LODZ UNIVERSITY OF TECHNOLOGY

DOCTORAL THESIS

INFLUENCE OF VULCANIZATION PROCESS PARAMETERS ON THE PHYSIO-MECHANICAL PROPERTIES OF TEXTILE MATERIALS USED FOR THE REINFORCEMENT OF RUBBER GOODS

A dissertation submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy in the Interdisciplinary Doctoral School at the Lodz University of Technology

Faculty of Material Technologies and Textile Design
Institute of Architecture of Textiles
Discipline of Materials Engineering

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AUTHOR'S DECLARATION

I hereby declare that this dissertation entitled "Influence of Vulcanization Process Parameters on the Physio-Mechanical Properties of Textile Materials used for the Reinforcement of Rubber Goods" was written by me during the realization of my doctoral study at the Interdisciplinary Doctoral School of Lodz University of Technology from the period of 2019 to 2023 under the supervision of Dr hab. Eng. Marcin Barburski, Professor of the Lodz University of Technology. The dissertation was developed from my own research work and has not previously been submitted in any application for a higher degree. All citations and data sources are fully acknowledged through references.

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ABSTRACT

Conveyor belts are mechanical rubber goods used to transport raw materials and finished products from one location to another in various manufacturing, mining, and logistics sectors. The demand for lightweight materials with high mechanical properties and affordable conveyor belt costs accelerated the use of textiles as reinforcement material for conveyor belts. In recent years, woven fabrics produced from synthetic yarns have been widely used to reinforce the conveyor belt because of their flexibility, lightweightiness, good mechanical property, and cost-effectiveness.

However, the presence of materials with distinct properties in the textile-reinforced conveyor belt's structure has created complexity in adhering the components together, determining the influence of processing parameters on the mechanical property of the belt, and achieving the necessary properties of the belt. In order to adhere the rubber with textiles, the woven fabrics were impregnated with Resorcinol Formaldehyde Latex adhesive solution, and the reinforcement was subjected to a vulcanization process. The vulcanization temperature is carried out at a high temperature under pressure depending on the type of fabric, rubber, and conveyor belt being produced.

Therefore, during the vulcanization process, woven fabrics are susceptible to high temperatures for a specific duration depending on the conveyor belt type, which leads to physio-mechanical property changes in the textile materials. Nevertheless, the change that can occur in fabrics' properties during vulcanization was never scientifically analyzed. Therefore, this thesis aimed to investigate the effect of vulcanization parameters on the mechanical and physical properties of conveyor belts, woven fabrics, and yarns used to reinforce mechanical rubber goods. Additionally, the optimum vulcanization parameter was aimed to be identified based on the investigations.

In order to achieve the goal of the thesis, the research was conducted on high-tenacity polyester yarns, polyester-polyamide woven fabrics (EP), and textile-reinforced conveyor belts. The yarn and woven fabric samples were subjected to different thermal aging with various aging duration. The thermal aging parameters used for aging yarn and woven fabric samples were designated based on the fiber's glass transition temperature and melting temperature. Furthermore, the physio-mechanical properties of yarns, woven fabrics, and conveyor belts at various levels were investigated with a focus on the tensile properties of these materials at different stages.

The tensile, shrinkage, thermal stability, and micro-structural property analyses were conducted on the high-tenacity polyester yarn of different linear densities with the objective of analyzing the effect of temperature on the property of the yarn. Following that, a tensile property investigation was carried out on woven fabrics at the greige and dipped level pre-and post-thermal aging.

The experiments conducted on the yarns and fabrics showed that the tensile strength was significantly diminished when the yarn and fabric samples were subjected to thermal aging at a high temperature (220 °C) for thirty-five minutes. In contrast, the yarn and fabric samples' elongation were incremented with the increase in aging temperature regardless of the duration of aging. Therefore, determining vulcanization parameters that yield optimum tensile strength and elongation of the conveyor belt was compulsory for the effective functioning of the belt.

Based on the experimental results obtained from the yarns and fabrics, the vulcanization parameters were designated, and three layers of textile-reinforced conveyor belts were produced under the designated parameters. In addition, the tensile property and adhesive strength of the conveyor belt samples were investigated to determine the optimum vulcanization parameters of the belt. Based on the works carried out, a vulcanization temperature of 160 °C and a vulcanization duration of thirty-five minutes were found to be the optimum parameters to vulcanize three layers of EP 200 fabric-reinforced conveyor belts.

In general, this work contributed to the science on determining the influence of vulcanization parameters on the carcass of textile-reinforced conveyor belts. The work concluded that the vulcanization temperature and duration of vulcanization have an immense influence on the tensile strength and elongation property of the textile-reinforced conveyor belts. Vulcanizing the EP fabric reinforced conveyor belt at a high temperature (≥ 220 °C) for a longer duration (≥ 35 min) yields a lower tensile strength of the belt and increments the elongation of the belt, which can affect the proper functioning and lifespan of the conveyor belt. Moreover, the glass transition and the melting temperature of fibers in the fabric composition need to be considered to design the vulcanization parameters of textile-reinforced conveyor belts.

The experimental tests were carried out in cooperation with Sempertrans Bełchatów Ltd. Company, and the results obtained from this work was resulted in the introduction of an optimal production process for this company.

WPŁYW PARAMETRÓW PROCESU WULKANIZACJI NA WŁAŚCIWOŚCI FIZYKO-MECHANICZNE MATERIAŁÓW WŁÓKIENNICZYCH STOSOWANYCH DO WZMACNIANIA WYROBÓW GUMOWYCH

STRESZCZENIE

Taśmy przenośnikowe to techniczne wyroby gumowe używane w różnych sektorach produkcji, górnictwa i logistyki do transportu surowców i gotowych produktów z jednego miejsca do drugiego. Zapotrzebowanie na lekkie materiały o wysokich właściwościach mechanicznych i przystępnych cenach przyspieszyło wykorzystanie tekstyliów jako materiału wzmacniającego taśmy przenośnikowe. W ostatnich latach, tkaniny wykonane z włókien syntetycznych, są szeroko stosowane do wzmacniania taśm przenośnikowych ze względu na swoją elastyczność, lekkość, dobre właściwości mechaniczne i opłacalność.

Jednak obecność materiałów o różnych właściwościach, w strukturze taśmy przenośnikowej wzmocnionej tekstyliami, powoduje pewne trudności w trwałym połączeniu ze sobą elementów, określaniu wpływu parametrów obróbki na właściwości mechaniczne taśmy oraz uzyskiwaniu wymaganych właściwości taśmy. W celu zwiększenia adhezji gumy z tekstyliami, tkaniny impregnowano roztworem kleju Resorcinol Formaldehyde Latex, a całe zbrojenie poddano procesowi wulkanizacji. Parametry procesu wulkanizacji, którym poddawana jest taśma przenośnikowa, tj. temperatura, czas i ciśnienie, uzależnione są od rodzaju wykorzystywanej tkaniny i gumy.

