervisor of Thesis: Prof. Faris, Tarlochan.

Reclaimed rubber composites can offer promising mechanical properties and a new way of incorporating waste materials for sustainable recycling. Sawdust is a good additive for producing reclaimed rubber composites due to its low density, lower cost, availability, sustainability, and ease of handling and processing. This thesis studies the performance of reclaimed rubber-sawdust composites of different wood content. Reclaimed rubber composites of different wood content were manufactured for performance evaluation. Samples of 0, 1, 5, 10, 15, and 20% weight content of sawdust were manufactured and tested to understand the effect of wood content on performance. The performance was assessed based on different tests: tensile testing, hardness testing, Mooney viscosity testing, and water retention. Three to five samples of each wood content were manufactured for each test to assure the repeatability of the results. The tensile strength and rupture strain (ductility) decreased with the increase of wood content. The highest tensile strength (6.67 MPa) was observed in the virgin samples, while the lowest strength (2.49 MPa) was observed in the 20% wood content sample. Moreover, the highest hardness was 78.50 for 20% wood content. At the same time, the lowest value was 58.25 for the virgin reclaimed rubber sample. Furthermore, the highest MU value was 29.80 for samples of 20% wood content corresponding to an increase of 30% relative to the virgin reclaimed rubber sample that exhibited an MU value of 23. The optimum wood content percentage was 1-5%, resulting in properties within the acceptable range of industry standards. Finally, a production cost analysis found that incorporating 5% sawdust would save up production costs by 617, 18510, 225205 QR daily, monthly, and yearly, respectively.

DEDICATION

I dedicate this work to my family and friends,

my father, Sami, who supported me and believed in me through the years. I would have not achieved what I have today without your love and support.

To the love of my life and my beloved wife, Linda, who supported me during my academic journey and encouraged me to finish my thesis.

To my sister, Reham, who believed in me and motivated me to stay on the right track to complete my master's degree.

To my best friend, Sami, who urged to continue pursuing my academic career.

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CHAPTER 1: INTRODUCTION

1.1 Introduction

Many countries are grappling with the problem of waste management. This issue becomes much more important in emerging countries, given the need to balance environmental and socioeconomic growth [1]. As a result, a long-term home waste management system optimized for the most outstanding results is required. According to Qatar and other Gulf Cooperation Council (GCC) countries, sustainable waste management is one of the significant issues that need to be addressed [2]. Due to the vast desert expanses of Qatar and other GCC nations, however, landfills appear to be the most cost-effective alternative, as other waste management methods are viewed as impractical, due to the limited research in controlling and applicable technology for waste management.

Qatar creates about 28000 tons of solid garbage each day [1]. Only around 3% is recycled, 4% is disposed of via incineration, and the remaining 93% is buried in massive landfills [1]. Domestic trash generation is expected to reach about 19000 tons per day in 2032 (excluding building and demolition), representing a 4.2 percent annual growth [3]. This is due to the state of Qatar's unsustainable gross domestic product and population growth since 2001. This upward tendency is only anticipated to continue in the near future.

One of the National Development Strategy (NDS) goals is to develop a waste management strategy that emphasizes the importance of recycling [4]. The strategy's objectives include increasing the solid waste recycling rate from 8% to 38%, lowering the total number of landfills to just 53%, and producing energy from trash [4]. Tire trash is one of the most common wastes produced in Qatar. Qatar is confronted with a massive amount of tire trash as its population and economy grow. This is due to the vast number of cars utilized for people's mobility and freight and construction trucks, especially with all the development taking on in Qatar ahead to the 2022 World Cup. This tire waste is both a significant concern and a significant economic opportunity. Tires are disposed of in large landfills and are frequently exposed to the elements. If lightning strikes a tire landfill during a severe rainstorm in the winter, it might produce a catastrophic fire [5]. This might have significant negative consequences for the ecosystem as well as possible harm. On the other hand, Tire waste may be recycled and re-exported to other nations as recovered rubber sheets or utilized locally for various purposes. In Qatar, rubber recycling factories create recycled rubber, which is exported and sold locally.

1.2 Reclaimed Rubber

The primary source of waste rubber is discarded rubber items such as rubber hoses, belts, shoes, and tires [6]. Rubber recycling methods include reclaiming, re-treading, landfilling, incineration, pyrolysis, ultrasonic devulcanization, usage in road pavement via asphalt modifications, and re-use as a filler in plastics and rubber compounds [7]. End-of-life tires are the source of the most significant rubber waste. Natural and synthetic rubbers, as well as additives and plasticizers, are frequently used [8].

Reclaimed rubber is frequently utilized to extend the life of virgin rubber compounds, lower their cost, and minimize the amount of virgin rubber elastomer required [7]. Adhesives, car floor mats, mechanical goods, passenger cars, light trucks, and off-road tire tread are just a few examples [9]. Recycled rubber reinforced rubber composites, on the other hand, have a limited industrial application due to their poor impact strength and brittleness [10].

The most likely predictor of composites' future use appears to be mechanical properties. In his research, Vorga [9] looked at how adding recycled rubber into virgin rubber changed the properties of the rubber. They observed that virgin rubber had higher tensile strength and elongation at break than virgin and recycled rubber combined. According to [11], adding recycled rubber to styrene-butadiene rubber improved tensile strength, modulus, elongation at break, and hardness with increasing recovered rubber %. When more recycled rubber is added to virgin rubber, mechanical properties degrade, according to Adhikari et al. [12]. The composites' strength and stiffness have substantially increased because of this. According to Sombatsompop and Kumnuantip [13], variations in mechanical properties between synthetic and natural rubber are due to a lack of consistency.

Using recycled rubber as a substitute for virgin rubber, according to Khaled [14], results in a loss of elasticity and a 10-15% degradation in physical characteristics. According to Nesrawy et al. [15], mechanical properties of NR/SBR blends were enhanced by adding a combination of recovered rubber and carbon black, and they were further improved by increasing the mixture. Elongation at break reduced, but hardness, tensile strength, tear resistance, and modulus increased [15, 16]. Nabil et al. [17] discovered that adding recycled EPDM to natural rubber vulcanizates increased the storage modulus and glass transition temperature. The high crosslink density reportedly caused the higher storage modulus in recycled EPDM, which includes a crosslinked precursor. The rise in glass transition temperature was attributed to a potential restriction in molecular mobility caused by higher crosslinking density.

1.3 Sawdust as an Additive

Sawdust (WF) is attractive to this study because of its low density, lower cost, availability, sustainability, and ease of handling and processing [18, 19]. While research on the creation of recovered waste tire rubber/WF composites is limited, there is an abundance of knowledge on the manufacturing of virgin rubber/WF composites. The single research on sawdust recycled rubber composites found that wood can improve some characteristics [20]. The composite with 10 phr of sawdust showed improved thermal stability and mechanical properties compared to composites with a high concentration of WF [20].

The thermal stability of the composite decreased as the fraction of WF rose because WF decomposes at a lower temperature (350 °C) than RR (400 °C). Furthermore, the inclusion of WF reduced the thermal stability of the composites by lowering the starting temperature. Furthermore, the development of microcells within the composites following the addition of WF indicated a poor interfacial adhesion between WF and the RR matrix, as evidenced by a reduction in tensile strength of the composites with high WF content [20]. SEM scans supported this discovery, revealing the development of microcells inside the composites after the addition of WF.

Furthermore, storage modulus and MDR tests indicated that as the WF content grew, the stiffness of the composites increased [20], showing that the generated materials had a high capacity to absorb energy from thermal or mechanical deformation. Finally, based on the rheology data, a high concentration of WF in the composites increases the curing time and stiffness (torque).

1.4 Problem Statement

Qatar is suffering from solid wastes being damped into open damp areas as it lacks applicable and sustainable waste management systems. Ultimately, this creates environmental and health problems. At the same time, existent tire recycling facilities are suffering from challenges such as cost and reduction of raw materials. Hence, there is a need to find a solution that will solve the issues of solid waste in open damping areas while contributing to current existing tire recycling facilities.

1.5 Objectives and Scope

1.5.1 Objectives

There are two main objectives to be accomplished in this study:

1. To find applicable sawdust weight percentages to be added to the reclaimed rubber, without compromising the mechanical performance of the reclaimed rubber.
2. To study the financial and environmental impact of adding sawdust to the reclaimed rubber.

1.5.2 Scope

In order to accomplish the objects, the following scope is considered

3. Manufacturing of sawdust reclaimed rubber composite samples of different sawdust weight content: 0%, 1%, 5%, 10%, 15%, and 20%.
4. Investigating the tensile performance of sawdust-reclaimed rubber composites of different wood content by conducting tensile test experiments.
5. Investigating the hardness of sawdust-reclaimed rubber composites of different wood content by conducting hardness test experiments.
6. Investigating the Mooney viscosity performance of sawdust-reclaimed rubber composites of different wood content by conducting Mooney tests.
7. Investigating the water retention of sawdust-reclaimed rubber composites of different wood content by conducting water retention/absorption tests.
8. Comparing the performance of sawdust-reclaimed rubber composites with virgin reclaimed rubber.

1.6 Methodology

The thesis relies mainly on the experimental testing of produced sawdust-reclaimed rubber composites. Hence, the production of testing samples is crucial for this study. As-received sawdust was sieved to a 600 μm particle size to assure homogeneity of the powder when mixed with reclaimed rubber. The reclaimed rubber was produced in the "Bright Future Tyre Recycling Factory" for tire recycling in Qatar. The process of reclaimed rubber production is outlined in Chapter 3. The sieved sawdust was added to the reclaimed rubber in the refinery machine, the final step of reclaimed rubber production. The produced sheets were then cut into dog bone-shaped samples for tensile and hardness tests. It is worth noting that the tensile and hardness samples were vulcanized before conducting the tests (see Chapter 3). Mooney tests were conducted on thick devulcanized samples, as well as the water retention test samples. Three to five samples were produced and tested for each of the prescribed tests to ensure the results' repeatability.

1.7 Contributions

This thesis aims to incorporate sawdust in reclaimed rubber to produce a composite, study its performance, and compare it to virgin reclaimed rubber. The amount of research conducted on reclaimed rubber composites is lacking. Studies that explore sawdust as an additive to reclaimed rubber are somewhat limited **[20].** Moreover, the type of reclaimed rubber is different according to the type of waste tires used. Also, the sawdust sizes can be different. This makes a huge area of research on sawdust-reclaimed rubber composites that have not been touched so far. Hence, the contribution of this thesis can be highlighted as follows:

1- Production of wood-powder reclaimed rubber composites where the reclaimed rubber is made out of waste truck tires in Qatar

2- Evaluating the performance of the produced sawdust-reclaimed rubber composites under a range of tests: tensile, hardness, Mooney, and water retention

3- Comparing the performance of the produced composites with virgin reclaimed rubber to see if it is feasible and beneficial to the environment.

1.8 Thesis Layout

This thesis is organized as follows:

Chapter 1: Introduction

This chapter describes the research problem and the motivation for this thesis. This chapter contains the study objectives, a brief methodology, the thesis outline, and its contributions.

Chapter 2: Literature Review

This chapter surveys the literature in terms of the work related to the research problem. The chapter is divided into sections that describe the problem of waste management in the world and Qatar, the recycling needs for tires, the applications of reclaimed rubber, and the properties of reclaimed rubber composites. This chapter finally defines the reason behind studying sawdust-reclaimed rubber composites.

Chapter 3: Methodology

The methodology chapter highlights the experiment design of sawdust-reclaimed rubber composites according to the type of tests and the wood content. In addition, it explains the production process of both reclaimed rubber and sawdust-reclaimed rubber composites.

Chapter 4: Performance of Sawdust-Reclaimed Rubber Composites

This chapter underlines the performance of sawdust-reclaimed rubber composites. The tensile stress-strain, hardness, Mooney viscosity, and water retention behavior and characteristics for the produced composites of different wood content are discussed. Moreover, the chapter explains the reasons behind the exhibited behaviors.

Chapter 5: Financial & Environmental Aspects

This chapter provides a simple cost analysis of the production of reclaimed rubber and compares the cost to production that incorporates of 5% wood content of total production daily capacity. This chapter highlights the cost reduction associated with incorporating wood content in reclaimed rubber production and the resulted environmental and health advantages.

Chapter 6: Conclusions

This chapter outlines the main findings of the research and experiments conducted in this thesis.

Chapter 7: Recommendations for Future Work

This chapter presents some suggestions and recommendations for future research in the same field of reclaimed rubber composites and sawdust-reclaimed rubber specifically.

CHAPTER 2: LITERATURE REVIEW

2.1 Introduction

This chapter reviews the research related to the thesis topic up to date. The literature review in this chapter will discuss various topics in a way that highlights the motivation behind the conducted research in this thesis. The topics that will be covered are as follows:

- Environmental aspects and sustainability
- Reclaimed rubber recycling and applications
- Reclaimed rubber composites
- Reclaimed rubber properties

2.2 Environment and Sustainability

Waste management is a significant issue facing many countries. This issue becomes more vital with developing nations, especially with the balance needed between environmental and socioeconomic development [1]. Hence, there needs to be a sustainable domestic waste management system that is optimized for the best outcomes. Qatar and other Gulf Cooperation Council (GCC) countries declare sustainable waste management to be one of the significant areas to be tackled [2]. However, due to the considerable desert areas in Qatar and other GCC countries, utilizing landfills seems to be the most economically feasible option.

Qatar generates solid wastes of a total of around 28000 tons per day [1]. Only around 3% is recycled, while 4% is disposed of by incineration, and the remaining 93% is buried in massive landfills [1]. Figure 1 depicts the domestic waste production per capita per day in Qatar. The anticipated generated domestic waste in 2032 (without including construction and demolition) is around 19000 tons per day, with a corresponding yearly increase of 4.2% [3]. This is a consequence of the unsustainable gross domestic product (GDP) and population increase since 2001 in the state of Qatar. This trend is only expected to continue increasing rapidly in the future. The significant increase in population and economic development places a significant toll on the environment that calls for strategies. Figure 2 shows the percentage distribution of waste by type in Qatar. One of The National Development Strategy (NDS) aims to create a strategy to manage wastes that stresses the significance of recycling [4]. The strategic goals are to increase the rate of recycling solid waste from 8% to 38%, reduce landfills to only 53%, and generate energy from wastes [4].

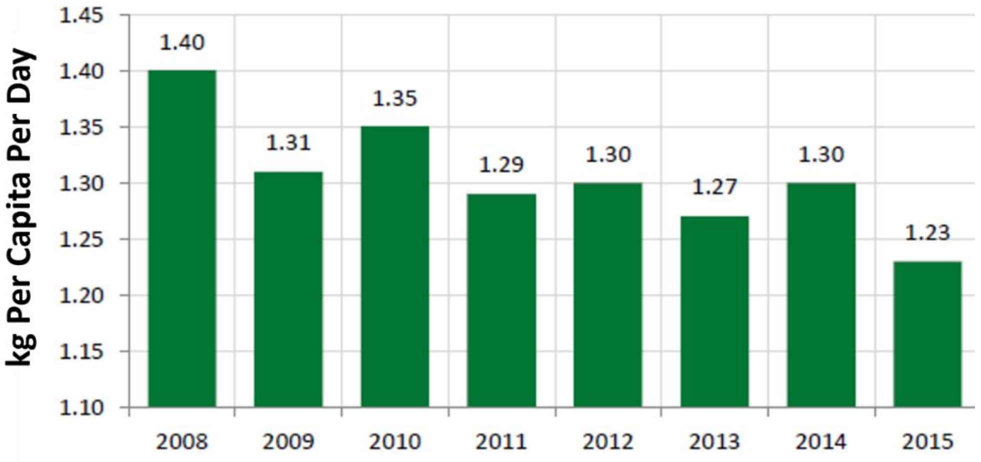


Figure 1 Domestic waste production per capita per day in Qatar [3]

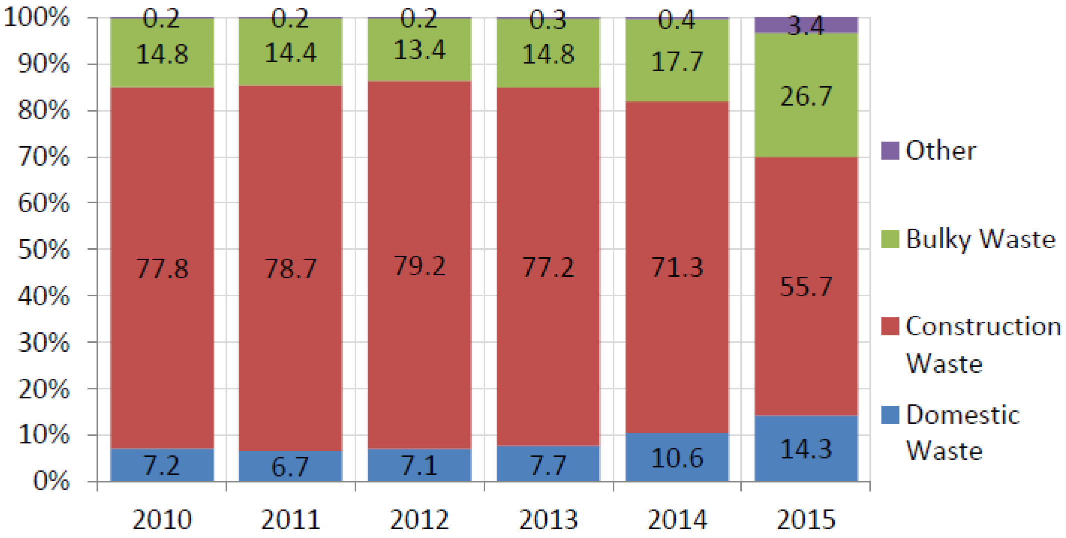


Figure 2 Percentage distribution of waste by type in Qatar [4]

Another goal of NDS is to restrict the generation of domestic waste per day [21]. Moreover, attracting attention to the topic and increasing the population's awareness of the significance of decreasing waste and promoting recycling is yet another critical goal [21]. To sum up, the plan is waste reduction, increasing the recycling rate, and promoting the efficient use of materials and recycling plants. To this end, Qatar has established the Domestic Solid Waste Management Centre (DSWMC) to tackle the issue of waste management utilizing sustainability [22]. Qatar also encourages the creation of recycling plants of all types to contribute to Qatar's solid waste management strategy.

One of the primary wastes produced in Qatar is tire wastes. With the increase in population and economic development, Qatar faces a large number of tire wastes. This comes from the large number of vehicles used for people's transportation of freight and construction vehicles, especially with all the construction taking place in Qatar before the World Cup 2022. This tire waste represents a considerable risk as well as a substantial economic opportunity. Tires are disposed of into giant landfills, and they are usually exposed to open air. In winter, during harsh rainy storms, lightning might cause a catastrophic fire if it strikes a tire landfill [5]. This may cause substantial adverse effects on the environment and potential injuries.