W związku z tym, podczas procesu wulkanizacji, tkaniny te są poddawane działaniu wysokich temperatur przez określony czas, co prowadzi do zmian właściwości fizyczno-mechanicznych materiałów tekstylnych. Niemniej jednak, zmiany te nie zostały dotychczas naukowo przeanalizowane. Celem pracy było zatem zbadanie wpływu parametrów wulkanizacji na właściwości mechaniczne i fizyczne taśm przenośnikowych oraz tkanin i przędz stosowanych do wzmacniania technicznych wyrobów gumowych. Dodatkowo, na podstawie przeprowadzonych badań, starano się określić optymalne parametry wulkanizacji.

Aby osiągnąć cel pracy, przeprowadzono badania własności mechanicznych na przędzach poliestrowych o dużej wytrzymałości, tkaninach poliestrowo-poliamidowych (EP) oraz taśmach przenośnikowych wzmacnianych tekstyliami. Próbki przędzy i tkanin poddano obróbce termicznej w różnych temperaturach i w różnych przedziałach czasowych. Wyprodukowano również taśmy przenośnikowe wzmocnione tkaniną przy różnych parametrach wulkanizacji. Temperatury użyte do obróbki termicznej próbek przędzy i tkaniny wyznaczono na podstawie temperatury zeszklenia i mięknienia polimeru PET. Zbadano właściwości fizyczno-mechaniczne przędz, tkanin i taśm przenośnikowych na poszczególnych poziomach produkcji, ze szczególnym uwzględnieniem wytrzymałości i wydłużenia tych materiałów.

Wysokowytrzymałą przędzę poliestrową o różnych masach liniowych poddano badaniom wytrzymałości na rozciąganie, kurczliwości, stabilności termicznej oraz właściwości mikrostrukturalnych, w celu przeanalizowania wpływu temperatury na właściwości przędzy. Następnie przeprowadzono badania własności mechanicznych tkanin surowych przed oraz po procesie napawania lateksem w różnych temperaturach obróbki termicznej.

Eksperymenty przeprowadzone na przędzach i tkaninach wykazały, że wytrzymałość na rozciąganie uległa znacznemu zmniejszeniu, gdy próbki przędzy i tkaniny poddano obróbce termicznej w wysokiej temperaturze (220°C) przez trzydzieści pięć minut. Natomiast wydłużenie próbek przędzy i tkaniny zwiększało się wraz ze wzrostem temperatury, niezależnie od czasu trwania starzenia. W związku z tym, określenie parametrów wulkanizacji zapewniających optymalną wytrzymałość na rozciąganie i wydłużenie taśmy przenośnika było niezbędne dla efektywnej pracy taśmy.

Na podstawie uzyskanych wyników badań przędz i tkanin wyznaczono parametry wulkanizacji i przy zadanych parametrach wykonano taśmę przenośnikową wzmocnioną trzema warstwami tkaniny. Ponadto, zbadano właściwości wytrzymałościowe oraz siły połączenia warstw w taśmie przenośnikowej w celu określenia optymalnych parametrów wulkanizacji taśmy. Na podstawie przeprowadzonych prac stwierdzono, że optymalnymi parametrami do wulkanizacji trzech warstw tkanin EP 200 w taśmie przenośnikowej jest temperatura wulkanizacji 160°C oraz czas trwania wulkanizacji 35 minut.

Podsumowując, przeprowadzone prace wniosły wkład w naukę poprze określenie wpływu parametrów wulkanizacji na osnowę taśm przenośnikowych wzmacnianych tekstyliami. W pracy stwierdzono, że temperatura i czas trwania wulkanizacji mają istotny wpływ na wytrzymałość na rozciąganie i wydłużenie taśm przenośnikowych wzmocnionych tekstyliami. Wulkanizacja taśmy przenośnika zbrojonego tkaniną EP w wysokiej temperaturze (≥220 °C) przez dłuższy czas (≥ 35 min) powoduje obniżenie wytrzymałości taśmy na rozciąganie oraz zwiększenie wydłużenia taśmy, co może mieć negatywny wpływ na prawidłowe funkcjonowanie i żywotność przenośników taśmowych. Ponadto, przy projektowaniu parametrów wulkanizacji taśm przenośnikowych wzmocnionych tekstyliami, należy wziąć pod uwagę temperaturę zeszklenia oraz mięknienia włókien, z których wykonana jest tkanina.

Przeprowadzone badania zostały realizowane przy współpracy z firmą Sempertrans Bełchatów Sp. z o.o., co zaowocowało wprowadzeniem optymalnego procesu produkcji w tej firmie.

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II. Lemmi, Ts. Sh.; Barburski, M.; Kabzinski, A., & Frukacz, K. Effect of Vulcanization Process Parameters on the Tensile Strength of Carcass of Textile-Rubber Reinforced Conveyor Belts. **Materials**, **2021**;14(24): 7552, 1-15. https://doi.org/10.3390/ma14247552.

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ACRONYMS

DSC- Differential Scanning Calorimetry

EP - A Fabric Woven from Polyester Warp Yarn and Polyamide 66-Weft Yarn

HMLS – High Modulus Low Shrinkage

HT - High Tenacity

LS – Low Shrinkage

MRG - Mechanical Rubber Goods

PA66 - Polyamide 66

PET - Polyethylene Terephthalate (Polyester)

PVC - Polyvinyl Chloride

RFID - Radio Frequency Identification

RFL - Resorcinol-Formaldehyde-Latex

SBR – Styrene Butadiene Rubber

SEM – Scanning Electron Microscope

SLS – Super Low Shrinkage

TGA -Thermogravimetric Analysis

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1. INTRODUCTION

Textile-reinforced conveyor belts are widely used in various sectors ranging from manufacturing to mining industries for transporting raw materials and finished products from one location to another. Over the years, the conveyor belt was a crucial mechanical equipment used to move lightweight to bulky materials from place to place; the fast growth of mining, manufacturing, e-commerce, and rapid expansion of various industrial sectors inflated the global demand for conveyor belts. The surging need for conveyor belts across the globe favors textile-reinforced belts in numerous industries because of their lightweightiness, affordability, and high versatility.

Conveyor belt manufacturers are anticipated to develop advanced high-quality conveyor belts to fulfill the market demand. However, achieving a conveyor belt that serves properly for the intended application has not been easy for conveyor belt producers over the years. The existence of distinct constituent materials in the conveyor belt construction and the processing parameters have created complexity in the advancement of the conveyor belt's property.

In textile-reinforced conveyor belts, the pivotal purpose of using textile in the reinforcement is to provide the necessary mechanical property, primarily the tensile strength of the conveyor belt for the intended application. Therefore, textile materials with a possible combination of fiber properties, enhanced yarn, and fabric properties are mostly utilized based on the application area of the conveyor belt.

The textile and rubber materials reinforcement undergo a vulcanization process at elevated temperatures and high pressure to adhere the constituent reinforcement materials and impart the necessary mechanical and physical properties for the conveyor belt. However, the properties of textile materials, mainly those made of thermoplastic fibers, are sensitive to elevated temperatures.

Therefore, the vulcanization temperature, time, and pressure are vital in determining the conveyor belts' physio-mechanical properties. Nevertheless, despite the cruciality of vulcanization process parameters, it has been unknown to what extent the temperature, time, and pressure impact the properties of the conveyor belt and the constituent materials. These parameters are used in conveyor belt producing companies with various ranges, but this was not a scientifically proofed parameters; instead, it is a form of trial and error and relies on the experience of the workers.

Thus, an in-depth investigation is necessary to quantify how the textiles behave under the vulcanization process during conveyor belt production. Therefore, this thesis was focused on investigating the physical and mechanical properties of yarns, woven fabrics, and textile-reinforced conveyor belts under thermal exposure.

1.1 Objective of the Thesis

The multifaceted material composition of the conveyor belt in its structure makes it difficult to determine the property of each component material under the vulcanization process. Therefore, the main goal of this thesis work was to investigate the influence of vulcanization process parameters on the physio-mechanical properties of textile materials utilized for the reinforcement of mechanical rubber products, mainly for conveyor belt reinforcement.

Specific Objectives of the Thesis are:

- Investigating the effect of thermal aging and duration of aging on the physical and mechanical properties of industrial polyester yarns.
- Investigating the effect of thermal aging, time, and pressure on the mechanical properties of industrial woven fabrics.
- Analyzing the effect of Resorcinol-Formaldehyde-Latex (RFL) adhesive on the mechanical property of industrial woven fabrics.

- Studying the effect of yarn and fabric properties on the physio-mechanical properties of textile-reinforced rubber goods.
- Investigating the effect of vulcanization temperature and time on the physio-mechanical properties of fabrics and textile-reinforced conveyor belts during the process of conveyor belt vulcanization.
- Investigating the influence of vulcanization parameters on the adhesion property of conveyor belt components.
- Establishing optimum vulcanization parameters and improving the quality and process for the textile-reinforced conveyor belt.

1.2 Statement of the Problem

The textile material-reinforced rubber goods pass through various processing stages, including the vulcanization process at high temperatures and pressure. Each processing stage has its own positive and negative impact on the properties of the reinforcement's constituent materials, such as yarns, fabrics, rubber, and the final product of the mechanical rubber good. The industrial conveyor belt is among the mechanical rubber goods that seem to be a simple product with a straightforward structure for casual observers. One can simply describe a conveyor belt as thick bands of endless black rubber that run around pulleys or conveyor frames.

In reality, the conveyor belt is among the essential products in various sectors, and the structure and process of the conveyor belt are highly complicated. However, the effect of each processing parameter has never been quantified numerically nor described in a precise scientific way. Therefore, this study intended to find out the influence of vulcanization process parameters on the mechanical and physical properties of yarns and fabrics used to reinforce rubber goods and narrow the knowledge gap in the area of the process and properties of textile-reinforced conveyor belts.

1.3 Justification of the Choice of the Study

This research was conducted by the corporation with Sempertrans Bełchatów Ltd., Poland, a Semperit group company. Semperit is one of the world's most technologically advanced rubber industry, with over 50 years of experience in conveyor belt production at their Sempertrans segment. The choice of research topic was based on the keen interest of this company in establishing a scientific way of determining the effect of conveyor belt processing parameters on the conveyor belt properties.

The motivation to conduct research on this area emerged from the excessive lowering of mechanical properties of textile-reinforced conveyor belts after the vulcanization process that was detected during production. Therefore, the problem raised by the company was taken on board to investigate the reason behind the loss of physio-mechanical properties of the textile-reinforced conveyor belts.

1.4 Hypothesis

The hypothesis of the thesis was formulated based on the research previously conducted by various prominent researchers on the area of this thesis' topic, the objectives of the thesis, and the results expected from the experimental investigations. The main hypothesis is formulated as follows:

The thermal aging parameters cause a physio-mechanical deterioration of textile fabric-reinforced conveyor belts. However, it is feasible to optimize the vulcanization process parameters of the textile-reinforced conveyor belts to enhance the mechanical and physical properties of the conveyor belt.

The main hypothesis was divided into specific points, as provided below:

- Thermal aging of synthetic yarn and fabric causes mechanical property deterioration.
- The vulcanization process has a negative impact on the reinforcing materials.
- It is possible to optimize the property of conveyor belts carcass and processing parameters.

1.5 Structure of the Dissertation

The dissertation contains seven chapters.

Chapter one of this dissertation, the general introduction of the research carried out, objectives of the thesis, statement of the problem, the justification behind the choice of this research subject, the thesis hypothesis, and the dissertation content were presented.

In **chapter two**, the state-of-the-art related to the thesis topic was thoroughly analyzed. Furthermore, the literature review was conducted on the general overview of conveyor belts with a focus on textile-reinforced conveyor belts, industrial polyester yarns, and woven fabric mainly used for the purpose of mechanical rubber good reinforcements specifically for heavy-duty multi-ply conveyor belts, mechanical and physical properties of the textile materials, property requirements of the textile-reinforced conveyor belts, and an overall summary of the works so far conducted by prominent researchers in relevant to the textile-reinforced conveyor belt.

In **chapter three**, the materials used to conduct the research and the property details were provided.

In **chapter four**, the methodology implemented to achieve the thesis objective was described in detail.

In **chapter five**, the scientific experimental tests conducted on various materials based on the methodology developed according to the applicable standards were described in detail.

In **chapter six**, in-depth analyses of the results obtained from the experimental tests were provided.

In **chapter seven**, the thesis conclusion and recommendations for future work were included.

In addition to the above-mentioned chapters, the thesis abstract, table of content, list of figures, list of tables, acknowledgments, acronyms, author's publications relevant to this thesis and conference participation relevant to the topic of research, references used during this work, and author's scientific curriculum vitae are included.

2. LITERATURE REVIEW

2.1 Introduction

The manufacturing of Mechanical Rubber Good (MRG) products, such as conveyor belts, v-belts, tires, hoses, etc., involves the utilization of temperature to vulcanize the rubber materials. During the vulcanization process, which is performed at temperatures varying from 130 to 180 °C and takes from a few minutes to as long as several hours, depending on the type and size of the composite, chemicals liberated from the rubber can cause the reinforcing material to degrade [1].