Rubber recycling plants exist in Qatar and produce reclaimed rubber that is exported and sold locally. On the other hand, this tire waste can be recycled and reexported as reclaimed rubber sheets to other countries or used locally for different applications. The following section explains the components of tire wastes and the different methods of recycling rubber.

2.3 Tires and Tires Waste

Tires underwent a long research and development journey with the continuous demand that has reached around 3 billion tires in 2019, corresponding to around 258 billion USD [23]. The tire consists of many layers and components that were developed and added to its design through the years [24]. Figure 3 shows the different components and layers of a tire. A regular tire is composed of 7 main parts as follows [23, 24]:

- The tread: this layer is in direct contact with the road enabling the vehicle to move in different directions. It mainly consists of natural and artificial rubber fibers. Pushes the water outward in case entrapped due to the paths engraved on the rubber.
- The belts: belts can be manufactured out of materials such as rubbers, textiles, or steel. Their primary function is giving structural support for the outer layer.
- The sidewalls: Sidewalls are usually manufactured out of rubber. Their primary function is to endure road bumps and maintain structural integrity while keeping the tire in contact with the wheel rim.
- The carcass: The carcass is manufactured of entangled metals or rubber-coated polymeric cords. It also provides the inner tire structure.
- The inner liner: It maintains the internal air at high pressure and provides excellent rolling resistance. It is made out of butyl rubber that does not allow air permeability.
- The beads and their fillers are manufactured out of steel wire coated with metal alloys of high tensile strength. Rubber is used to encapsulate the wire. The beads maintain the link between the wheel rim and the tire. On the other hand, the beads filler offers a transition between the beads wire rigid part and the internal liner.

The tire composition might rely on the mode of use, such as long distances or the driving environment, such as the quality of the road or the environment temperature. Table *1* reorganizes the average composition of various tire components based on the tire class.

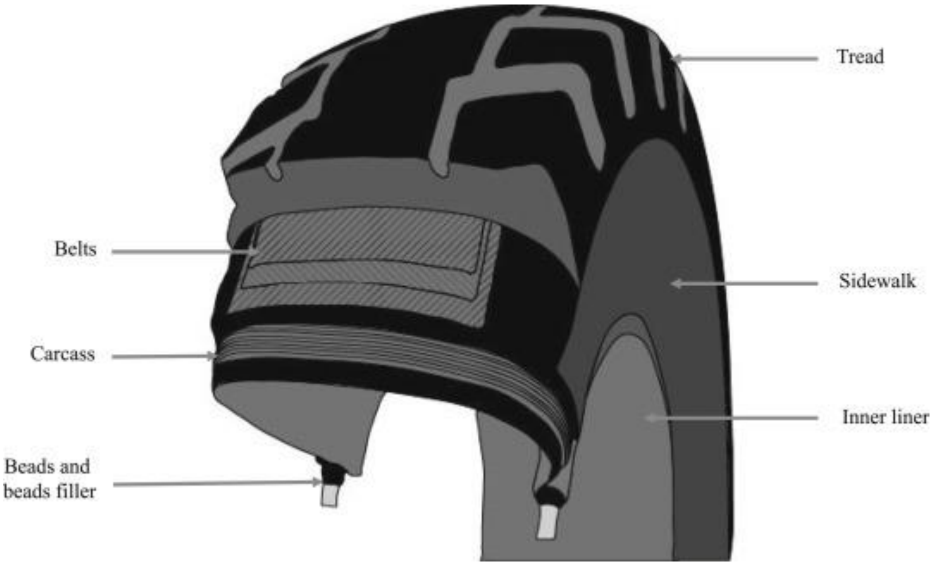


Figure 3 Tire structure and components [5]

TABLE 1 TIRE COMPOSITION ACCORDING TO THE TIRE CLASS [25]

Material	Car tire	Truck tire	Off-road tire
Rubber/Elastomers (wt. %)	47	45	47
Carbon black and silica (wt. %)	22.5	21	22
Metals (wt. %)	14	23.5	12
Textiles (wt. %)	5.5	1	10
Vulcanization agents (wt. %)	2.5	3	3
Additives (wt. %)	8.5	6.5	6

The main parts of tires are made of a blend of various natural or synthetic rubbers. Natural rubbers include polyisoprene, while synthetic rubbers include polybutadiene, styrene-butadiene rubber (SBR), and (halo)butyl rubber. The proportions of these rubbers in the blend depend mainly on the tire intended use. The rubbers mentioned above are shown in **Figure 4**. Those rubbers mainly exist in the sidewalls (22%) and treads (32.5%) of the tires [24, 26].

The following two main components in making up tire composition are silica and carbon black. They maintain enhanced protection against cuts and wears and reinforce the tire mechanically [26]. Their structure and size vary based on their location within the tire. Compounds of smaller size are found in the treads and carcasses of the tire. On the other hand, more prominent compounds are found in the internal liner. Nowadays, silicas are more preferred than carbon black for environmental reasons [26].

Metallic elements are also part of the tire composition. Metals and usually used for tire reinforcement. Different metal alloys can be used; for instance, steel alloys can be found in tire belts or bead wires in different percentages according to the vehicle and its class of use [26]. Textiles can also be used in tires for reinforcement purposes such as polyester, nylon, and rayon. They are sometimes used instead of metals for weight-lightening purposes [23].

Finally, to enhance the production process of tires, different sulfur groups are added in a process known as vulcanization. Hence, different vulcanization additives can be found in tires composition. Sulfur groups, stearic acids, and zinc oxides are vulcanization agents that increase the rate of forming 3D polymer networks [27]. The vulcanization process is also known as curing. The process involves creating links between the rubber and sulfur [27]. Rubber that has been vulcanized is more durable and resistant to deformation because of the developed cross-linking [27]. It is worth noting that used tires have different compositions as they wear with use and time [23]. The term crumb rubber gathers the remaining rubber contaminated by metals and fibers [23]. Table *2* lists the composition of various components in scrap tires.

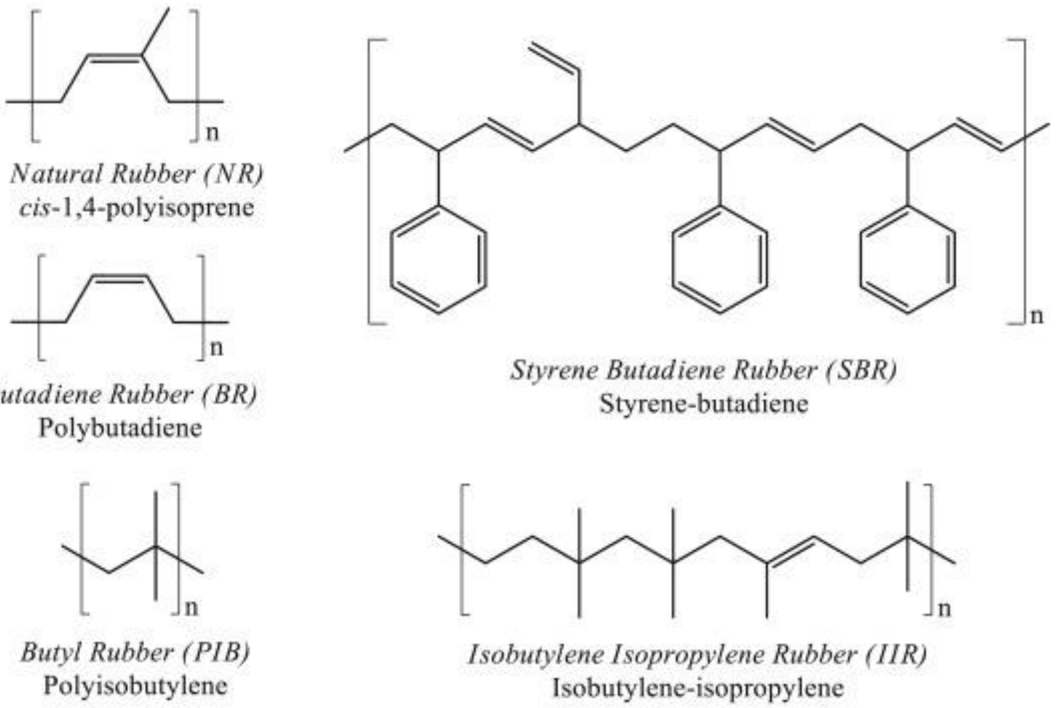


Figure 4 Rubbers used in making up tires [24]

TABLE 2 COMPOSITION OF USED TIRES BASED ON THE USE [5]

Material	Car tire	Truck tire	Off-road tire
Crumb rubber (wt. %)	70	70	78
Steel (wt. %)	17	27	15
Fibres and scrap (wt. %)	13	3	7

2.4 Waste Tire Recycling

2.4.1. Recycling Needs

The ever-increasing need for tires accompanies a surge in recycling requirements [28]. As mentioned earlier, many materials go into the composition of tires and not rubber [30]. Furthermore, the newly developed fabrication technologies add novel components and materials into the tire composition [29]. This, in turn, increases the difficulty of recycling tires.

Waste tires are usually stored in landfills in huge piles. This method of storage causes vast environmental problems as it results in soil contamination. It may also create an environment for rats and bugs [29]. Another problem with waste tire landfills is that tires are flammable, which may cause wildfire [5]. To eliminate the risks involved with piling waste tires in landfills, sometimes waste tires are burned on purpose [5]. Burning waste tires burning may last a long-time, causing health problems and environmental risks. Due to the risks mentioned above, the European Commission released the Directive 1999/31/EC to prevent waste tires' disposal in landfills.

Nonetheless, many recycling methods have been created and developed during the last 20 years, while new methods are still being developed to enhance the recycling rate of rubber tires. These methods account for a rate of 90% and 85% recovery of tires in Europe and countries like Japan and the US, respectively, based on European Tire & Rubber Manufacturers’ Association and the Global End-of-Life Tire Management [5].

2.4.2 Strategies of Tires Recovery

There have been various treatments and different types of technologies to recycle waste tires and reclaim their materials. Executing these methods and strategies can be categorized in the following three primary classes [5]:

- Civil engineering: Civil engineering applications make use of the End-of-Life Tire (ELT) structure. Waste tires, for instance, can be used in crash barriers in roads, as basins for holding water, and for backfilling for mining sites or land. Using reclaimed rubber in asphalt blends is not included in this class.
- Energy recovery: Energy can be reclaimed back from waste tires of ELTs by using them as fuel substitute directly on cement kilns or indirectly by extra processing such as pyrolysis to get fuel.
- Material recovery: The components making up the composition of the tire can be reclaimed back, primarily steel and rubber. The definition of recycling by the Parliament and Council of the European Union in the Directive 2008/98/EC states: "‘Recycling’ means any recovery operation by which waste materials are reprocessed into products, materials or substances whether for the original or other purposes. It includes the reprocessing of organic material but does not include energy recovery and the reprocessing into materials that are to be used as fuels or for backfilling operations".

This material recovery class fits this definition perfectly. The material recovery process covers rubber size reduction up to the process of devulcanization. This is done to produce rubber powder that is similar in characteristics to the initial product. Products that have been reduced in size are utilized in different engineering projects, predominantly civil, can be used as fuel (energy recovery), or can undergo further processing for different applications. The devulcanization treatments are different from recycling or reclaiming processes because devulcanization aims to produce pure rubber. This is done via the scission of the polysulfide bonds created through the vulcanization treatment. The reuse of raw materials is vital to reduce the usage of fossil materials to ensure sustainability.

There exist four levels of treatments of waste tires linked by the increasing complexity of the process [23]. Table 3 lists those levels and their description.

TABLE 3 DIFFERENT LEVELS OF WASTE TIRES TREATMENTS [23]

Level	Description
Level 1	Waste tire structure destruction via a basic mechanical process destroys the tire's primary physical characteristics, such as shape and flexibility. Removing beads, treads, and sidewalls are involved in this level and balling, compressing, and cutting. The final products of this level are utilized in thermal insulation projects or as filler to achieve lightweights. Final products of this level can also be used in other recycling levels.
Level 2	This level involves decomposing and separating the tire's elements via processes that split the tire into three significant materials: rubber, metals, and textiles. Ambient and cryogenic size reduction processes are prevalent at this level. It involves shredding, chipping, and grinding. Pyrolysis can also be involved at this recycling level.
Level 3	This level includes consequent processes that alter some of the structural features of the waste tire's materials. Those processes can be mechanical, thermomechanical, chemical, or mechanochemical. For instance, reclaim processes, surface modifications, pyrolysis, and devulcanization are used in this recycling level.
Level 4	This level includes the process that improves specific properties or features of the material. Thermoplastic elastomers production and enhanced reclaim and carbon products are famous examples [30, 31].

2.5 Rubber Reclaiming: Physical Processes

Physical reclamation techniques include breaking the three-dimensional network of cross-linked rubber using various external energy sources [12]. Due to network breakdown, rubber from trash tires is converted to low molecular weight pieces, subsequently blended with virgin rubber [12]. Physical processes provide products that can be utilized as feedstock for other processes (chemical and biological) or directly valorized uses such as concrete manufacturing [32-35].

2.5.1 Thermo-mechanical Processes

Among the contemporary rubber reclamation processes, thermo-mechanical techniques are typically the most widely used. Mechanical shearing and a high rise in temperature, approximately 200 °C, caused by an external heat source, and friction between the crumb rubbers, are used in these systems. The rearrangement of polysulfide cross-links and the breakdown of carbon-carbon bonds cause devulcanization and the creation of shorter polymer chains. The polysulfide cross-links are evacuated under the influence of hydrogen sulfide, carbon desulphated, and sulfur dioxide [25]. Before or during the grinding process, solvents such as hexane, supercritical fluids, subcritical water, or oils can be introduced to help speed up the process, solubilize the tiny chains, and produce swollen rubber [12, 36].

2.5.2 Mechano-chemical Processes

Mechanical forces such as shearing, temperature, and chemical reactions are used in mechano-chemical processes [12, 36].

2.5.3 Grinding Processes

Since the mid-1960s, cryo-mechanical techniques for recovering rubber from discarded tires have been described [12, 37]. Cyano-mechanical techniques are now used as a pretreatment before the devulcanization process to create fine rubber powder with uniform size. Small crumb rubber pieces are submerged in liquid nitrogen until they reach their glass transition temperature (Tg). They are transported to a ball mill and crushed into fine particles ranging from 30 to 100 mesh. This process not only allows for the production of finer powders with higher value, but it also allows for the modification of physical characteristics such as tensile strength, elongation modulus, and elongation at break [12].

Dry ambient grinding is a mechanical grinding process that involves placing scrap tire parts in a grinder with a jagged edge [38]. Rubber particles are decreased in size from 10 to 30 mesh. While this technique is called "ambient grinding," the term is not entirely accurate because the heat generated during the grinding process can induce polymer chain breakdown, especially in high modulus or older tires. Due to the production of pendant groups during the grinding process, the reclaimed rubber may be directly connected to the virgin rubber matrix.

The rubber is submerged in a liquid media, usually water, during wet or solution grinding, also known as "micro-milling." Because the tiny particles are continually washed away while the liquid medium removes contaminants such as fiber residues, the generated particles, up to 200 mesh, have superior cleanliness and homogeneity than dry grinding products [38]. The wet grinding method produces a more processable product and allows for smoother extrusion [6].

2.5.4 Microwave Procedures

Using a precise frequency and energy level, microwave techniques can break down carbon-carbon bonds [10]. Waste rubber must be made up of polar groups to be recovered; otherwise, microwave radiation will not be able to create enough energy to devulcanize the material. This method does not depolymerize the rubber, allowing it to be reused and devulcanized, yielding characteristics that are extremely similar to the original vulcanizate.

2.5.5 Ultrasonic Techniques

Ultrasonic techniques induce cavitation bubbles in the medium by a series of extension-compression stresses generated by high-frequency mechanical vibrations. This phenomenon is taken advantage of to generate enough energy to break the carbon-sulfur and sulfur-sulfur bonds required for devulcanization. In a patented work [39], ultrasonic techniques were employed for the first time in rubber reclamation. An ultrasonic field is used to immerse solid rubber in liquid media. The rubber pieces collide, resulting in the disintegration and solubilization of the fragmented portions in the liquid medium.

2.6 Rubber Reclaiming – Chemical Processes

Among the rubber reclamation methods, chemical procedures are the most utilized by industrial businesses. Rubber is reclaimed using a variety of organic and inorganic chemicals. In such procedures, sulfides and mercaptans compounds are commonly employed. Non-sulfured compounds, on the other hand, are now being studied due to their more environmentally friendly and cost-effective nature. Furthermore, due to the chemical breakdown that happens even when no chemicals are introduced, pyrolysis is also considered a chemical reclamation process [40]. Pyrolysis does not fall under the concept of recycling as defined by Directive 2008/98/EC because it results in energy recovery.

2.6.1 Pyrolysis

Pyrolysis is a kind of thermolysis in which organic molecules are broken down, altering their chemical composition and phase [40]. Thermochemical breakdown takes place in an anaerobic environment and is irreversible. After waste tire pyrolysis, three stages emerge solid (carbon black and impurities), oil, and gas (organic molecules), all of which may be recycled to generate energy, fuel, chemicals, or materials. The steps of pyrolysis are discussed in depth in [41, 42].

2.6.2 Organic Disulfides and Mercaptans

In order to recover rubber from waste tires, several disulfides and mercaptans (Figure 5) were created and evaluated throughout the last century. The devulcanization of organic disulfides and mercaptans involves multiple reaction stages. However, they can be generalized as shown in Figure 6 [25, 43]. To continue to the homolytic scissions of the components, this type of procedure necessitates heat. As a result, radical forms of polysulfide cross-links and a devulcanizing agent are produced. They can pair with one another, resulting in rubber devulcanization. However, homolytic scission of the main chain and coupling with a devulcanizing agent may result in polymer breakdown. Furthermore, these cross-links do not generate free radicals in these circumstances due to the temperature stability of the monosulfide bond. A larger quantity of heat, on the other hand, would cause the main chain to degrade faster, resulting in a product with poor mechanical characteristics.