The conveyor belts are widely employed for the continuous transportation of semi-finished and finished lightweight to bulky industrial products over short to long distances in various industries, shown in Figure 1 [2–4]. The invention of the conveyor belt in the late 19th century by Thomas Robins was the primary solution for this era's smooth running of warehouses and manufacturing items across the globe. The primitive version of the conveyor belt invented by Thomas Robins, which was awarded the grand prize in 1900 at the Paris Exposition World Fair, was intended to transport ore, coal, and other products [5].

Figure 1. Conveyor belt in the mining industry [6].

In the early 20th century, mining engineer Richard Sutcliffe introduced the first underground conveyor belt made of natural rubber and cotton fabric, which revolutionized the transportation of coal in the mining industry. At the time, the mining industry's requirements mostly influenced the conveyor belt's design. And yet again, the mining sector demonstrated its ability to set trends, specifically in underground mining, where strict standards have resulted in high belting standards [5, 7].

The development of the conveyor belt was not stopped there; throughout the years, modification of conveyor belt design, properties, and materials used to reinforce the conveyor belt has been developing from different perspectives. As a result, the belt's materials and properties have changed significantly over time. Belt users have joined with conveyor belt producers and engineers to create more robust and cost-effective conveyor belting in response to the requirement for enhanced tensile characteristics and abrasion resistance. Moreover, the invention of synthetic rubbers and thermoplastic fibers substantially contributed to the development of conveyor belts.

However, the fast growth of modern manufacturing technologies and the global supply chain demands affordable, durable, and efficient conveyor belts and conveying systems. In order to meet the global market demand, researchers have conducted various studies related to the design [8–11], properties [12–15], modeling, and process technologies [16–19] of the conveyor belt. The various relevant research conducted so far has been analyzed from different perspectives in the following sections of this chapter, and the research gap has been identified.

2.2 Construction of Conveyor Belts

The continuous bulk materials handling of conveyor belts is based on the belt's structure, which is made up of three main components, namely, carcass, skim, and cover parts, shown in Figure 2. The integrity of the structural components of any conveyor belt type is crucial not only to convey the material but also to absorb the tensile load imposed on the belt during the operation in order to increase its lifespan [20, 21].

The carcass is the reinforcement part found inside the conveyor belt structure and is often referred to as the heart of the conveyor belt. The carcass can be either steel cord or woven fabric. Its main function in the conveyor belt structure is to provide the necessary tensile strength needed to convey the material from one place to another, absorbing the impact load levied on the conveyor belt by the material being conveyed and providing the necessary lateral stiffness required to support the load. The total strength of the belt primarily relies on the strength of each carcass ply [22]. The number of carcass plies and material types is selected based on the tensile strength of the belt required to transport the material, the belt width, maximum operating tension, and the weather condition under which the conveyor belt operates [23–25].

The skim part of the textile-reinforced conveyor belt is the rubber or polyvinyl chloride (PVC) material located between the plies of the conveyor belt. The skim component provides load support, impact resistance, and the necessary adhesion between the carcass plies of the conveyor belt [26].

Covers of the conveyor belt - natural rubber and styrene butadiene rubber are mostly used for the bottom and top covers of the conveyor belt based on the application area and the required properties of the conveyor belt.

The top cover of the conveyor is responsible for protecting the carcass of the belt from external factors such as impact, wear, abrasion, tear, moisture, etc., and provides necessary gripping to avoid slipping or sliding of materials being conveyed on the belt [27, 28].

The thickness of the cover depends on the material being conveyed. The impact energy of the materials transported is first absorbed by the top cover of the belt; this results in stress and strain development on the cover layers. Marasová et al. [27] presented the model of a conveyor belt covering layer and analyzed the stresses and deformations induced by the dynamic force of the material being conveyed on the conveyor belt's top cover.

The bottom cover of the conveyor belt is also responsible for providing necessary protection to the carcass and reducing friction between the conveyor belt and roller, idler, or other components of the conveyor belt system. Fedorko et al.[29] analyzed the effect of selected material properties on the conveyor belt cover materials using a finite element. The study signifies that the modulus of elasticity of the conveyor belt materials determines the contact force on rollers, which significantly affects the belt's lifespan.

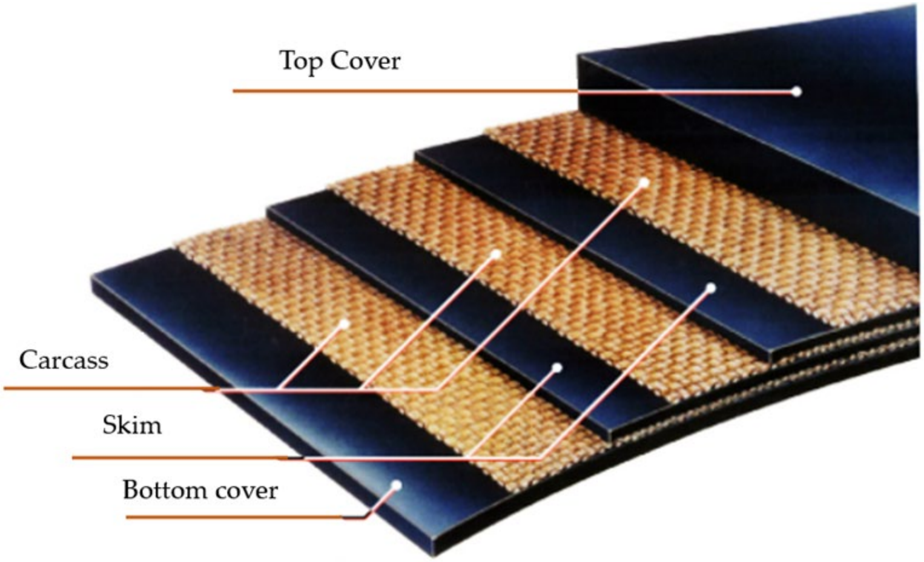

Figure 2. Construction of textile-reinforced multiply conveyor belt [30].

2.2.1 Nomenclature of Conveyor Belts

Regardless of the structure and type of the belt, conveyor belts are commonly described as the following exemplary nomenclature (coding) system. The below example was taken from the coding system of Sempertrans Ltd. company.

Figure 3. Sempertrans textile-reinforced conveyor belt [31].

1000 EP 1000/5 12 + 4, TGU

Belt width

Belt material

Belt's tensile strength

Number of carcass layers

Thickness of the top cover

Thickness of the bottom cover

Quality grade of the conveyor belt

Irrespective of the conveyor belt producer companies, the belt coding must include the following parameters. In addition to the parameters below, the manufacturers add some supplementary information about the belt depending on the application areas [32].

Belt material – the material used to make the conveyor belt; in the above example, the material was expressed as EP, which means the belt was reinforced with the woven fabric produced from polyester(E) yarn in the warp direction and polyamide 66(P) in the weft direction.

Belt strength – nominal tensile strength of the belt in newton per millimeter (N/mm) should be included in the coding.

Number of layers: The number of carcass layers in the conveyor belt needs to be mentioned.

Thickness – the top and bottom covers thickness of the rubber also must be included.

2.3 Categories of Conveyor Belts

Around the world, the use of conveyor belts for light to bulk material handling operations plays a crucial role in many different industries. The nature of material handling varies from industry to industry, depending on the type of materials conveyed and the environmental conditions under which the conveyor belt operates. However, in each industry, conveyor belts are designed and operated to handle the materials with maximum efficiency and reliability [33].

Conveyor belts are categorized based on numerous aspects, such as structural design, reinforcement material composition, the weight of the material being conveyed, application areas, etc. For example, the structural design of conveyor belts is determined by the application areas of the belt, the nature and volume of the conveyed material, the required operating speed of the belt, and the belting system requirements such as driving units, the width of the belt needed and diameter of the pulleys [34, 35].

Based on the weight of the material being conveyed, conveyor belts are categorized into four groups, these are:

Light-duty conveyor belts – these types of belts are designed for transporting lightweight materials for short to medium distances, which ranges from meter to few hundred meters (< 500 m) depending on the application area.

The construction of such belts is typically made of rubber, nylon, or PVC with single-ply construction and thinner than other types of belts. It is mainly used in packaging, food processing, glass, logistic center and parcel services, and recycling industries [32].

Medium-duty conveyor belts are stronger and thicker than light-duty conveyors and are designed to handle medium-weight materials in mining and quarrying industries, construction, manufacturing, and distribution. These kinds of belts are made of rubber, polyester, or PVC with two or more layers of the carcass [36].

Heavy-duty conveyor belts – are designed to handle heavy and bulk materials over short to long distances with optimized properties that match the application area of the belt. Heavy-duty conveyor belts are often made from synthetic or natural rubbers reinforced with steel cord or fabric layers and PVC [37].

Super-heavy-duty conveyor belts – are a specialized type of conveyor belts designed to transport extremely heavy and abrasive materials in harsh conditions. These kinds of conveyor belts are also designed with additional features such as monitoring systems that detect belt misalignment or excessive surface wear and dust containment systems to prevent material spillage. Super-heavy conveyor belt surfaces can be coated with special materials to provide additional abrasion, wear, and chemical resistance [38, 39].

Based on the material used to reinforce the belt, conveyor belts are categorized into three main groups, these are:

Steel cord-reinforced conveyor belts - are reinforced with high-strength steel cords, which are either arranged in a parallel configuration or embedded in rubber to provide the necessary tensile strength required to convey heavy materials with minimum elongation over long distances.

Steel cord-reinforced conveyor belts are mainly used in the areas where abrasive and heavy materials are transported, mainly in the construction and mining industries[40, 41].

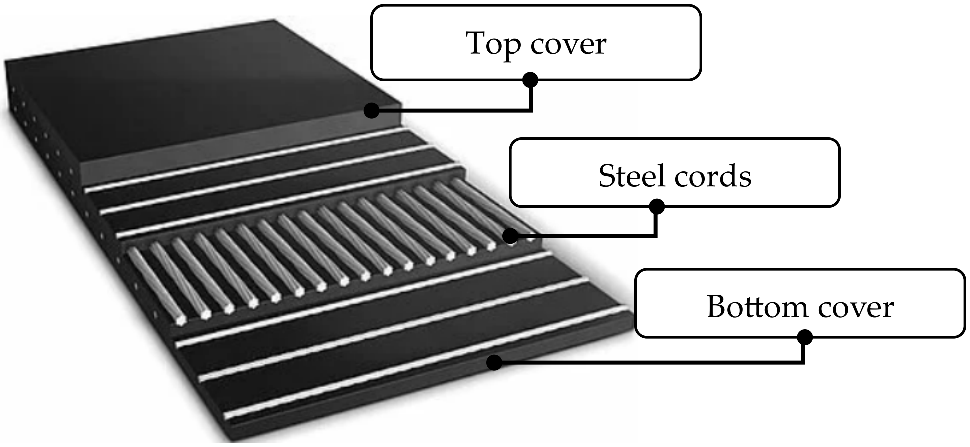

Figure 4. Steel cord reinforced conveyor belt [31].

Fabric-reinforced conveyor belts - are reinforced with either single or multi-plies of fabrics to enhance the tensile strength of the conveyor belts. Details about textile-reinforced conveyor belts are provided in section 2.4.

Solid woven fabric reinforced conveyor belts – are made from a single layer of woven fabric with PVC or rubber materials. Solid woven fabrics impregnated with PVC are primarily used in underground coal transportation where fire resistance is required in chemical and metallurgy industries. Besides the fire resistance, this conveyor belt type has high tensile strength, no delamination, and excellent impact resistance [42, 43].

Figure 5. Solid woven fabric conveyor belt [43].

2.4 Textile-Reinforced Conveyor Belts

The use of textile materials as a carcass of conveyor belts has been dominating the conveyor belt sector because of their flexibility, lightweightiness, and affordability. In the last decade, scholars have focused on the different areas of textile-reinforced conveyor belts; these were reviewed in this section.

During the operation of the conveyor belt, the nature of the materials conveyed, such as the weight of the material, the structure of the material, the height from where the material is loaded to the conveyor, and the distance, have the possibility of damaging the conveyor belt. Ali [44] studied the effect of loading direction, the number of reinforcement layers, and loading speed on the conveyor belts' tensile strength using the Taguchi method, and the finding signifies that loading direction has an immense effect on the tensile property of the belt. The failure of the conveyor belt causes adverse economic impacts, not only the high costs associated with the repair of the belt but also the losses caused by the downtime of the whole conveying system. Fedorko et al. [45] investigated the damage of textile-reinforced conveyor belts by falling material, and the impact of falling material was determined using mathematical-statical models developed from the experimental test data. Dynamic analysis is key in determining the functionality of the conveyor belt and safe operational conveying system [46]. Researchers have used computer tomography and metro tomography to analyze the failure of the inner structure of textile-reinforced conveyor belts by impact and dynamic wear during operation, and the results indicated that the change in the properties of the carcass could be identified to some extent using this equipment [47–49]. Radio Frequency Identification (RFID) based sensors were also proposed to detect the crack presence and propagation on the surface of the belt [50]. Digital X-ray imaging was also used to monitor the conveyor belt conditions in order to ensure the reliability of the belting system [51].

2.5 Industrial Woven Fabrics

The woven fabrics are used in a conveyor belt construction to provide the belt with the necessary tensile strength required for the intended application. Woven fabrics can be used in the form of mono-ply, multi-ply, or solid woven fabric with various weave structures in the conveyor belt construction. Woven fabrics are widely used to reinforce conveyor belts due to their cost-effectiveness, abrasion, heat, and oil-resistant properties, wide tensile range, and design flexibility [52].