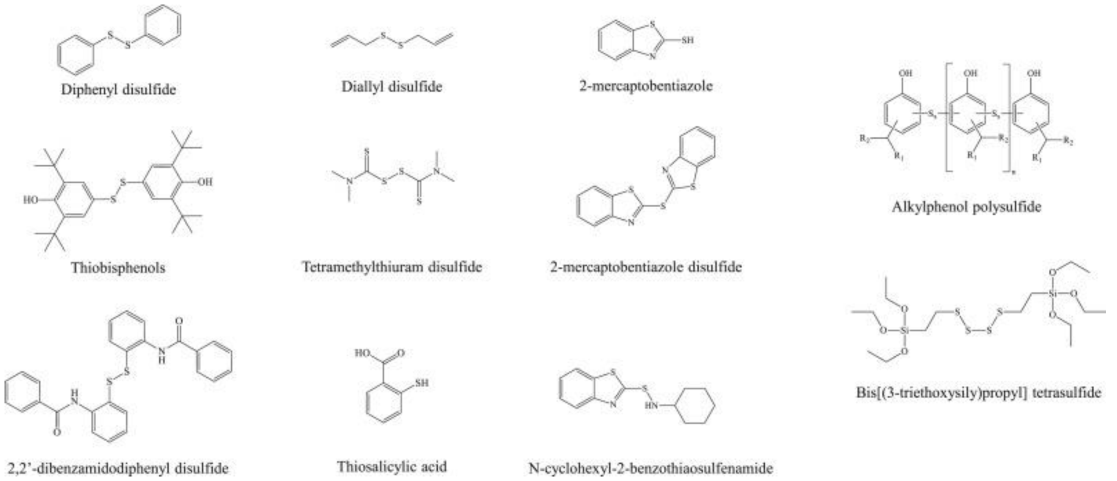


Figure 5 Sulfides and mercaptans used in waste tire rubber reclaiming

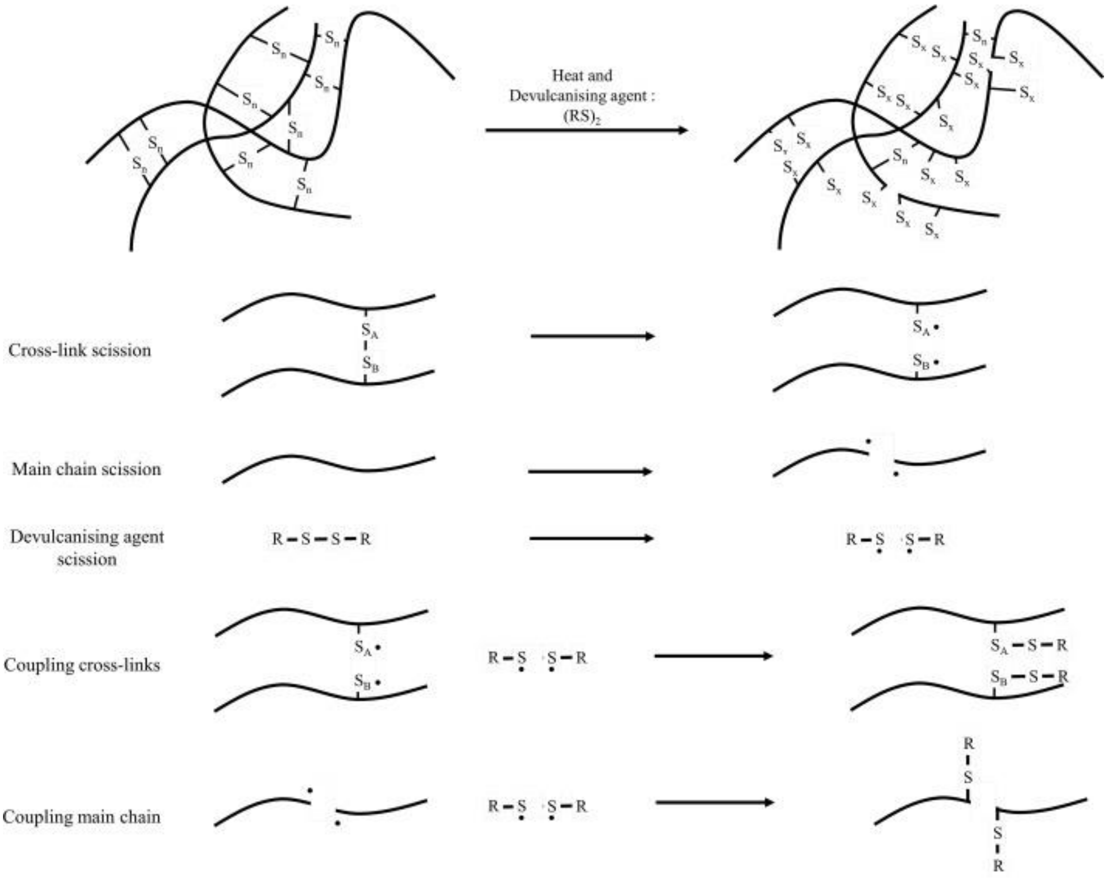


Figure 6 Devulcanisation mechanism with sulfide agent

2.6.3 Catalysts, Inorganic & Sulfur Free Organic Compounds

Further organic compounds were developed to selectively break carbon-sulfur and sulfur-sulfur bonds while leaving the carbon-carbon bond intact: propane thiol/piperidine [44], triphenylphosphine (PPh3), trialkyl phosphites [45], lithium aluminum hydride [46], and methyl iodide [47]. Inorganic compounds are also being developed for the recycling of discarded tires.

2.6.4 Solvents

In the rubber reclamation process, organic solvents are also used. The effects of alcohol and ketone were studied. After being vulcanized, the resultant compounds must be combined with virgin rubber to get the desired mechanical characteristics.

Turpentine liquids, notably α-terpineol, have been proposed for devulcanization procedures using organic solvents [48]. These liquids can be bio-sourced and can reduce 2-butanol by 50% during the devulcanization process. For temperatures below 150 °C, a blend of turpentine liquids and 2-butanol was tried, and 75–100% devulcanization was produced.

Figure 7 depicts an outline of the different rubber reclaiming processes and categories for convenience.

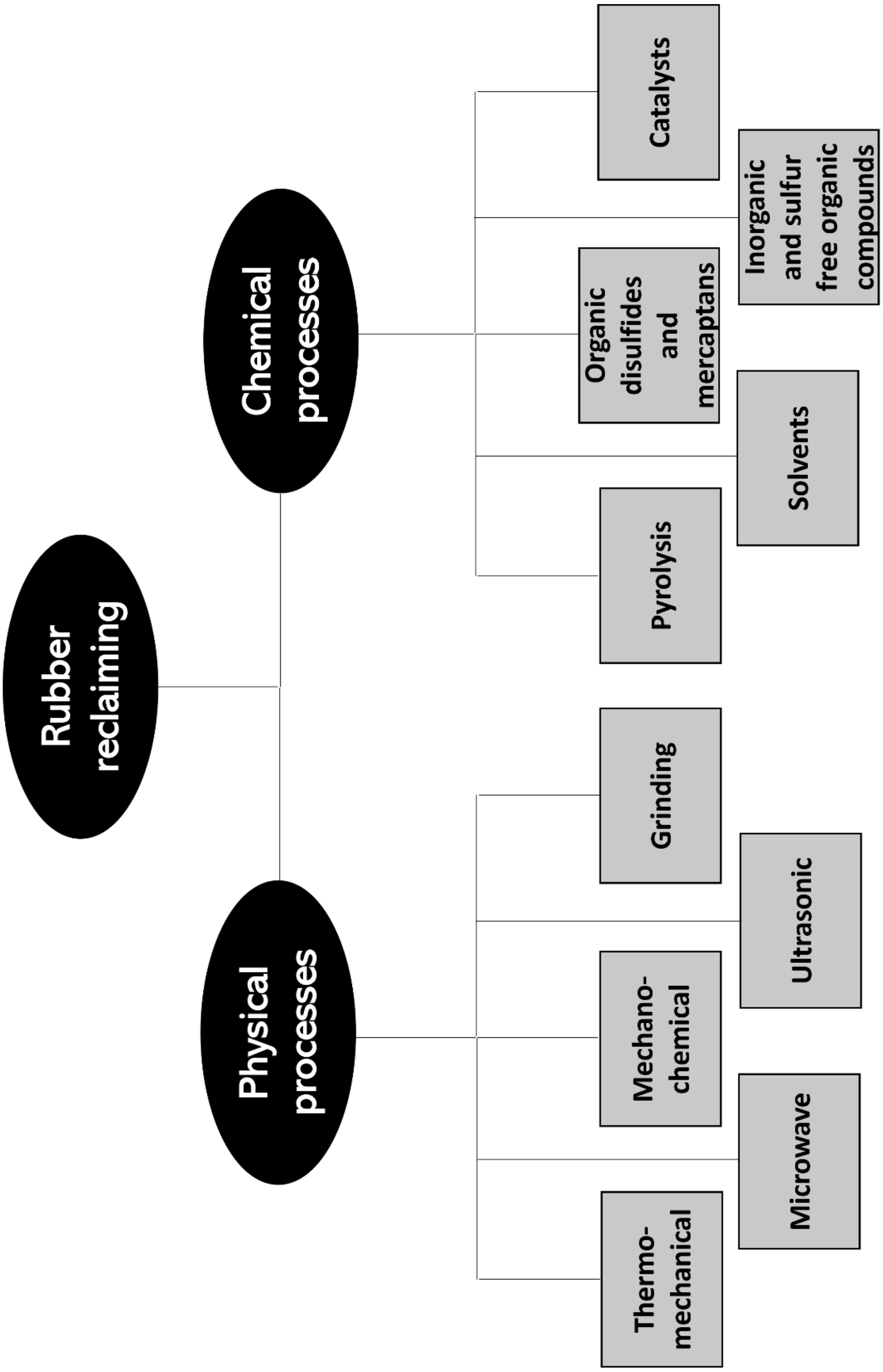


Figure 7 Summary of the various rubber reclaiming processes

2.7 Reclaimed Rubber Composites

2.7.1 Applications

Waste rubber goods, such as hoses, straps, and tires, are the primary source of waste rubber [6]. Re-use as a filler in plastics and rubber compounds has been studied to recycle rubber [7]. Waste tires contribute the most to the amount of rubber waste. They are often made up of two or more polymers, such as natural and synthetic rubbers, as well as additives and plasticizers [8]. To make ground tire rubber (GTR), waste tires must be grinded at temperatures below the glass transition. The rubber matrix particles' diameters are reduced because of this procedure.

GTR that is smaller than 2 mm in size can be utilized as a filler in other applications. Because of the sulfur crosslink network, it is also impossible to integrate GTR in virgin rubber due to incompatibility. A reclamation procedure, on the other hand, can enhance compatibility. Vulcanized rubber is converted to mixtures that may be reprocessed, re-cross-linked, and molded via reclaiming [49]. It causes the crosslinking sites to break, resulting in rubber with a low molecular weight [50]. The use of recycled rubber to reinforce virgin rubber improves quality and lowers manufacturing expenses. Nevertheless, high compatibility between recycled and virgin rubber must be achieved [12]. The use of recycled rubber in rubber compositions is every day in the industry for various reasons. Better processing, homogeneity, reduced heat growth, reduced thermo-plasticity, reduced swelling and shrinkage, increased curing rate, excellent shape retention, and enhanced tack are only a few of these benefits [7, 9, 51]. Reclaimed rubber is often used to extend the life of virgin rubber mixtures, reduce the price of rubber mixtures, and reduce the amount of virgin rubber elastomer required [7]. Adhesives, automobile floor mats, mechanical products, passenger car tread, light truck, and off-road tires are just a few examples [9]. However, recycled rubber reinforced rubber composites have limited industrial use due to their low impact strength and brittleness [10].

Because its tack exhibited minor modification with weather changes, reclaimed rubber was appropriate for pressure-sensitive applications. In contrast to natural rubber, that was sticky in hot climate and dry in cold climate. Rubber was plasticized during reclamation because of the significant mechanical effort, resulting in mixing durations nearly half of those of virgin rubber during rubber formation [6]. Different reclaim varieties are available on the market. High-quality reclaim allows more significant amounts of recovered rubber to be integrated into fresh rubber with less property degradation [52]. The kind of curing system and vulcanizing circumstances altered the quality of recycled rubber, influencing crosslinking density and, as a result, thermal and mechanical characteristics [13]. The applied shear force to the particles of rubber impacted the reclaiming degree in mechano-chemical processes [8]. Not all crosslinks in the rubber substance were removed during the reclamation process. After re-vulcanizing the reclaim, this produced a significant crosslink density. Reclaimed rubber molecules were firmly bonded and did not have adequate flexibility to entangle and interact with the matrix due to the strong crosslinking, resulting in poor interfacial adhesion [10]. As a result, waste rubber appeared to prefer treatment with coupling agents before mixing to improve compatibility [10, 53]. The overall characteristics of the composites were impacted by the content and processing of scrap rubber. Mechanical characteristics like modulus, rip strength, tensile strength, storage modulus, and others have been influenced by recycled rubber concentrations in virgin rubber [6]. Antioxidants were once necessary in rubber compositions to preserve rubber components from thermo-oxidation and to prevent vulcanization aging. The aging procedure can begin as a result of environmental factors [54].

The way composites are processed may have an impact on their ultimate characteristics. TGA was used by Krzysztof et al. [10] to describe GTR. They found that GTR comprised roughly 50% elastomer (NR and SBR), 30% carbon black, and 15% additives. Zhang et al. [55] examined the characteristics of waste tire fiber-reinforced reclaimed rubber composites made with a two-roll mixer with composites made with pan milling. However, because recovered rubber has been found to contain anti-aging properties, this becomes a benefit when reclaimed rubber is mixed with virgin rubber, as antioxidants may not be necessary. The tensile characteristics of traditionally produced composites decreased as the fiber content increased. With 5% fiber loading, the pan composites showed the best tensile characteristics. According to Krzysztof et al. [10], recovered rubber with a high degree of reclamation achieved under high shear stress has deteriorated tensile characteristics, hardness, resilience, and abrasion resistance.

2.7.2 Properties

2.7.2.1 Curing Properties

Debapriya and Debabish [11] investigated the integration of recycled rubber into styrene-butadiene rubber. Using recycled rubber, they saw a rise in cure rate, a reduction in cure time, and no significant differences in scorch time. However, when Sombatsompop and Kumnuantip [13] mixed recycled rubber with natural rubber, they found that the cure rate improved, the scorch time decreased, and the cure time remained unchanged. Khaled [14] found a drop in maximum torque and a rise in minimum torque, scorch time, and curing rate accompanying the inclusion of recycled rubber into virgin rubber. It may be argued that when recycled rubber is mixed with virgin rubber, the cure rate improves. This curing rate behavior has been linked to active crosslinking sites and untreated curatives in recycled rubber, both of which have been shown to speed up crosslink production [17,65-70] [10, 11, 13, 14, 55]. Farahani [56] also studied the cure properties (Figure 8) of natural rubber/recovered rubber blends, finding that adding up to 50 percent reclaimed rubber reduced cure time and scorch time while increasing cure rate. Above 50 phr, the cure rate dropped, the scorch time rose, and the cure remained unchanged. The varying amounts of sulfur found above and below 50 phr were ascribed to this pattern. Ravichandran and Natchimuthu [7] found that adding recycled rubber (500 phr) to a mixture of natural rubber (100 phr) and leather protein fiber reduced maximum torque (100 phr). However, the minimum torque values have been raised. The physical stiffening impact of recovered rubber on natural rubber matrix before vulcanisation was blamed for the rise in minimum torque. The reduction in maximum torque was due to the diluting effect of a large amount of recycled rubber relative to the amount of curatives present.

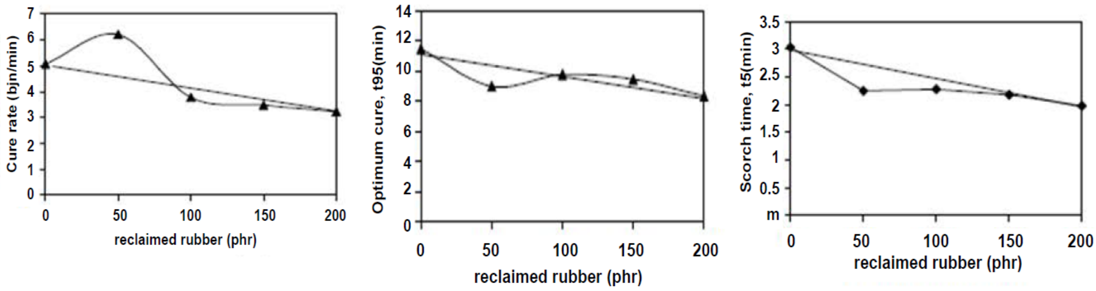


Figure 8 Curing properties and scorch time for rubber/reclaimed rubber blends [56]

Phiri et al. [20] studied the effect of sawdust filler in reclaimed rubber. With a high concentration of WF in the composites, the curing time and stiffness (torque) rise, according to the rheology data.

2.7.2.2 Mechanical Properties

Mechanical characteristics appear to be the most likely determinant of composites' future use. Vorga [9] examined the alteration of rubber characteristics by incorporating recycled rubber into virgin rubber in research. They discovered that virgin rubber has better tensile strength and elongation at break than a combination of virgin and recycled rubber. In comparison to the original combination, the addition of various compatibilizers enhanced specific characteristics. However, the incorporation of recycled rubber in virgin rubber resulted in a rise in elongation at break and a loss in tensile strength, according to Khaled [14]. The inclusion of recycled rubber into styrene-butadiene rubber enhanced tensile strength, modulus, elongation at break, and hardness as reclaimed rubber percentage increased, according to research by Debapriya and Debabish [11]. The existing carbon black and the huge crosslink density in recycled rubber was reportedly responsible for improving tensile strength and modulus (Figure 9) [11, 57]. The degree of adhesion between virgin and recycled rubber was blamed for increasing elongation at the break of composites [11]. Adhikari et al. [12] found that mechanical characteristics deteriorate when more recycled rubber is introduced to virgin rubber. Xiaoou [16] found that adding filler to recycled rubber enhanced tensile strength while decreasing elongation at rupture when the filler was raised. This showed the significantly improved strength and stiffness of the composites. According to Sombatsompop and Kumnuantip [13], less uniformity explains the differences in mechanical characteristics compared to natural rubber. Defects produced by the lower homogeneity are reported to have resulted in a reduction in tensile strength and elongation at break.

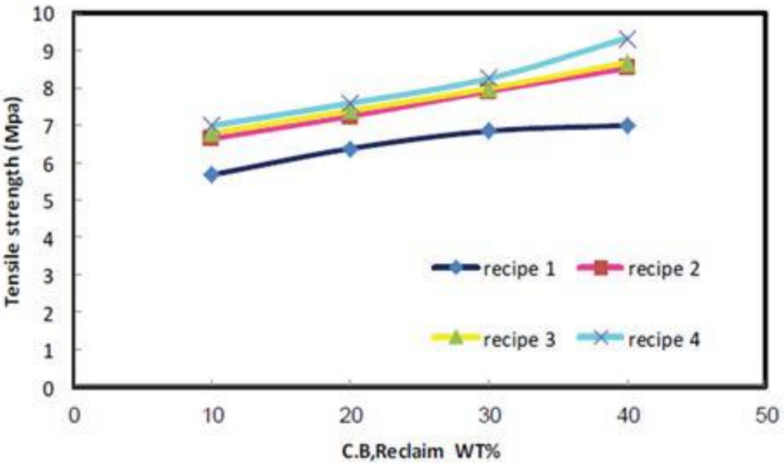


Figure 9 Carbon black impact on tensile strength in reclaimed rubber of virgin rubber/reclaimed rubber blends [11].

According to Khaled [14], using reclaimed rubber as a substitute for virgin rubber causes a loss of elasticity and a 10-15% weakening in properties, that could be because of a decrease in the average length of rubber polymer chains as a result of the addition of reclaim, resulting in a loss of tensile strength (Figure 10). Mechanical characteristics of NR/SBR blends were enhanced by adding a blend of recovered rubber and carbon black, according to Nesrawy, and they were increased more by increasing the mixture. Hardness, tensile strength, tear resistance, and modulus increased while elongation at break decreased [15, 16].

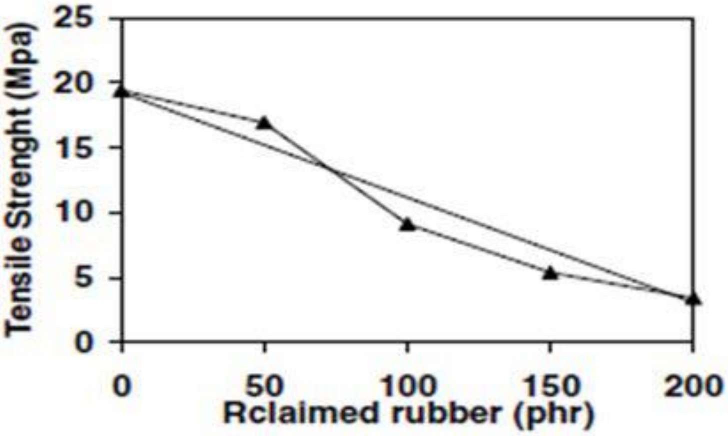


Figure 10 Tensile strength and reclaimed rubber content in virgin rubber/reclaimed rubber blends [14]

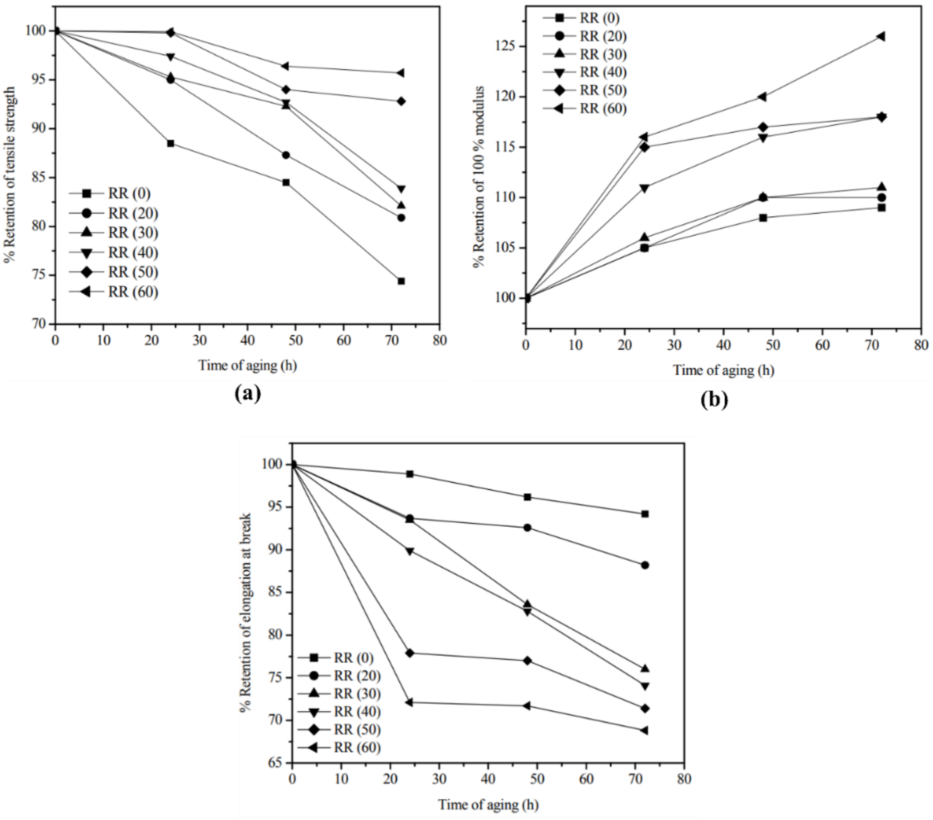
Farahani [56] observed a somewhat different pattern in which hardness and modulus rose. Hardness did not vary significantly at low reclaim content, but it increased significantly at highly high reclaim content [11, 58-62]. At the same time, tensile strength and elongation at break dropped as the quantity of recycled rubber integrated into natural rubber increased. Also, according to Debapriya [11], tensile strength rose as reclaim content increased. However, it was less for natural rubber/reclaim rubber mixtures than for virgin-rubber-alone preparations. The damping factor (tan delta) is crucial in determining composite materials' damping characteristics and energy dissipation capability. The matrix has the most impact on damping characteristics. Composites use energy due to the stress transmission mechanism between the matrix and the filler. As a result, in most situations, filled composites dampen better than empty matrices [16].

Xiaoou [16] observed the damping factor, storage and loss moduli of filled recycled rubber blends in dynamical mechanical analysis research. The damping factor was reduced when the filler quantity was raised, while the storage and loss moduli were enhanced. Filler content does not influence the loss and storage moduli of filled recycled rubber. The composites have improved energy dissipation capability, according to the findings. Debapriya [58] reported viscoelastic behavior, observing that storage and loss moduli rose consistently with increasing reclaim rubber percentage, although tan delta reduced. The inclusion of recycled rubber improved the viscoelastic properties of the rubber compositions, according to their findings. With the addition of recycled EPDM to natural rubber vulcanizates, Nabil et al. [17] found increased storage modulus and glass transition temperature of natural rubber vulcanizates. The high crosslink density in recycled EPDM, which is thought to contain a crosslinked precursor, was allegedly responsible for the increased storage modulus. A potential limitation in molecular mobility induced by increased crosslinking density was blamed for the rise in glass transition temperature.

Other reclaimed rubber composites utilized sawdust as a filler in the reclaimed rubber matrix. Phiri et al. [20] studied the effect of sawdust filler in reclaimed rubber. The formation of microcells within the composites after adding WF revealed a poor interfacial adhesion between WF and RR matrix, as evidenced by a decrease in tensile strength of the composites with high WF content. This observation was confirmed by SEM images, which revealed the formation of microcells within the composites after adding WF. Furthermore, storage modulus and MDR tests revealed that the stiffness of the composites increased as the WF content rose, indicating that the produced materials had a strong potential to absorb energy provided for thermal or mechanical deformation. Manaila et al. [59] also studied the effect of wood sawdust in rubber. Because of the inclusion of wood sawdust, the physical and mechanical properties of the produced blends were found to be better than those of pure natural rubber, except for the elasticity and elongation set. As a result, hardness, 100% Modulus, 300% Modulus, ripping, and tensile strength have improved.

2.7.2.3 Thermal Properties

The % preservation of characteristics after aging is the best way to study the condition of rubber degradation [54]. When compared to virgin rubber, reclaimed rubber has been shown to have improved aging characteristics [6, 58]. The stability of the hydrocarbon chains during reclamation by heating, digesting, and mechanical shearing was ascribed to the improvement in thermal aging behavior [6]. If recycled rubber is utilized in rubber compounding, antioxidants may not be required because of the improved aging characteristics. Debapriya and Debasish [11] reported on a thermal aging investigation of recycled rubber reinforced composites. They found that as thermal aging progressed, percentage retention of tensile strength and elongation at break decreased. However, percentage retention of tensile strength rose as recovered rubber content increased. However, percentage retention of elongation at break decreased considerably. The percentage retention of hardness and 100 percent modulus increased as thermal aging progressed (Figure 11).



(a) (b)

(c)

Figure 11 Retention of (a) tensile strength, (b) 100% modulus, and (c) elongation at a rupture with different aging times [11]

However, Debapriya et al. [58] found that natural rubber/reclaimed rubber mixes had better percentage holdings of tensile strength and elongation at break than natural rubber. According to Nabil et al. [17], reclaimed EPDM/natural rubber vulcanizates have aging characteristics. After aging, they saw a decrease in tensile characteristics, which they ascribed to chain scission induced by polymer oxidation, causing entanglement and lower strength. Despite this, the maintained property percentage indicated that the compounds' thermal stability improved with the addition of recovered EPDM, which was ascribed to creating more crosslinks. In a thermal-gravimetric study (Figure 20) [11], it was reported that increasing the amount of recovered rubber in the rubber formulations improved the thermal stability of the rubber formulations. Their thermal aging research agreed with the results of the analysis. TGA was used by

Krzysztof et al. [10] and Nadal et al. [60] to examine the breakdown profile of recovered rubber produced from tires. Krzysztof et al. [10] observed a three-step breakdown profile, with natural and synthetic rubber degradation at 350 and 600 degrees Celsius, respectively. Krzysztof et al. [10] also noticed a breakdown between 200 and 350 C, attributed to the reclaims plasticizers and low molecular weight additives disintegration/evaporation. Volatile chemicals were produced at about 200C, according to Nadal et al. [60]. In contrast, natural rubber and butyl rubber/styrene-butadiene rubber breakdowns occurred just about 382C and 461C, respectively.

Phiri et al. [20] studied the effect of sawdust filler in reclaimed rubber. Compared to composites with a high concentration of WF, the composite with 10 phr of sawdust had better thermal stability and mechanical characteristics [20]. Because WF decomposes at a lower temperature (350 °C) than RR (400 °C), the thermal stability of the composite reduced as the proportion of WF increased. Furthermore, with the addition of WF, the onset temperature reduced the composites' thermal stability.

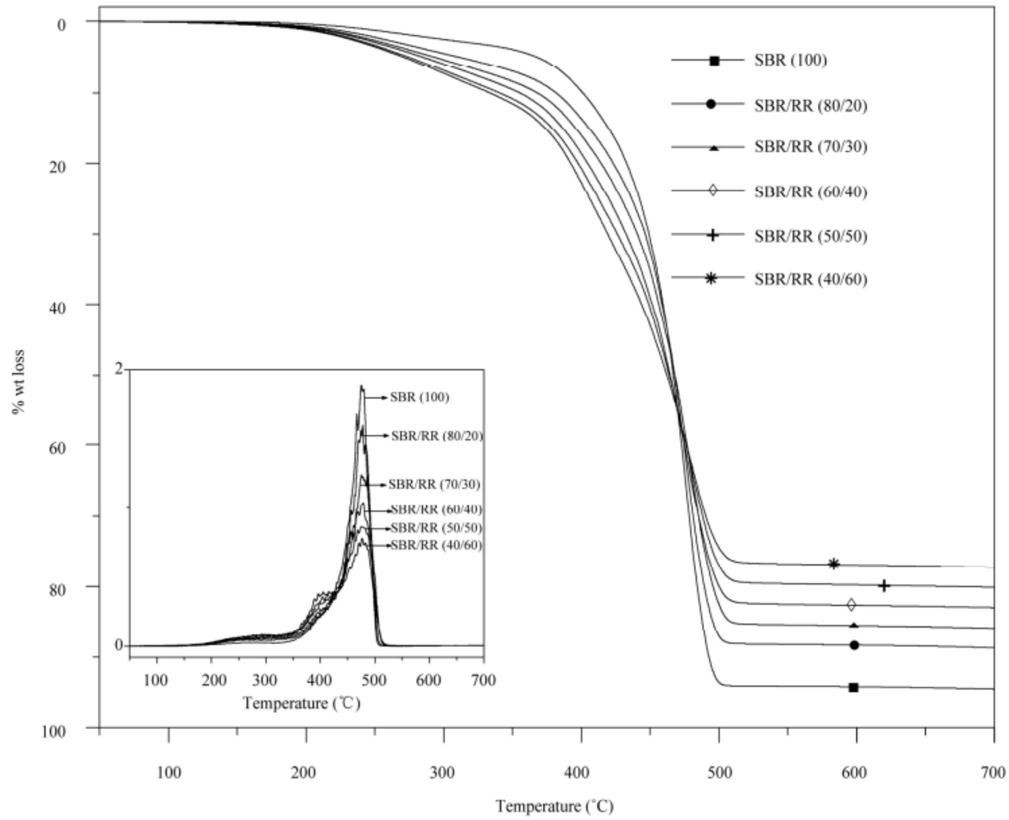


Figure 12 Thermogravimetric analysis of SBR/RR Vulcanizates [11]

2.8 Summary of Literature

This chapter provided a complete literature survey on the topics primarily related to the thesis. The chapter covered the different aspects of reclaimed rubber and reclaimed rubber composites. It covered the effect of recycling and its significance for the state of Qatar. It then covered the different aspects of tire recycling, starting with the structure and components of tires, the recycling need for tires, and the different methods of recycling tires. It then discussed the rubber reclaimed methods, the applications of reclaimed rubber composites, and their properties.

2.8.1 Main Findings

The surveyed literature revealed the importance of recycling waste tires and producing reclaimed rubber. Moreover, there has been a massive number of research studies on reclaimed rubber and reclaimed rubber composites. Those studies mainly investigate the different curing, thermal and mechanical properties. Reclaimed rubber can be used in different engineering applications, and reclaimed rubber composites offer different properties that can be beneficial. Most of the investigated reclaimed rubber composites mainly focused on blends of natural rubber and reclaimed rubber. Composites of reclaimed rubber and other materials were lacking in the literature. For instance, the WF is appealing to this study because of its low density because of its cheaper cost, availability, sustainability, and simplicity of handling and processing [18, 19]. While there is a scarcity of research on the development of recovered waste tire rubber and waste tire rubber/WF composites, there is an abundance of information on the production of virgin rubber composites.

2.8.2 Research Gaps and Thesis Aims

According to the surveyed literature and the author's knowledge, the research conducted on sawdust reclaimed rubber composites is limited. Rather, the work incorporating sawdust was only conducted for natural rubber and not reclaimed one. Sawdust has many advantages: low density, cheaper cost, availability, sustainability, and ease of handling and processing. The study on sawdust reclaimed rubber composites revealed that wood can enhance some of the exhibited properties [20]. Therefore, this thesis aims to manufacture and study the performance of sawdust-reclaimed rubber composites. Despite the lack of studies on such composites, the different types of reclaimed rubbers and wood and their particle size make the investigation space huge. To this end, this thesis will incorporate sawdust of 600 μm size in the produced reclaimed rubber composites. The thesis will investigate 6 different percentages of sawdust filler: 0%, 1%, 5%, 10%, 15%, 20%. The performance of the sawdust-reclaimed rubber composites will be evaluated via different mechanical tests, including tensile, hardness, Mooney viscosity, and water retention tests.

CHAPTER 3: METHODOLOGY

3.1 Introduction

This chapter details the methods and procedures followed in carrying out the research. The tests done in this thesis were conducted experimentally on samples prepared locally from recycled rubber tires mixed with recycled sawdust. Different types of tests were conducted to achieve the objective of this thesis, namely, tensile tests, hardness tests, Mooney (viscosity) tests, and water retention tests. The sample preparation was done in the Bright Future Tyre Recycling Factory in Qatar. The tests were also carried out in the Bright Future Factory Tyre Recycling Factory quality testing facility. The following sections explain the sample preparation methods, the design of experiments, and the testing procedure.

3.2 Fabrication of Sawdust-Reclaimed Rubber Composites

The production of reclaimed rubber starts by collecting old waste tires from large landfills. Most of the time, waste tires are purchased for low prices from different factories. A tire consists of more than one part [5]. **Figure 3** depicts a pic of the different tire components. The process of producing reclaimed rubber starts by cutting the tire into small components. The sidewalls of the tires are first cut, and the steel band inside is removed. Only the tread part of the tire is used in reclaimed rubber production. The treads are cut into smaller rubber blocks that go through a rubber cracking machine turning the block into fine rubber powder.

The rubber powder then goes through a devulcanization tank to remove the sulfur content of the rubber powder. The left-over steel particles inside the rubber powder are removed using magnets. The final product is devulcanized pure rubber powder. The devulcanized rubber powder is milled into smooth rubber cloths using mixing mills. Then, the rubber cloths are fed into a strainer to eliminate any impurities that may have been added in the previous step. Finally, a refining mill is used to produce reclaimed rubber sheets. Those sheets are exported and sold to various rubber industries to produce rubber goods such as tires, inner tubes, general molding, belting, adhesives, footwear, matting belting, cable bedding compound, and sound reduction. The process of reclaimed rubber production is shown in **Figure 13**.

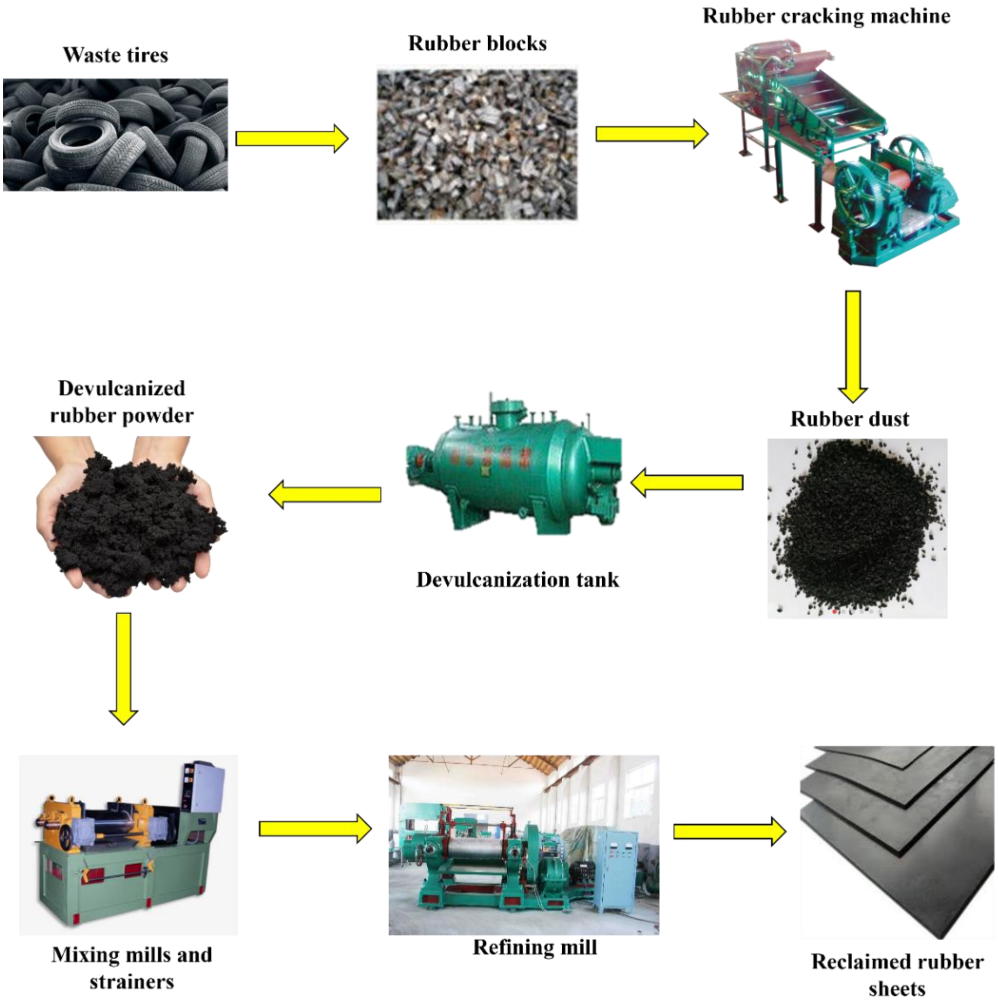


Figure 13 Reclaimed rubber production process

The addition of sawdust occurs in the refining mill, where the devulcanized rubber is shaped into sheets. The wood dust was sieved using a 28-mesh sieve to unify the particle size and ensure a homogeneous wood mixture inside the rubber, as shown in **Figure 14**. After sieving, the sawdust was dried in an oven at 120^{o} C to remove any entrapped moisture. The sawdust was weighed after 10 minutes. Then the process was repeated until no change in mass was observed, ensuring moisture was removed. The final unchanged mass of the powder was then jotted down, and the sawdust was saved in a dehumidifying container with silica gill.