Özdemir et al.[53] investigated the effect of weave and yarn settings on the tensile, impact, and bursting strength of woven fabrics. The result indicates that the presence of float yarns in the weave structure, whether in the warp or weft direction, has the ability to enhance the tensile strength and impact resistance of the fabric, particularly in the direction of the float yarn. Halaoua et al. [54] analyzed the relationship between the woven fabric properties, such as weave structure, fiber composition, surface mass, and fabric thickness with the thermal property of the fabric. The study showed that the plain weave structure has the highest thermal properties compared to twill and satin weave structures. Additionally, the thermal resistance of the fabric increased with the increase in fabric thickness. Barburski [55] analyzed the structural change of woven fabrics subjected to various static loads with respect to the fundamental parameters of textile fibers and yarns. In his study, a new method of fabric structure modeling that allows to predict the mechanical properties of the fabric was developed. Additionally, Barburski examined in another work the effect of weave and heat treatment on the internal geometry of synthetic warp and weft yarns by varying the thermal treatment duration for different weave structures while the temperature was constant. The study revealed that the weave structure under thermal treatment influenced the fabric thickness, warp and weft crimp, and fabric covers [56].

2.5.1 Fabric Structure

The fabric weave structure for the multi-ply conveyor belts is mostly plain weave and twill weave, shown in Figures 6a & b, respectively. The repeat unit of the fabric samples was marked in red in Figure 6. Plain weave is the simplest structure in which warp and weft yarns are interlaced alternative to each other, as shown in Figure 6a. Woven fabrics used for technical and industrial purposes, including for conveyor belt reinforcement, are mainly produced with the plain weave and its derivates due to the maximum binding points of this type of weave, which increases the fabric strength [57].

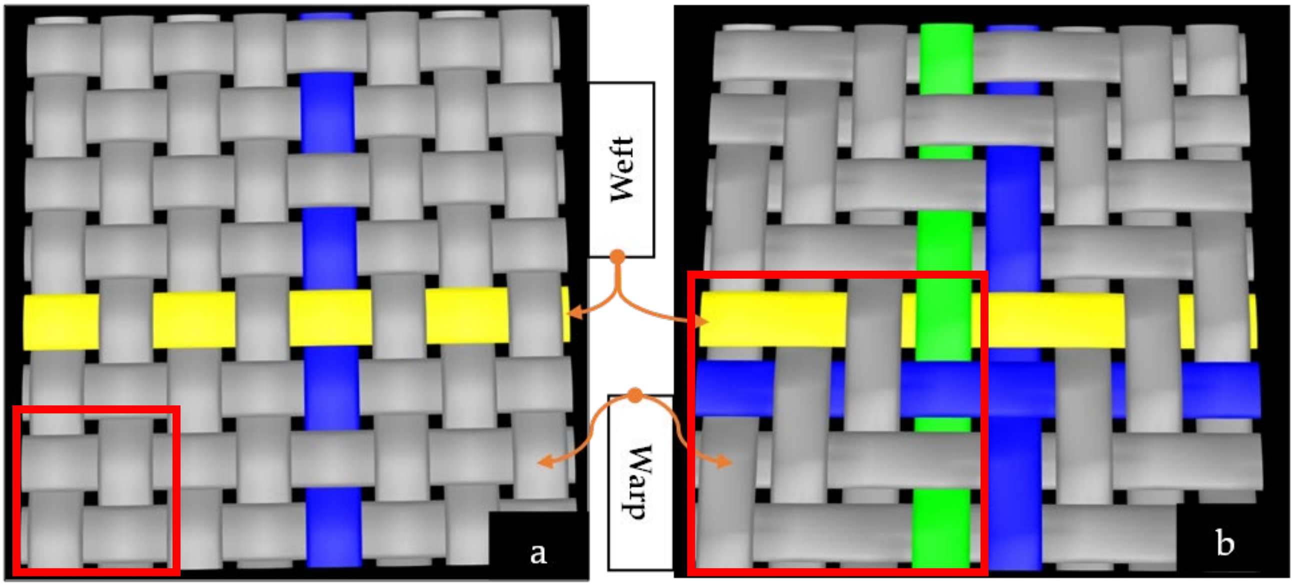

Figure 6. Woven fabric structure. (a) Plain weave, (b) 2/2 Twill weave.

Özdemir et al.[58] studied the effect of plain weave and its derivates on the tensile and impact properties of woven fabric-reinforced composites. The plain weave derivatives (2/2 matt weave, 3/1 matt weave, and 2/2 rib weave) were considered for the study. The investigation shows that the tensile strength and impact resistance of woven fabrics are dependent on the weave type with high tensile properties in the warp direction obtained with the 2/2 matt weave fabric, high impact resistance obtained with the 3/1 matt weave, and high tensile strength in the weft direction was obtained with the 2/2 rib weave.

Twill weave, shown in Figure 6b, is distinguished from other weave types by the presence of diagonal lines along the width of the fabric. The twill weave can be constructed in various ways by manipulating the number of warp and weft yarns depending on the fabric property required. However, due to the lower number of intersections in the fabric structure, there is a longer float of yarns from one intersection to the other; this improves the tear strength of the fabric, but the use of such fabric in applications where the mechanical fastener is involved can cause lower fastener retention strength because of the possibility of float yarns can be combed out during the operation [59].

In the solid-woven fabric structure, the weft yarn lies at least in two layers, with the warp yarns interlacing all the weft yarns.