(a) **(b)** **(c)**

Figure 14 Sieving process of wood dust: (a) as received wood dust, (b) sieving through a 28-mesh sieve, and (c) sieved wood dust used in reclaimed rubber

3.3 Design of Experiment

The main goal of this thesis is to study the effect of sawdust on the mechanical performance of reclaimed rubber. To achieve this, sawdust-reclaimed rubber samples of different sawdust weight amounts were prepared: 1%, 5%, 10%, 15%, and 20%. Virgin samples with no sawdust were also tested for reference comparison. The performance of the sawdust-reclaimed rubber was evaluated according to tests specified by rubber manufacturers and importers, namely, tensile strength, hardness, Mooney (viscosity), and water retention. Hence, four tests were conducted on sawdust-reclaimed rubber of 6 different wood content. Using a simple experiment design, we obtain a total of 24 experiments to be conducted:

Number of experiments = Number of varying samples (6) x Number of tests (4)

To account for repeatability, 5 or 3 samples of each wood content were tested. This resulted in a total of 96 experiments being conducted. Table 4 lists the test conditions and the Number of samples tested.

Table 4 Number of samples prepared, and tests conducted

Local reclaimed rubber replicates		
Test name	**Replicate name**	**Number of replicates**
Tensile test	Virgin (0%wood)	5
	1%wood	5
	5%wood	5
	10% wood	5
	15% wood	5
	20% wood	5
Hardness test	Virgin (0%wood)	5
	1%wood	5
	5%wood	5
	10% wood	5
	15% wood	5
	20% wood	5
Mooney viscosity	Virgin (0%wood)	3
	1%wood	3
	5%wood	3
	10% wood	3
	15% wood	3
	20% wood	3

Water retention test	Virgin (0%wood)	3
	1%wood	3
	5%wood	3
	10% wood	3
	15% wood	3
	20% wood	3
Total number of experiments		**96**

3.4 Mechanical Testing

3.4.1 Tensile Testing

The tensile samples were prepared by hot pressing the devulcanized rubber sheets with the sawdust and sulfur. The process is depicted in Figure 15. The hot-pressed sheets were then cut into dog-bone tensile specimens according to GB/T 528-2009 standard, as shown in Figure 16. Tensile testing was conducted using the MZ-900 Jiangsu Mingzhu tensile testing machine (Figure 17). The tests were conducted under quasi-static conditions, and five samples of each wood content were tested to ensure repeatability.

Figure 15 Tensile sample preparation process (1% wood content example)

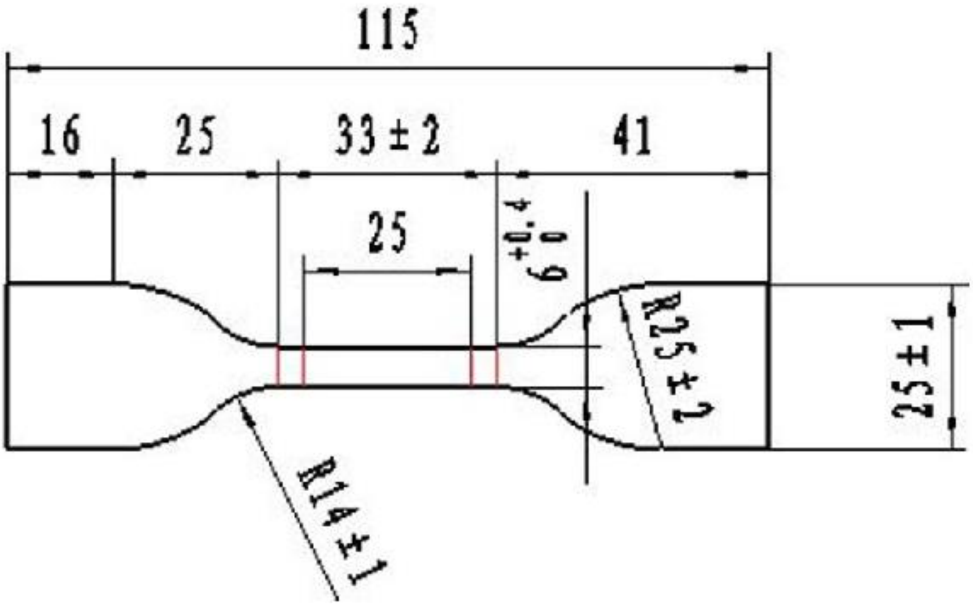


Figure 16 Tensile test dimensions (in mm) according to GB/T 528-2009 standard

Figure 17 MZ-900 Jiangsu Mingzhu tensile testing machine

3.4.2 Hardness Testing

Figure 18 shows the LX-C Shore Hardness Tester that was used to determine the hardness. Table 5 [61] shows that this hardness tester includes three modes for different materials and constructions. The Shore rubber hardness gauge is a tool for determining the hardness of vulcanized rubber and plastic goods. There are three types of this apparatus: Type A, Type C, and Type D. Each model is split into single pointer and double pointer kinds. Types A and D are used to evaluate low and medium hardness materials and high-hardness materials. The produced wood-powder reclaimed rubber samples were tested using Type A. Type C tests, a microporous material used to produce shoes with a 50 percent compression rate and stress of 0.049 MPa or higher. This type of material is comprised of rubber and has a blister in it. This hardness measure complies with the GB/T531-99, GB2411-80, hg/t2489-93, and JJG304-2003 standards. **Table 6** lists the most important technical characteristics.

Figure 18 LX-C Shore Hardness Tester

Table 5 LX-C Shore Hardness Tester test modes and types [61]

Test type	Materials/Structures
Type A	Rubber in general, synthetic rubber, vulcanized rubber, soft rubber, leather, wax, and other types of rubber.
Type B	It may be used to measure the hardness of microporous rubber materials.
Type C	Hard rubber, hard resin, acrylic, glass, cushiony plastic cement, printing plates, fiber, and other materials

Table 6 Main technical parameters of the LC-X Shore Hardness Tester [61]

	Type-A	**Type-B**	**Type-C**
Calibration Value	0-100HA	0-100HC	0-100HD
Resolution	1HA	1HC	1HD
Pressure Head Size	Φ1.25mm	R2.5mm	Φ1.25mm
End pressure of Pressure Head	0.55N-8.06N	0.55N-8.06N	0-44.5N
Pressure Needle Range	0-2.5mm		
Apparatus Weight	0.3kg		

3.4.3 Mooney (Viscosity) Testing

The Mooney viscosity test is one of the most popular tests performed in the rubber industry today. It is frequently used to determine the viscosity of raw rubbers and characterize the natural and synthetic rubber conditions. Mooney tests are conducted via a Mooney viscometer which Melvin Mooney invented. The viscometer comprises rotating a serrated spindle fixed on a rubber specimen, contained within a closed, pressurized cavity, and heated dies. Due to its constant speed, the spindle experiences a resistance to spin that is logged as torque in N-m. The temperature needs to be applied to the sample during the rotation. The temperature applied to the samples was (100+5 ^{o}C). The standard ASTM D 1646 explains the process used to convert the torque values into Mooney Units (MU). The real Mooney viscosity to be observed is the value preceding the exact time of reading. This must be defined because of the thixotropic nature of rubber (where the obtained viscosity changes with time) [62]. The Mooney viscometer used was MZ-8005 and is depicted in

Figure 19. Mooney tests usually take around 5-6 minutes. The 1st minute of the tests is used to condition the dies and heat them. Then the rotor applies torque to the sample, and the torque is measured and converted to MU values. The MU of the sample is usually taken at the 4-minute mark of the test. **Figure 20** depicts a typical Mooney viscosity test diagram along with the different steps of the tests.

Figure 19 MZ-8005 Mooney viscometer

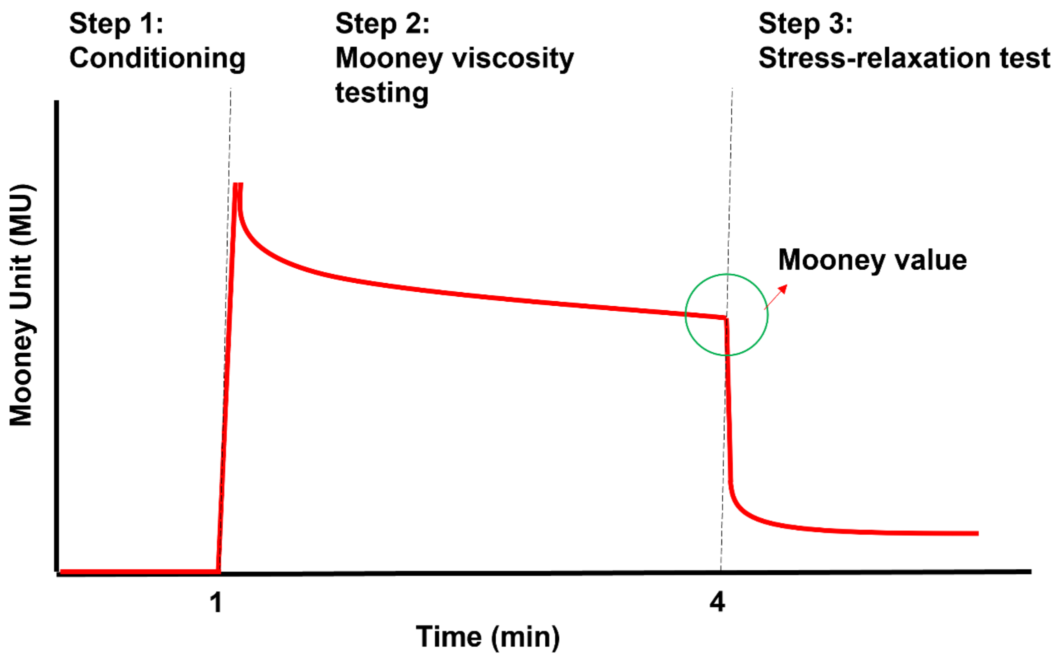


Figure 20 Typical viscosity test diagram

3.4.4 Water Retention Tests

Water retention/absorption testing is essential for rubbers, as water has an adverse effect on rubber strength [63]. Water retention tests are basic tests to check the amount of water absorber by reclaimed rubber. The water absorption tests were conducted according to the ASTM D570 standard. For the water retention test, samples of different wood content are dried in an oven for a 1-hour time at a temperature of 75 ^{o}C (below melting) and then placed in a desiccator to cool. Instantly upon cooling, the samples are weighed using a scale. The samples are then submerged in water at 23°C for 24 hours or until equilibrium. Samples are then removed, patted dry with a lint-free cloth, and weighed again. The water absorption percentage can be calculated based on the difference between the initial and final values of the sample.

CHAPTER 4: PERFORMANCE OF SAWDUST-RECLAIMED RUBBER COMPOSITES

4.1 Introduction

This chapter discusses the performance aspects of sawdust-reclaimed rubber composites. First, the mechanical behavior will be discussed in terms of tensile testing and hardness performance. The effect of wood content on both strength and hardness is investigated. The Mooney viscosity behavior of samples of different wood content is also evaluated. The effect of wood content on water retention performance will also be addressed. Finally, a summary is provided, and the optimum wood content resulting in the best acceptable performance is identified.

4.2 Mechanical Behavior

4.2.1 Tensile Behavior

The tensile strength of rubber materials refers to the amount of force a rubber sample can take before it ruptures. Samples of different wood content were hot-pressed and cut into dog bone shapes of the dimensions indicated in Figure 4 according to GB/T 528-2009 standard. It is worth mentioning that sulfur was added to the mixing mill in a process known as vulcanization. Vulcanization is essential for testing the tensile strength of the rubber as sulfur enhances it and is usually added to increase the strength before production [64]. The tensile properties, namely, strength, and rapture strain, are listed in **Table 7** for convenience. The stress-strain diagrams for the tested samples are shown in **Figure 23-Figure 26**. The figures show that the behavior of sawdust-reclaimed rubber composites is similar to regular elastomers and other rubbers. All samples exhibit an elastic behavior up to the point of fracture. Hence, the wood does not affect the overall stress-strain behavior.

Table 7 Tensile strength and rupture strain values of samples of different wood content

	Tensile strength (MPa)						Strain at rupture (%)					
% Wood	**0%**	**1%**	**5%**	**10%**	**15%**	**20%**	**0%**	**1%**	**5%**	**10%**	**15%**	**20%**
Replicate 1	6.71	5.41	4.64	3.10	2.98	2.45	217.68	178.53	154.69	112.13	87.44	65.31
Replicate 2	6.59	4.77	4.44	3.37	2.51	2.39	209.14	169.17	147.02	107.87	67.01	54.23
Replicate 3	6.81	5.90	4.38	3.27	2.90	2.64	215.95	193.84	153.83	112.13	84.88	59.34
Replicate 4	6.39	5.76	4.29	3.33	3.02	2.44	220.22	189.58	151.29	105.31	87.44	51.68
Replicate 5	6.58	5.21	4.38	3.23	2.94	2.51	211.69	174.26	146.17	101.91	86.59	49.12
Replicate 6	6.95	5.33	4.19	3.23	2.90		227.88	175.97	139.36	108.00		
Average	6.67	5.40	4.39	3.26	2.88	2.49	217.09	180.23	148.73	107.89	82.67	55.94
STDV	0.18	0.37	0.14	0.09	0.17	0.09	6.06	8.68	5.25	3.61	7.89	5.78

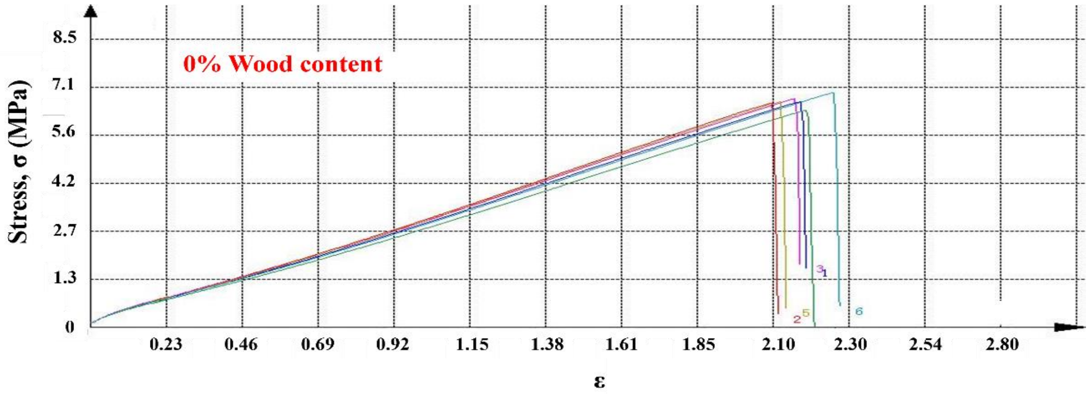


Figure 21 Tensile stress-strain diagrams of samples of 0% wood content

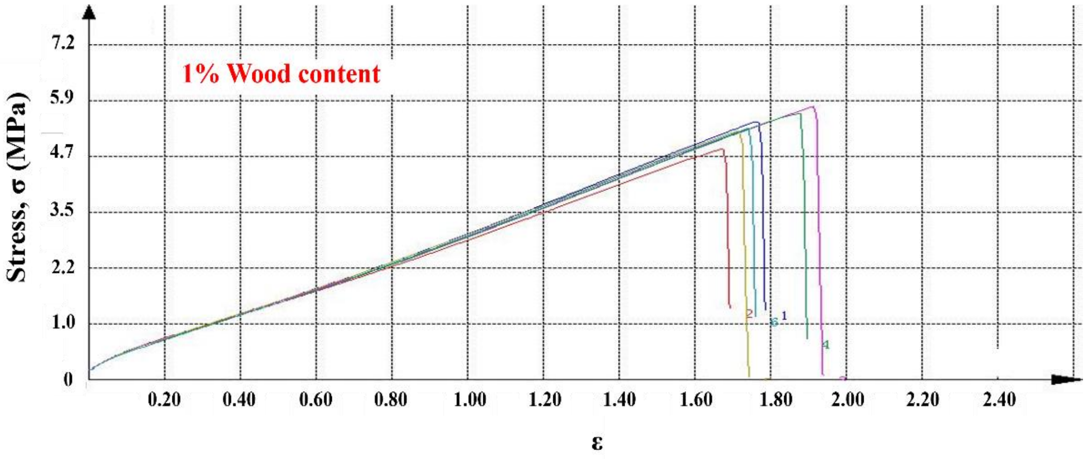


Figure 22 Tensile stress-strain diagrams of samples of 1% wood content

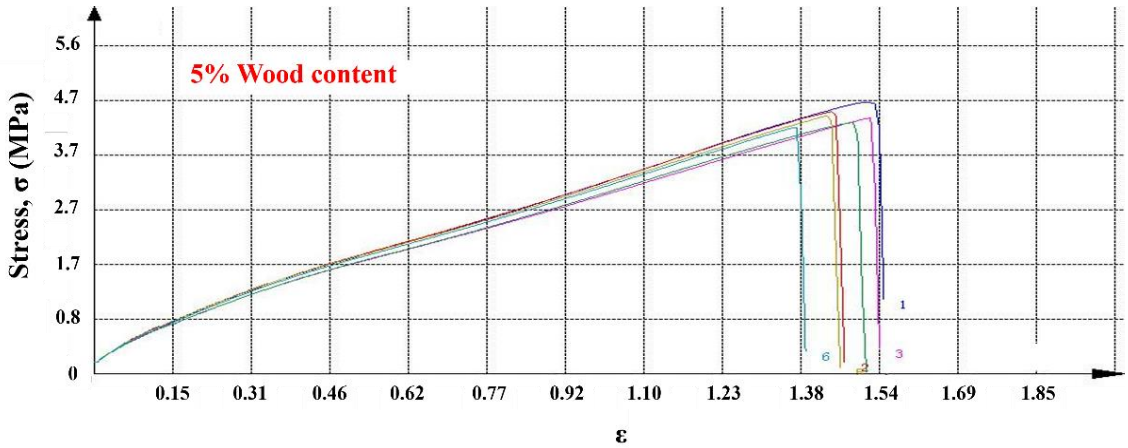


Figure 23 Tensile stress-strain diagrams of samples of 5% wood content

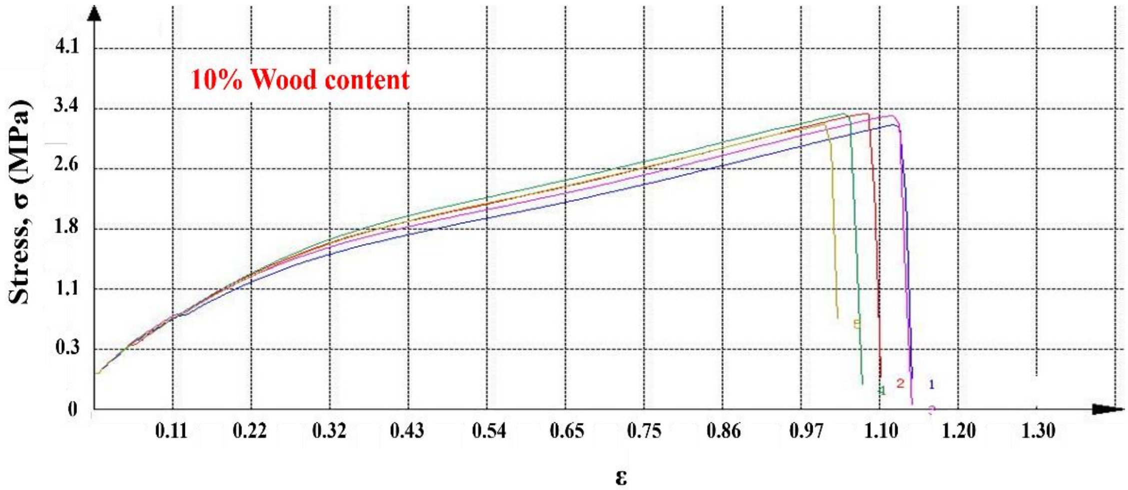


Figure 24 Tensile stress-strain diagrams of samples of 10% wood content

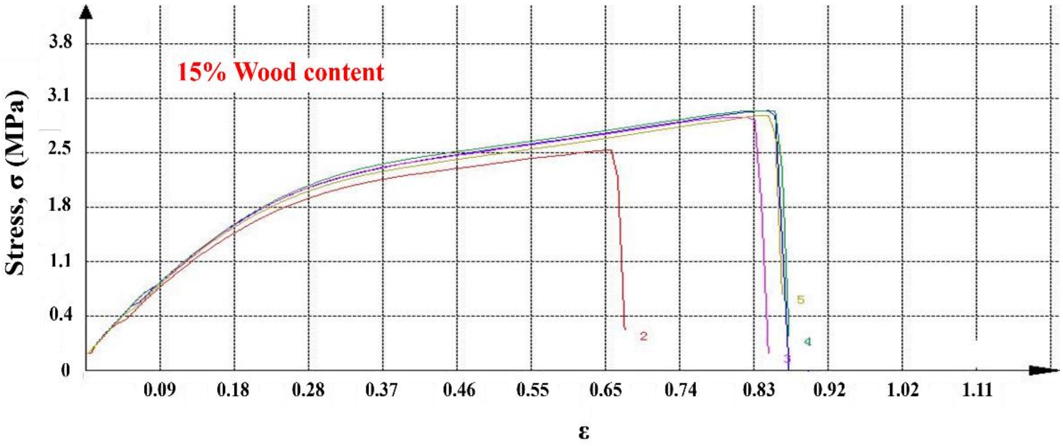


Figure 25 Tensile stress-strain diagrams of samples of 15% wood content

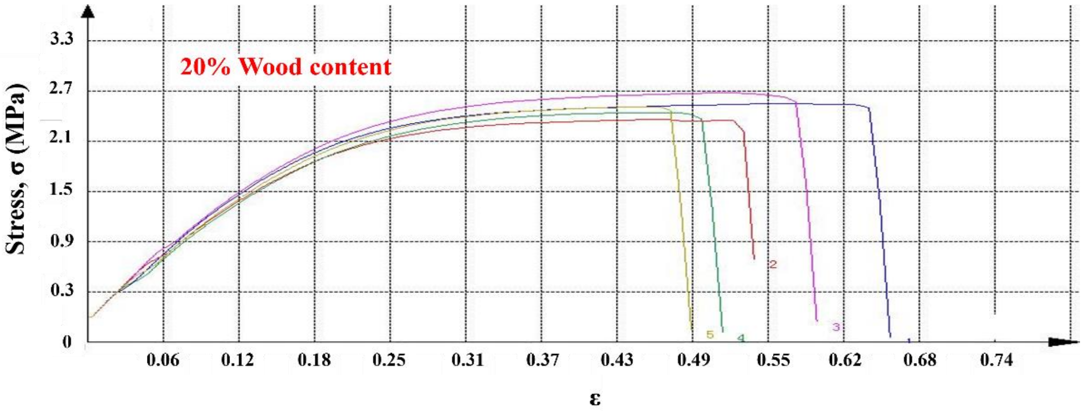


Figure 26 Tensile stress-strain diagrams of samples of 20% wood content

However, the effect of wood content is evident on the exhibited tensile strength of the material and its ductility represented by the final rupture strain. **Figure 27** depicts the observed tensile strength values of the sawdust-reclaimed rubber composite samples of different wood contents. From **Figure 27**, it is clear that increasing the sawdust content in the samples reduces the overall tensile strength. The highest value of tensile strength (6.67 MPa) was observed in the virgin sample (0% wood content), while the lowest strength (2.49 MPa) was observed in the 20% wood content sample. This represents an overall decrease in tensile strength of around 63% with 20% sawdust. This reduction in tensile strength can be attributed mainly to the embedded fine wood particles within the rubber matrix. The fine wood particles within the matrix do not contribute to the load-bearing during the tensile load. Hence, they work as voids, the decreases the overall tensile strength of the material. The received sawdust was sieved using a 600 μm size sieve. This produced a fine particle that can function as micro-voids that reduce the overall strength of the sample.

Moreover, the sawdust was added to the reclaimed rubber sheet in the mixing mill without any binder or adhesives. This can also contribute to the observed reduction effect. Manaila et al. [59] have studied the effect of wood sawdust on the performance of natural rubber. They reported a different behavior than the one observed in this work. An increase in tensile strength was observed with the increase of wood sawdust filler content [59]. The reason was the excellent interaction between the natural rubber matrix and the filler material due to the adhesion. This was not the case in this thesis, as no binding materials or adhesives were used to bind the sawdust particles to the reclaimed rubber matrix. The interaction between the rubber matrix and the wood particles plays a significant role in determining the final tensile strength of the material. A strong interaction would constrain the polymer chain's motion [65, 66]. This is mainly due to the adequate adhesion of the wood in the matrix due to the accumulation of the sawdust particles [67, 68]. To this end, studying the effect of wood particles size as well as the effect of using different types of binders is recommended in future studies.

It is also worth mentioning that a 1% and 5% wood content resulted in a 5.4 and 4.39 MPa tensile strength, respectively. These values are acceptable for reclaimed rubber in different industries [69].

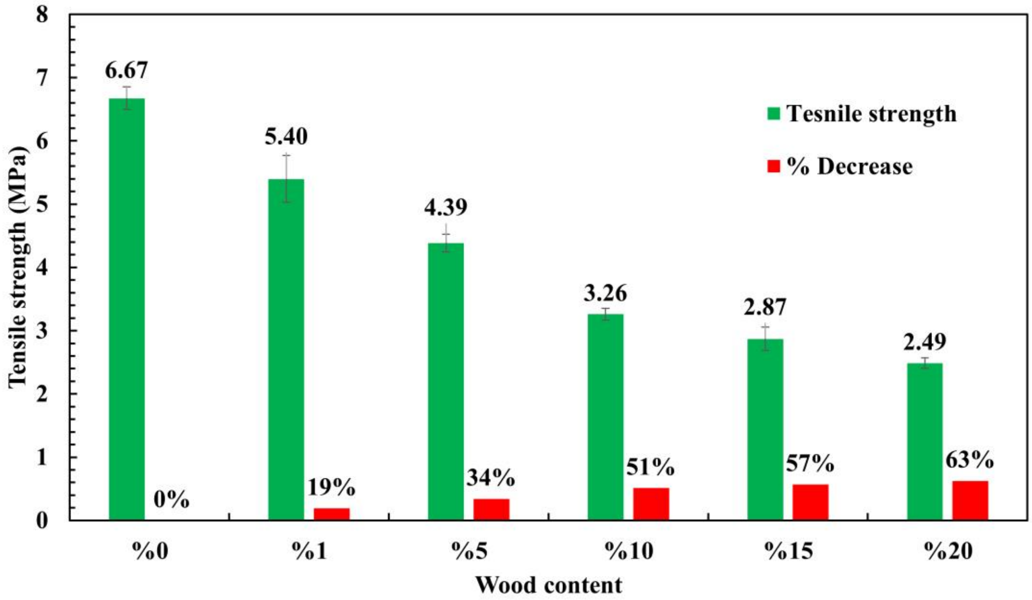


Figure 27 Tensile strength values of sawdust-reclaimed rubber samples of different wood content

Figure 28 depicts the final rupture strain values of the tested samples according to their wood content. It is evident from the figure that increasing the amount of wood content contributes to decreasing the exhibited rapture strains of the samples. Hence, reducing the overall elasticity and ductility of the reclaimed rubber composite. The highest rupture strain was reported for the virgin (0% wood) sample of around 217%. In comparison, the lowest was reported for the 20% wood content sample of around 56%. This represents a reduction in ductility/elasticity of around 74%, which essentially makes the material unsuitable for general reclaimed rubber applications.

This reduction in final rupture strain can also be attributed to the sawdust filler in the rubber matrix. This reduction in ductility happened because the sawdust incorporated in the rubber matrix has resulted in a reduction of plasticity and flexibility of the rubber chains giving the overall material an increased rigidity [68]. The results agree with Manaila et al. [5]. They studied the effect of wood sawdust on the performance of natural rubber. Their results showed a decrease in the overall plasticity of the material with the increase of the wood sawdust in the matrix [59].

It is worth noting that an addition of 5% sawdust would result in around a 31% decrease in the overall plasticity of the reclaimed rubber composite. This corresponds to a rapture strain of 148.73%, an acceptable value for reclaimed rubber in various industrial applications [69]. Hence, a 1-5% sawdust content is redeemed suitable for overall plasticity for reclaimed rubber production.

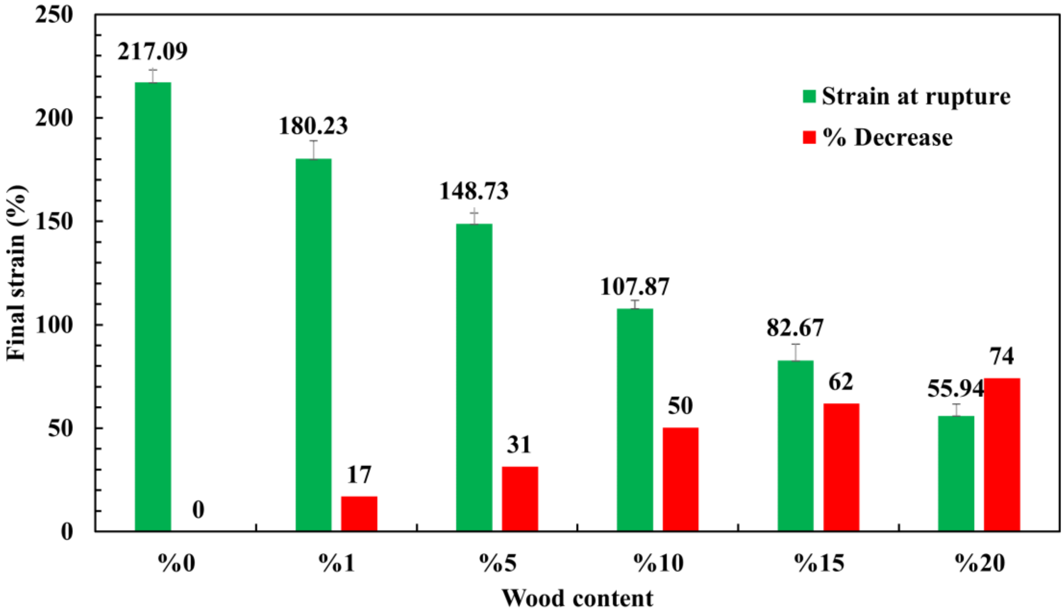


Figure 28 Final rupture strain values of sawdust-reclaimed rubber samples of different wood content

4.2.2 Hardness

Hardness refers to the material's ability to resist the applied force's indentation. Hardness values of rubbers are measured according to different scales and shores. The Shore-A hardness values are measured for the sawdust-reclaimed rubber samples of different wood content. The Shore hardness is measured with a device known as "LC-X Shore hardness tester." The hardness value is determined by the penetration of the

Durometer indenter foot into the sample being tested. The hardness samples were also prepared by hot pressing the vulcanized reclaimed rubber sheet forming them into dog-bone-shaped samples.

Figure 29 depicts the Shore A hardness values of reclaimed rubber samples of different wood content. Increasing the wood content in the sample increases the overall hardness of the material. The highest Shore A hardness value was 78.50, which was observed for 20% wood content. On the other hand, the lowest value was 58.25 for the virgin reclaimed rubber sample (0% wood content). Addition of 20% sawdust to the reclaimed rubber results in around a 35% increase in the overall hardness. This increase is mainly attributed to the interactive nature between the sawdust and the rubber matrix. As mentioned in the previous section, the sawdust particles reduce the rubber chains' plasticity and flexibility, giving the overall material an increased rigidity [68]. This, in turn, increases the overall hardness of the material.

Moreover, the wood particles have a reinforcement effect that enhances the overall hardness. The cross-linking in the polymeric material also results in increased hardness [59, 68]. Manaila et al. [59] have also reported the same observed results as their wood sawdust filler increased overall hardness. It is worth noting that generally, a Shore A hardness value of 58 is within the acceptable range of reclaimed rubber industrial applications [69]. Therefore, selecting a sample with higher wood content would bring on higher hardness. However, selection must be made according to the desired application. However, one should remember that a higher wood content would also mean lower overall tensile strength and ductility. Hence, a wood content between 1-5% would be the most suitable, as indicated in the previous section.

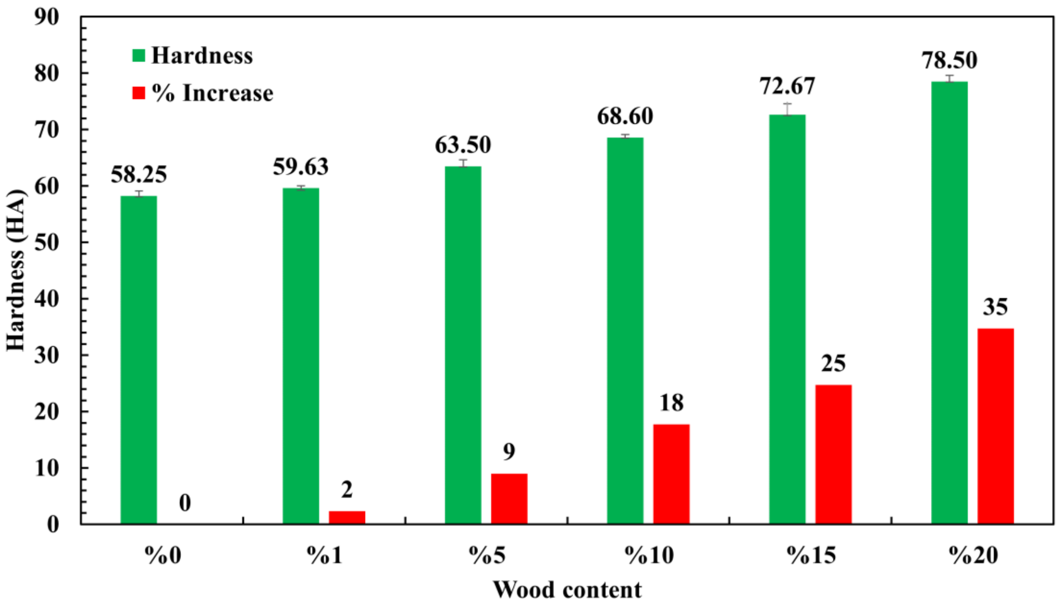


Figure 29 Shore A hardness values of sawdust-reclaimed rubber samples of different wood content

4.3 Mooney Performance

Mooney viscosity is characterized as the shearing force resisting rotation of a rodlike metal plate (or rotor) fixed in rubber within a cylinder-shaped cavity. The Mooney viscosity was measured for different samples of sawdust-reclaimed rubber composites of different wood content. The samples prepared for Mooney viscosity testing should be prepared from devulcanized reclaimed rubber sheets. The Mooney values were obtained using the MZ-8005 viscometer. Mooney tests were conducted at a dies' temperature of 100+5°C. The dies heat up to take around 1 minute (conditioning step), and then the rotor starts applying torque to the specimen. The software recorded the torque values and converted them to Mooney Unit (MU) values plotted against time. The test duration for each sample takes around 6 minutes. Three tests were conducted for each wood content to assure repeatability of the obtained results. The Mooney Unit (MU) value is generally taken at the 4-minute mark of the test, just before the relaxation step.

Table 8 lists the obtained MU values for different samples for the reader's convenience. **Figure 30-Figure 32** shows the Mooney behavior with time for virgin reclaimed rubber samples and 1-5% wood content samples. The figure shows that the performance of 0%, 1%, and 5% wood content is similar as the wood content is still relatively low within the material. Almost no change can be observed from the graphs. The MU values of samples of 0%, 1%, and 5% wood content are 23, 23.54, and 23.90, respectively. This shows that no change in Mooney viscosity is apparent in the sample up to a wood content of 5%.