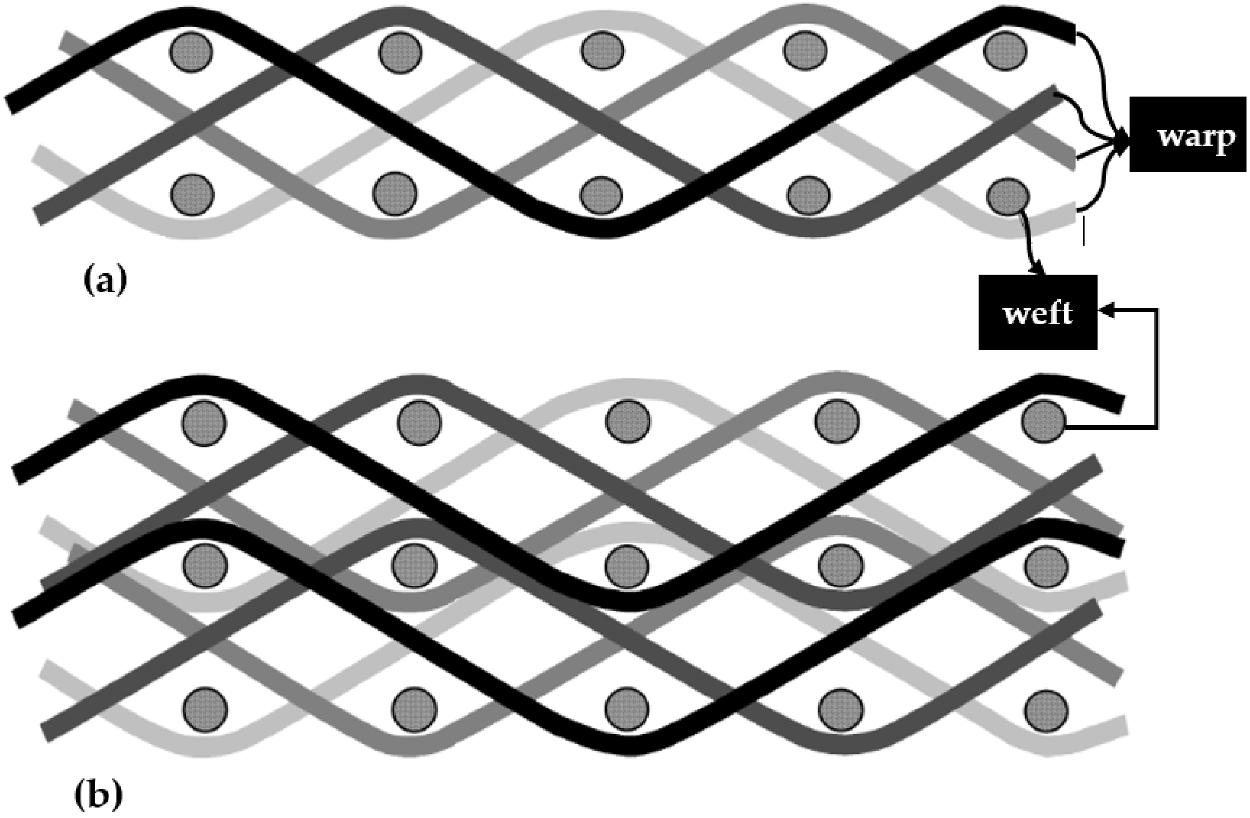

Figure 7. Solid woven fabric structure. (a) double equal plain fabric structure, (b) Three layers of woven fabric structure [59].

The simplest form of solid-woven fabric and three layers of woven fabric structure were respectively illustrated in Figures 7a & b. This type of fabric structure enables the possibility of producing very heavy and thick woven fabric. Witczak et al. [60] examined the possibility of shaping bending rigidity and mechanical strength of multilayer woven fabrics used to reinforce conveyor belts by changing the order of weft yarn insertion into individual layers. The study signified that the tensile strength and bending rigidity could be improved by introducing different options of weft insertion while producing multilayer woven fabrics.

2.5.2 Mechanical Properties of Industrial Woven Fabric

The mechanical properties of fabrics depend on the material used, the type of yarns, the weaving parameters, and the weave types. Dixit et al.[61] conducted a comprehensive review of the various modeling aspects for predicting the mechanical properties of woven fabric-reinforced composites. The study conducted by Yüksekkaya et al. [62] shows that yarn diameter is the crucial parameter that determines the stiffness properties of the woven fabric. The study revealed that the woven fabric stiffness is directly proportional to the increase in the yarn diameter. The analytical and numerical models undertaken by various researchers indicate that the mechanical property of woven fabrics primarily depends on the fabric’s weave structure [63–65].

2.6 Yarns

In reinforcing mechanical rubber goods, aramid, high tenacity polyester, rayon, polyamide 6, and polyamide 66 cords are used to produce woven fabrics or directly reinforce the rubber material. In the conveyor belt case, high tenacity polyester and polyamide 66 are predominantly used to produce woven fabrics to reinforce the rubber materials. However, the choice of yarn types for the conveyor belts depends on the belt's application area.

2.6.1 Poly (ethylene terephthalate) Yarn

In the textile industry, polyester is the general name given to fibers made from polyethylene terephthalate (PET). Polyester fiber is a melt-spun fiber prepared from Ethylene glycol and Terephthalic acid. The PET polymer is produced from low molecular weight monomer or oligomer by polycondensation reaction at high temperature ($290^{o}c$) and pressure (400 kPa) [66]. The monomer of Poly(ethylene terephthalate) is produced either by ester interchange of dimethyl terephthalate and ethylene glycol (Figure 8), which is widely used in Europe or by direct esterification of terephthalic acid with ethylene glycol (Figure 9) to form an oligomer mainly used in the United States of America [67, 68]. After polymerization, the polymer passes through melt spinning and drawing stages to produce the fiber. Polyester fiber is the largest volume, the most versatile synthetic fiber in the world, with 51.5 percent market share of total global fiber production in 2018 [69, 70]. Despite the impact of COVID-19 pandemic on global fiber production, the global market share of polyester was grown to 52 percent in 2020 with 57 million tons of production volume [71]. Polyester fiber consumption is increasing at a sustained rate because of its versatility, low production cost, recyclability, physical properties, and the large spectrum of applications ranging from consumer apparel to home furnishing products and heavy-duty industrial applications.

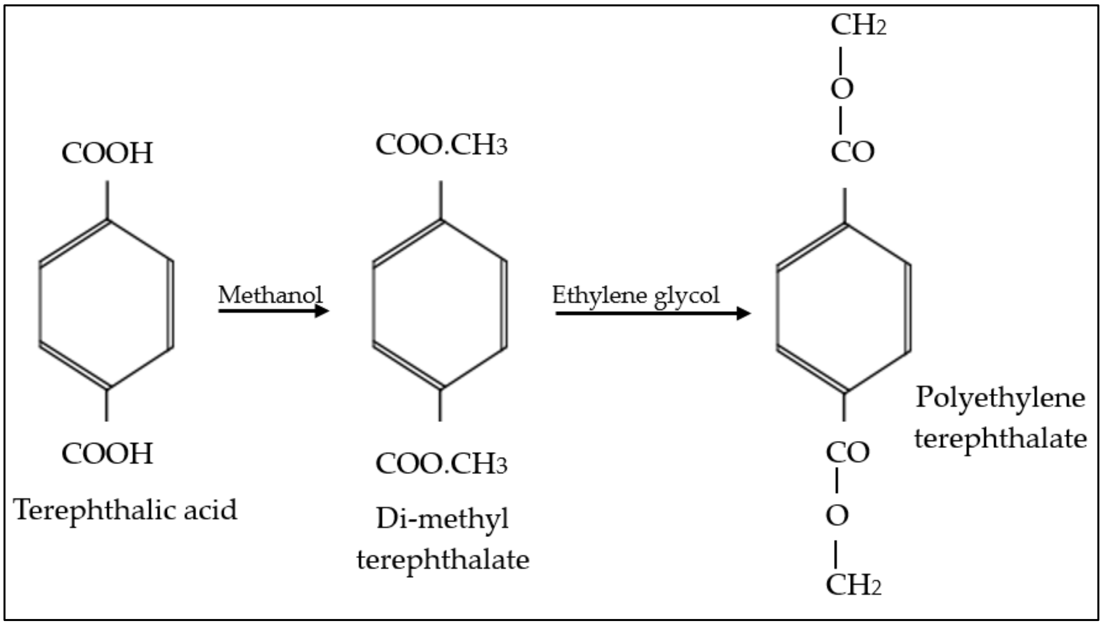

Figure 8. Synthesis of polyethylene terephthalate by ester exchange method [59].