Table 8 Mooney Unit (MU) values of the tested samples

Wood content	**s1**	**s2**	**s3**	**Average**	**Standard deviation**	**MU**	**% Increase**
0%	22.94	23.78	22.24	23	0.55	**23.00**	0
1%	22.33	25.42	22.88	23.54	1.17	**23.54**	2
5%	23.55	24.26	23.87	23.90	0.25	**23.90**	4
10%	26.63	24.69	25.00	25.44	0.74	**25.44**	11
15%	28.29	26.67	27.15	27.37	0.59	**27.40**	19
20%	29.26	30.73	29.31	29.77	0.59	**29.80**	30

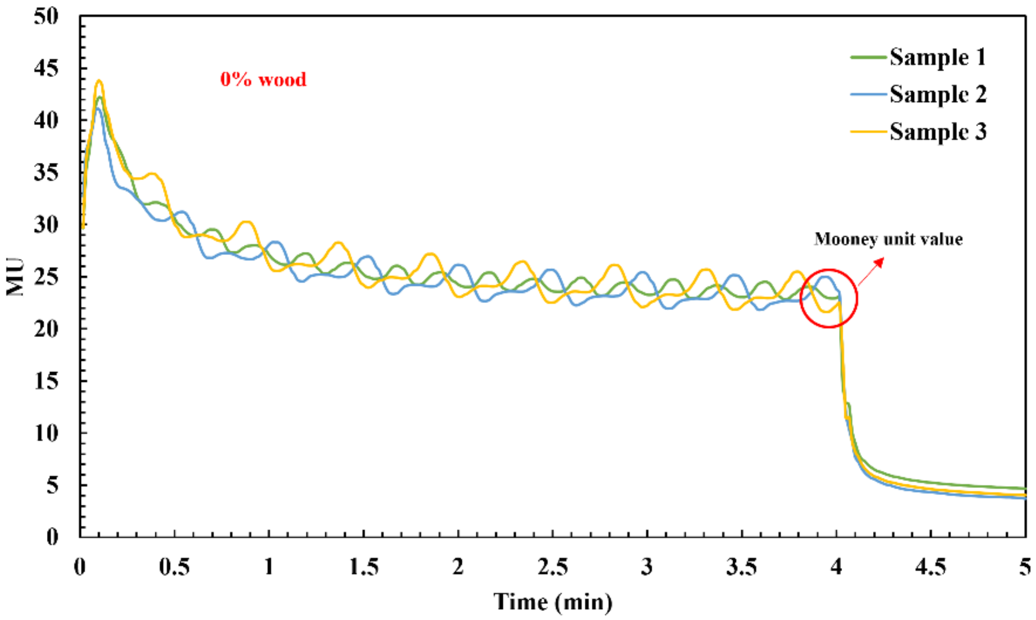


Figure 30 Mooney performance for samples of 0% wood content

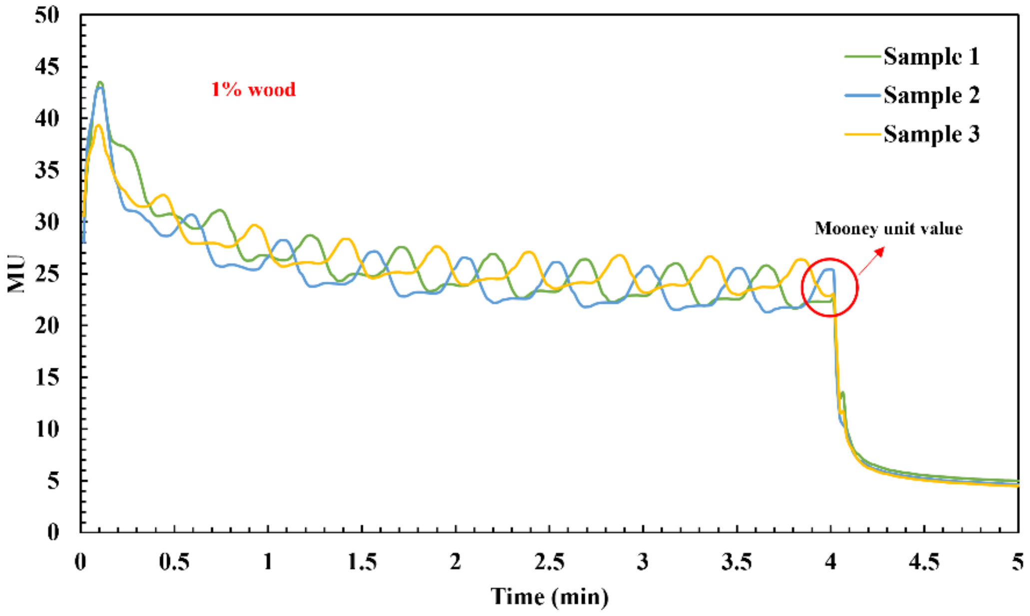


Figure 31 Mooney performance for samples of 1% wood content

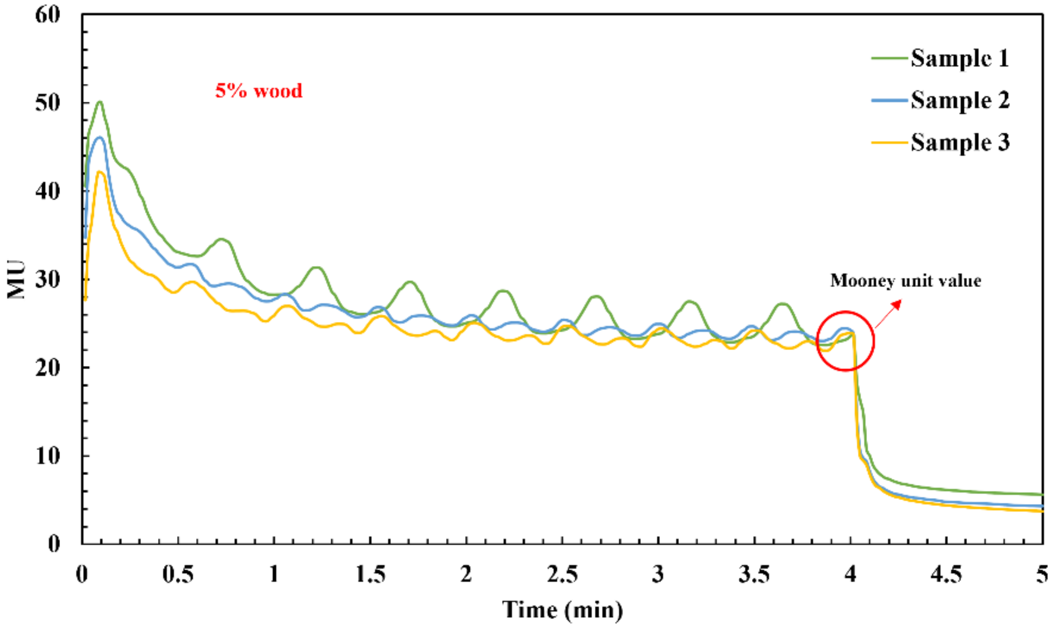


Figure 32 Mooney performance for samples of 5% wood content

Figure 33-

Figure 35 depicts the Mooney viscosity performance of 10%, 15%, and 20% wood content samples. From the figure, one can see that the magnitude of the Mooney Unit value has increased slightly with the increase of the wood content within the material, relative to the samples shown in **Figure 30-Figure 32**. The effect of wood content on the Mooney Unit values and performance is better illustrated in the bar chart in **Figure 36**. From here, one can see that increasing the wood content increases MU values. The highest MU value was 29.80, which was observed for samples of 20% wood content. This corresponds to an increase of 30% relative to the virgin (0% wood content) reclaimed rubber sample that exhibited an MU value of 23. This increase agrees with the previously reported results of hardness. As discussed earlier, Shore A hardness of the materials increased with the increase of the wood content. This was mainly attributed to the increased rigidity introduced by the wood particles (refer to section 4.2.2) [59, 68]. It is, therefore, expected to see an increase, however slight, in MU values with the increase of wood content in the material.

It is worth noting that Mooney tests are usually conducted immediately after production. This is done because as the rubber age, the Mooney viscosity shoots up. Higher Mooney viscosity values reflect poorly on the machinability of reclaimed rubber during production. It makes it difficult to cut and shape for different applications. Hence, a lower MU value is generally required for reclaimed rubber as per customer specifications. Therefore, a wood content of 1-5% would be suitable for Mooney viscosity performance.

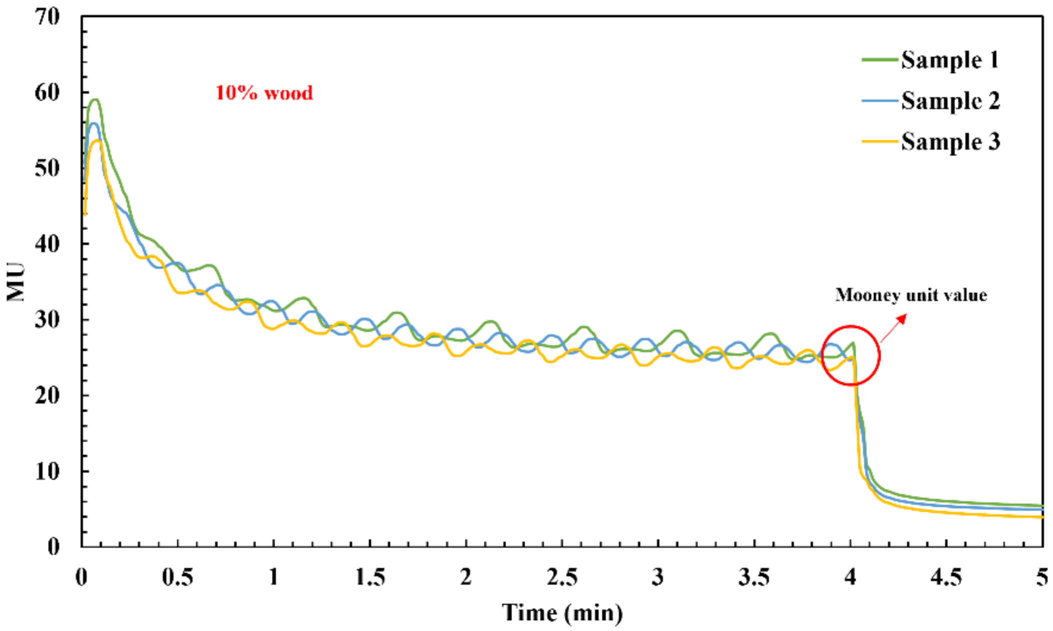


Figure 33 Mooney performance for samples of 10% wood content

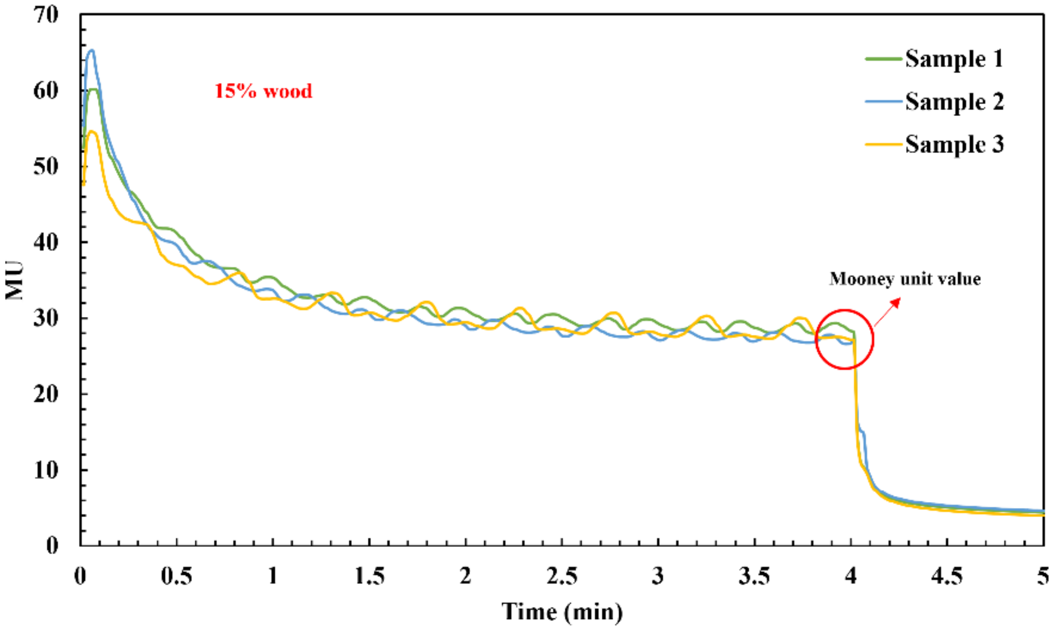


Figure 34 Mooney performance for samples of 15% wood conten

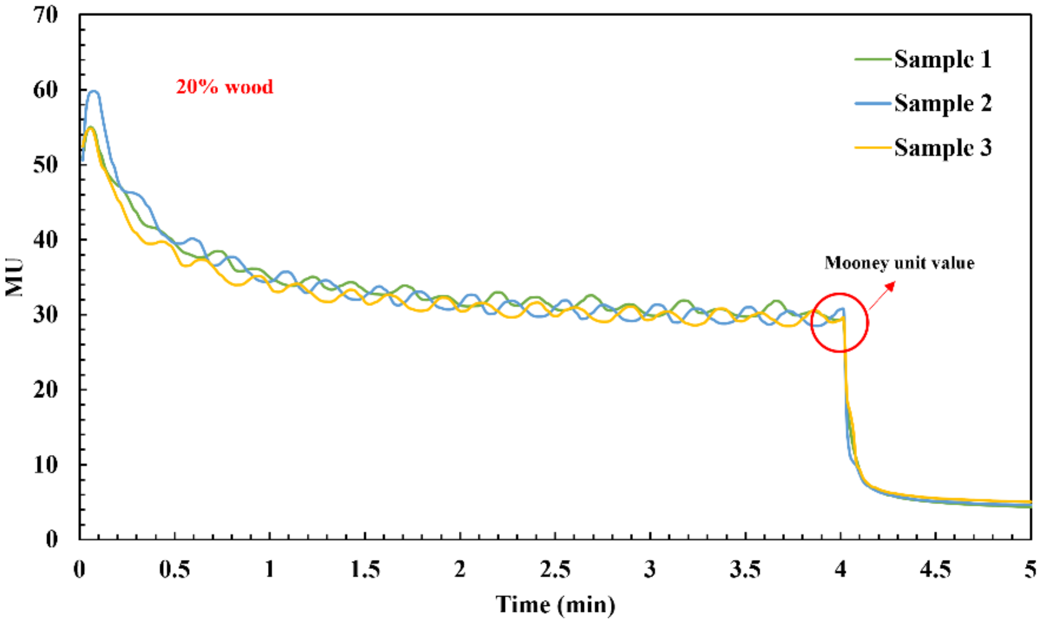


Figure 35 Mooney performance for samples of 20% wood content

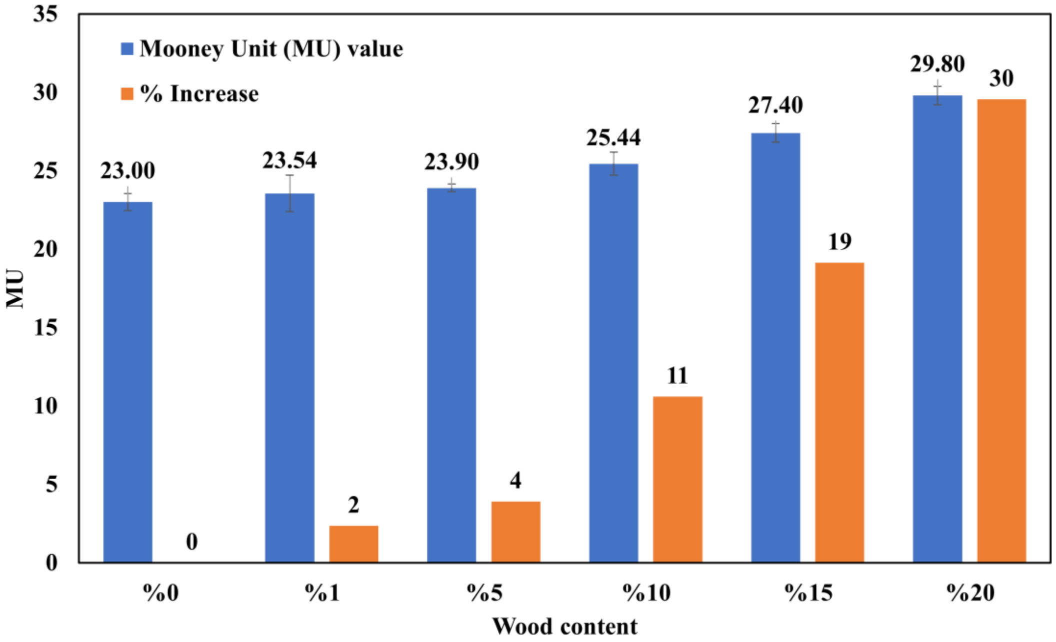


Figure 36 Mooney Unit (MU) values of sawdust-reclaimed rubber samples of different wood content

4.4 Water Retention

Water retention or water absorption tests are generally conducted to determine the water uptake percentage of the material. This is an essential aspect of rubber testing as water has an adverse effect on rubber strength. Since the proposed material includes wood, the material is prone to retain water and moisture. Samples of different wood content were tested for water absorption. The samples were first oven-dried to get rid of any entrapped moisture, and then their initial weight was recorded. They were then submerged in water, and their weight was recorded every 24 hours for one week. **Figure 37** and **Figure 38** depict the water uptake of reclaimed rubber samples of different wood content. The figure shows that water uptake increases for all samples with time, except for the virgin (0% wood content) sample. This is mainly due to the hydrophilic nature of the wood particles that tend to absorb the water [59]. In sawdust-reclaimed rubber composites, the water is absorbed mainly by wood because rubber is hydrophobic, and its water retention can be neglected [70]. **Figure 39** shows the final water absorption percentages after one week. As expected, the highest water absorption values were observed for 15 and 20% wood content, both reported at 14%. Virgin rubber has only gained 1% water after one week, which is typical for rubber samples. 1-5% wood content samples have absorbed 5 and 8% water, respectively, around 50% of the water absorption of 15 and 2-% wood content samples. This redeems 1 and 5% wood content samples usable for reclaimed rubber applications

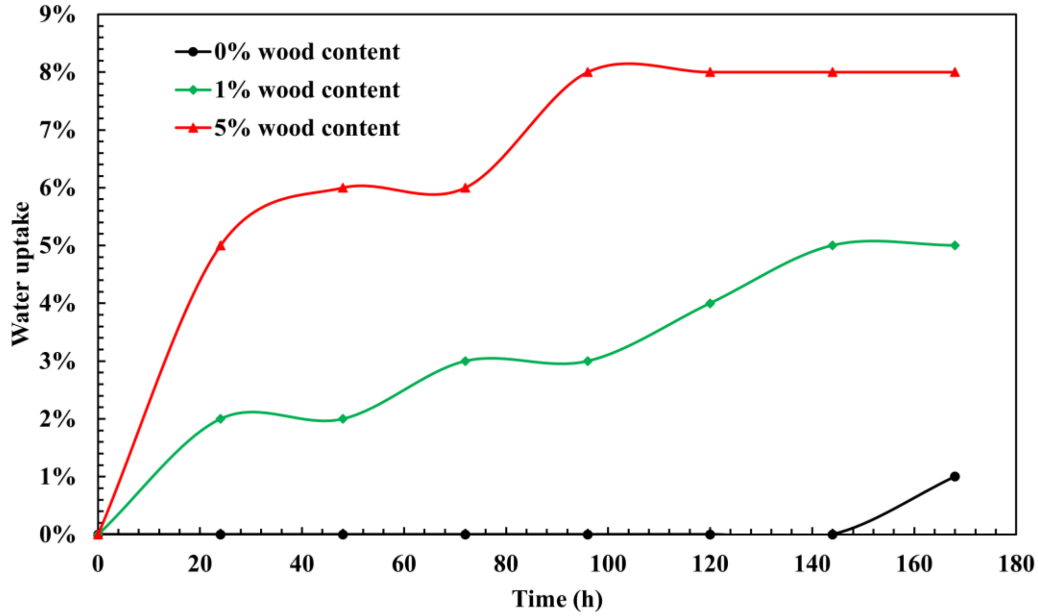


Figure 37 Water uptake of reclaimed rubber samples of 0%, 1%, and 5% wood content

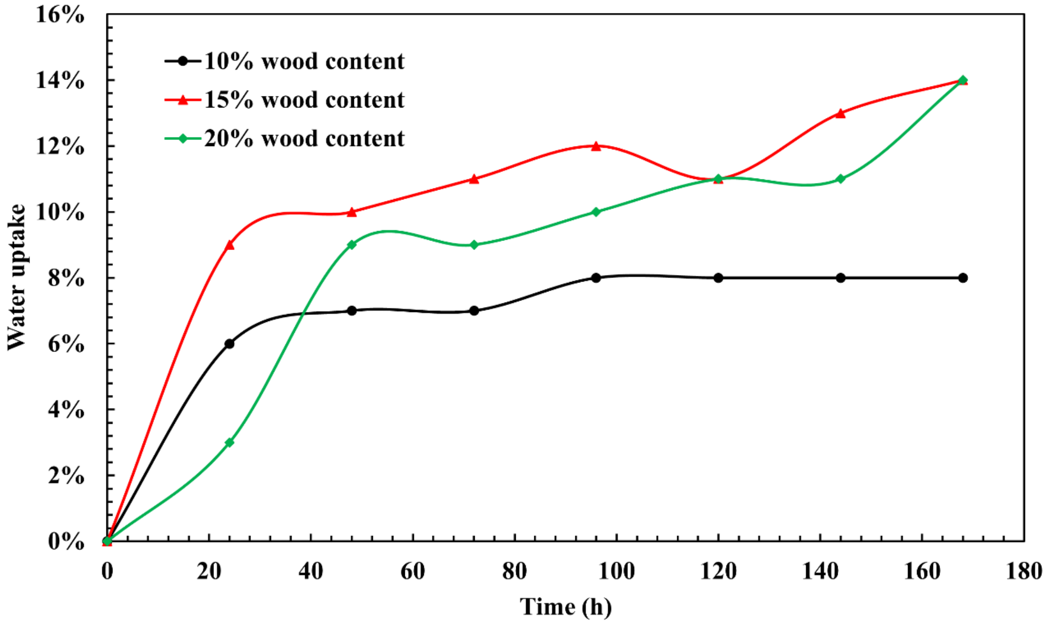


Figure 38 Water uptake of reclaimed rubber samples of 10%, 15%, and 20% wood content

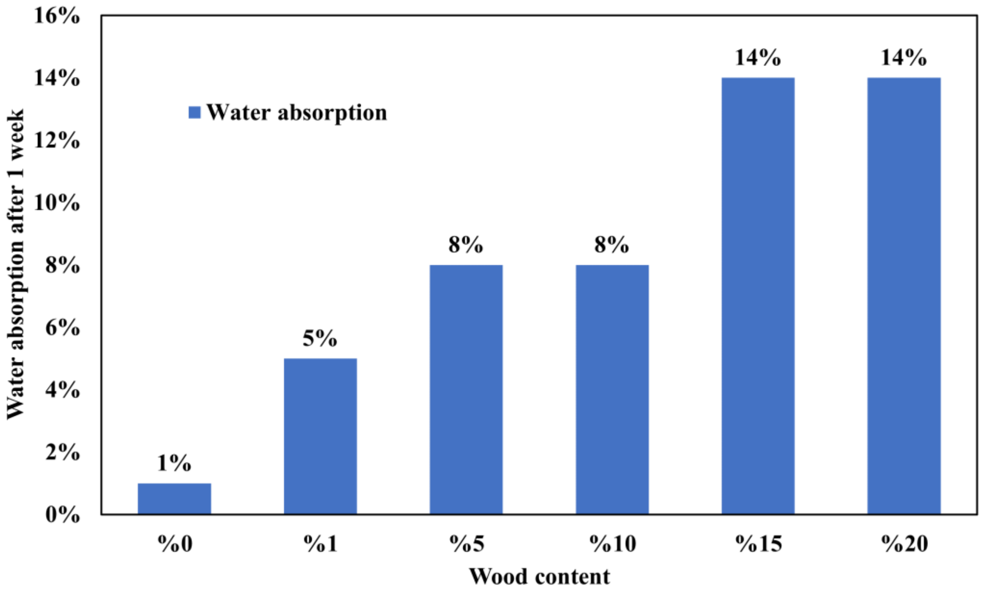


Figure 39 Water absorption percentage after one week

4.5 Summary

The sawdust-reclaimed rubber composite performance was investigated in tensile behavior, hardness, Mooney viscosity, and water retention. The performance was investigated over a range of wood content, namely: 0%, 1%, 5%, 10%, 15% and 20%. The results revealed that increasing the wood content reduces the overall tensile strength and ductility but increases the overall hardness. The results also revealed an increase in Mooney viscosity with the increase of wood content inside the samples. Based on the obtained results, a wood content of 1% and 5% would result in acceptable properties for industrial specifications [69]. The reductions in tensile strength for both 1% and 5% are 19% and 34%, respectively.

Moreover, the reductions in ductility are 17% and 31%, respectively. The corresponding hardness increase is only 2% and 9%, respectively. Furthermore, the MU values are close to virgin rubber with no noticeable change. The reported changes due to adding 1-5% wood would still be within the acceptable industrial specifications. Hence, 1-5% wood content is the most suitable for reclaimed rubber production without significantly compromising tensile strength, ductility, hardness, and viscosity.

CHAPTER 5: FINANCIAL & ENVIRONMENTAL ASPECTS

5.1 Introduction

This chapter discusses some of the environmental and financial aspects of incorporating sawdust in reclaimed rubber production. First, the environmental aspects of sawdust are discussed. Then, an explanation of the reclaimed rubber production is presented. Finally, the positive financial and environmental effects of incorporating wood in reclaimed rubber productions are outlined.

5.2 Environmental Effects of Sawdust

The sawdust can have a lot of adverse effects on both the environment and human health. Wood dust may aggregate in piles and add harmful leachates to the local water systems creating a significant environmental hazard [71]. Wood dust has significant health risks. Inhaling sawdust into the lungs may cause breathing difficulties and cause lung diseases such as occupational asthma and lung cancer [71]. Inhaling in wood dust is the most common type of sawdust exposure. Moreover, getting sawdust in the eyes may cause inflammation and injury [71].

The following section will explain the advantages of incorporating sawdust in reclaimed rubber production financially and environmentally. This will be highlighted through a simple cost analysis of reclaimed rubber production incorporating 5% wood rubber in the daily production routine.

5.3 Cost Analysis

This section presents the cost analysis of reclaimed rubber production with incorporating 5% wood content of daily production capacity. The numbers used in this section are based on the daily production of reclaimed rubber in the Bright Future

Tyre Recycling Factory in Qatar. The section will highlight the original cost and reduced costs resulting from using 5% wood content.

Reclaimed rubber production starts with acquiring waste tires from landfills or factories that have huge tire waste. It is worth mentioning that only large truck tires are used in production. Hence, waste truck tires are purchased from other factories for reclaimed rubber production. The Bright Future Tyre Recycling Factory produces 15 tons (15000 kg) of reclaimed rubber per day. The waste truck tire weighs around 60 kg, and as mentioned in chapter 3, only the tread part is used for reclaimed rubber production. The tread weighs about 30 kg, and 20% of it is steel (6 kg) removed in the process, making the used weight of the tread 24 kg. Hence, to produce 15 tons of reclaimed rubber a day, the factory requires 625 truck tires as follows:

$$\begin{aligned} &\mathit{Rubber\ weight\ per\ tire} \\ &\qquad = \mathit{Tire\ weight} - \ \mathit{Tread\ weight} - \mathit{Steel\ weight\ in\ tread} \\ &\qquad = 60\ kg - 30\ kg - 6kg = 24\ kg \end{aligned}$$

$$Number\ of\ tires = \frac{Production\ per\ day}{Weight\ of\ rubber} = \frac{15000\ kg}{24\,\frac{kg}{tire}} = 625\ tire$$

The waste truck tire costs 5 QR. A mini truck is dispatched with three workers and a driver to purchase and load the tires into the truck. The truck can take up to 30 tires per trip, and the overall trip is 1 hour long from the Bright Future Tyre Recycling Factory to the industrial area where the waste tires are purchased. The costs associated with bringing in the tires to the Bright Future Tyre Recycling Factory yard for a full day production (15000 kg) of reclaimed rubber are detailed as follows:

$$Cost\ of\ tires = \#\,Tires\ \times Tire\ cost = 625\ tire\ \times 5\,\frac{QR}{tire} = \mathbf{3125\ QR}$$

$$Number\ of\ trips = \frac{\#\ Tires}{\#\ Tires\ per\ trip} = \frac{625\ tire}{30\frac{tire}{trip}} = 21\ trip$$

$$Fuel\ cost = \#\ Trips\ \times Fuel\ cost\ per\ trip = 21\ trip\ \times 50\frac{QR}{trip} = \mathbf{1050\ QR}$$

$$Labor\ cost_{Bringing\ tires} = \#\ Workers\ \times \#\ Trips\ \times Trip\ time \times Worker\ rate$$

$$= 4\ \times 21\ trip \times 1\frac{hour}{trip}\ \times 20\frac{QR}{hour} = \mathbf{1680\ QR}$$

Once in the factory yard, the tires are moved via a forklift to the cutting machine. The tires are cut into treads and sidewalls, and the treads are cut into rubber blocks. It takes around 1 hour to cut 30 tires and involving four workers. The costs associated with cutting tires for full-day production of 15000 kg or reclaimed rubber are detailed as follows:

$$Cutting\ time = \frac{\#\ Total\ Tires}{Cutting\ time\ for\ 30\ tires} = \frac{625\ tire}{30\frac{tire}{hour}} = 21\ hour$$

$$Labor\ cost_{Tire\ cutting}\ = \#\ Workers\ \times \#\ Hours\ \times Worker\ rate$$

$$= 4\ \times 21\ hour\ \times 20\frac{QR}{hour} = \mathbf{1680\ QR}$$

The rubber blocks are then moved to the production line, turned into reclaimed rubber sheets, as indicated in Chapter 3. The production of 15000 kg reclaimed rubber takes about a full day's work of 10 hours and involves ten workers. The power required to run the production line equipment costs around 25000 QR per month. The total cost of producing reclaimed rubber through the production line is detailed as follows:

$$Daily\ power\ cost = \frac{Monthly\ power\ cost}{30\frac{day}{month}} = \frac{25000\frac{QR}{month}}{30\frac{day}{month}} = \mathbf{833\frac{QR}{day}}$$

$$Labor\ cost_{Main\ production\ line} = \#\ Workers\ \times \#\ hours\ \times Worker\ rate$$

$$= 10\ \times 20\ hour\ \times 20\frac{QR}{hour} = \mathbf{4000\ QR}$$

The total cost of achieving the reclaimed rubber daily production of 15000 kg is broken down as follows:

$$\begin{aligned} &Production\ cost\ per\ day \\ &\qquad = Cost\ of\ tires + Labor\ cost_{Bringing\ tires} \\ &\qquad + Labor\ cost_{Tire\ cutting} + Labor\ cost_{Main\ production\ line} \\ &\qquad + Fuel\ cost + Power\ cost \\ &= 3125\ QR + 1680\ QR + 1680\ QR + 4000\ QR + 1050\ QR + 833\ QR \\ &\qquad = \mathbf{12368\ QR} \end{aligned}$$

Incorporating 5% wood in the factory's reclaimed rubber production means 750 kg of sawdust will be used daily. This amount would reduce the number of waste tires purchased from 625 to 594 tires. Hence the costs associated with purchasing the tires, delivering them to the factory, and processing them by cutting and going through the main production line will reduce by 5%. This corresponds to a reduction in production cost of 617 QR daily, 18510 QR monthly, and 225205 QR yearly. From an environmental point of view, we would be utilizing 750 kg of sawdust daily, 22500 kg monthly, and 273750 kg yearly, that would have been aggregated in piles adding harmful leachates to the local water systems or causing health hazards. **Table 9** lists a summary of the production costs with and without incorporating sawdust for convenience.

Table 9 Summary of costs associated with producing virgin reclaimed rubber (RR) and RR with 5% wood content

15000 kg RR/day		**Virgin RR**	**RR + 5% sawdust**
Weight of tires needed			
Number of tires		625	594
Tire cost (QR)		5	5
Total tire cost (QR)		**3125**	**2970**
Number of shipping trips		21	20
Fuel cost per trip (QR)		50	50
Total fuel cost (QR)		**1050**	**990**
Labor cost (bringing tires) (QR)			
	# Workers	4	4
	# Trip time (hour)	1	1
	Worker rate (QR/hour)	20	20
		1680	**1600**
Cutting time		21	20
Labor cost (Cutting) (QR)			
	# Workers	4	4
	Worker rate (QR/hour)	20	20
		1680	**1600**

Power cost (QR)		**833**	**791**
Labor cost (Production line) (QR)			
	# Workers	10	10
	Work time	20	19
	Worker rate (QR/hour)	20	20
		4000	**3800**
Total cost (QR)		12368	11751
Total savings (QR)	Per day	617	
	Per month	18510	
	Per year	225205	

CHAPTER 6: CONCLUSIONS

Recycling waste tires and producing reclaimed rubber are vital for environmental reasons. Reclaimed rubber composites are produced to provide specific properties, and those composites can be used in different engineering applications. Many research studies have explored the performance of reclaimed rubber composites. Most of the research on reclaimed rubber composites has focused on blends of natural rubber and reclaimed rubber. Composites of reclaimed rubber and other materials were lacking in the literature. Sawdust/powder, for example, is appealing because of its cheaper cost, availability, sustainability, and simplicity of handling and processing.

Furthermore, there is a scarcity of research on the development of reclaimed rubber/WF composites. This study investigated the performance of reclaimed rubber/sawdust composites of different wood content. The performance was evaluated using different tests, including tensile, hardness, Mooney viscosity, and water uptake tests. The optimum wood content percentage was determined, and a simple cost analysis was conducted based on it. The following are the conclusions drawn from the research conducted in this thesis:

- The tensile strength was found to decrease with the increase of wood content in the composite. The highest tensile strength (6.67 MPa) was observed in the virgin sample, while the lowest strength (2.49 MPa) was observed in the 20% wood content sample. This represents an overall decrease in tensile strength of around 63% with 20% sawdust. This decrease is mainly attributed to the weak interaction between the wood particles and the rubber matrix due to not using adhesives or binders. The particles hence work as voids that reduce the composite's strength.
- The rupture strain was found to decrease with the increase of wood content. The highest rupture strain was reported for the virgin sample of around 217%. In

comparison, the lowest was reported for the 20% wood content sample of around 56%. This represents a 74% reduction in ductility. The interaction between the wood particles and the matrix was also the reason behind the reduction in ductility.

- The hardness values were found to be increasing with the increase of the wood content. The highest hardness was 78.50 for 20% wood content. At the same time, the lowest value was 58.25 for the virgin reclaimed rubber sample. This corresponds to a 35% increase in the overall hardness. This increase is mainly attributed to the sawdust particles reducing the rubber chains' plasticity, and flexibility thus increased rigidity.
- The Mooney viscosity (MU) was found to increase slightly with the increase of sawdust content. The highest MU value was 29.80 for samples of 20% wood content corresponding to an increase of 30% relative to the virgin reclaimed rubber sample that exhibited an MU value of 23. The increased MU values are the increased overall rigidity with the increase of sawdust content.
- The water uptake was found to increase with the increase of wood content. The highest water absorption values were observed for 15 and 20% wood content (14%). In comparison, virgin rubber has only gained 1% water after one week.
- Using percentages of 1-5% of sawdust in reclaimed rubber composites does not compromise the mechanical properties. Hence, composites of such percentages can be used in different rubber manufacturing applications as per industry requirements.
- Incorporating 5% sawdust in reclaimed rubber production would save up 617, 18510, 225205 QR of production costs daily, monthly, and yearly, respectively.

CHAPTER 7: RECOMMENDATIONS FOR FUTURE WORK

The following recommendations are made to support the findings of this study and to broaden our understanding of the reclaimed rubber/sawdust composites:

- Different sizes of sawdust particles need to be investigated as additives used in reclaimed rubber. This will allow us to understand the effect of the sawdust size on the mechanical properties.
- Due to time and cost constraints, no binders or adhesives were used to bind the powder particles with the reclaimed rubber matrix. This is one of the reasons the tensile strength was observed to be reduced with the addition of powder. Hence, different binders are recommended in future research endeavors on this topic, as they may offer better mechanical performance.
- Conducting more tests is also another essential recommendation. For instance, dynamic mechanical analysis where the temperature is varied with cyclic loading is vital for polymer testing for specific applications.
- Scanning electron microscope (SEM) imaging is highly recommended to study the interaction between the sawdust particles and the reclaimed rubber matrix. Such investigation will help relate the microstructure to the macro mechanical properties such as tensile strength and hardness.
- Using the reclaimed rubber/sawdust composite in functional part or structure production to check its feasibility in real-life applications.

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