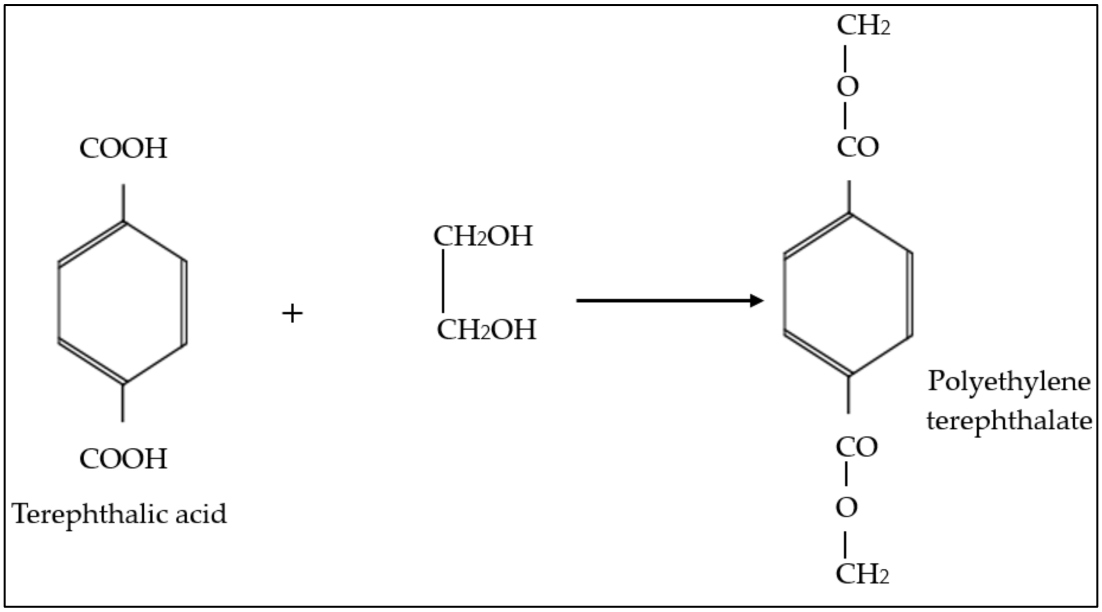

Figure 9. Synthesis of polyethylene terephthalate by direct esterification method [59].

2.6.2 Industrial Poly (ethylene terephthalate) Yarn

Based on the areas of applications, polyester yarns can be broadly divided into two segments: apparel and industrial-grade yarns [66]. Apparel-grade polyester yarns are used mainly for clothing and other household purposes; this yarn category has the lowest tenacity compared to industrial-grade yarns, which have above 6.5 N/tex[72].

The major types of industrial polyester yarns that are commercially available for a wide range of applications are High Tenacity (HT) polyester yarn, High Modulus Low Shrinkage (HMLS) polyester yarn, Low Shrinkage (LS) polyester yarn, and Super Low Shrinkage (SLS) polyester yarn [73].

High tenacity polyester has been used since the 1950s as the basic raw material for the reinforcement of Mechanical Rubber Goods (MRG) due to its high strength (≥7 N/tex), resistance to stretching, high modulus of elasticity, and high thermal stability. In the early development of high tenacity polyester yarn, the production process was made in two steps: spinning & drawing. Nevertheless, in the 1980s and 1990s, the production process was enhanced to a single stage spin process with the aim of increasing the average molecular weight of PET to meet the higher demand of high tenacity yarns for rubber reinforcements like tire cords and fabric carcass for conveyor belts [74].

2.6.3 Structure of PET Industrial Yarns

The PET polymer molecules in the fiber structure are oriented along the fiber axis to form fibrils (Figure 10). The coherence of crystalline and amorphous regions is predominantly found in the longitudinal direction of the fibrils. In the amorphous domain, the molecules are ordered in an inhomogeneous structure, unlike crystals, where the molecules are ordered in a highly oriented way. Because of the nonuniform orientation of the molecules, the amorphous region of the structure is the weakest point in the fiber structure [75].

Therefore, the tenacity and young's modulus of PET fibers are significantly influenced by the molecular arrangements in the amorphous region. The amorphous regions are categorized into two, and the first kind is the molecules running in the structure from one crystal to the other, which are called taut molecules. The second category of amorphous is the molecules folding at the boundaries of the crystals. The taught molecules are responsible for bearing the load with crystalline regions, and it determines the mechanical property of the fiber[73, 75, 76].

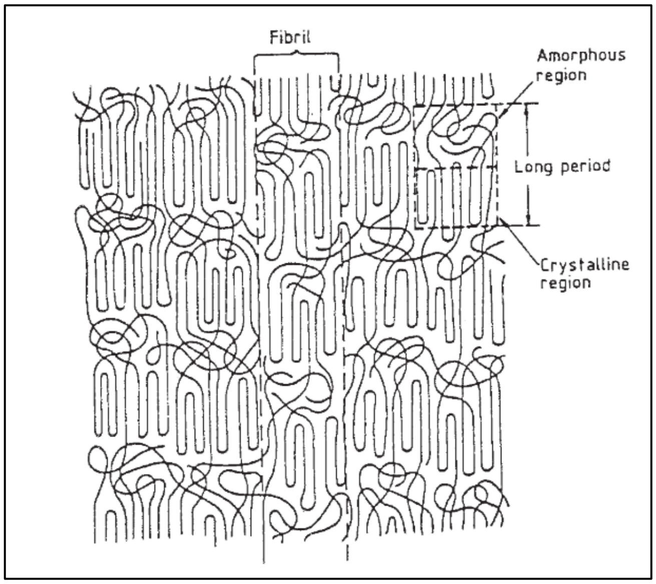

Figure 10. Structural model of drawn PET yarn [77].

However, the folding molecules do not affect the tensile strength or modulus of the fiber. Under a tensile load, the molecular rupture is first initiated by the uncoiling of molecules in the amorphous region and followed by the crystalline regions [77]. The disintegration of the entanglement network between the molecules determines the tensile strength, elongation, and modulus properties of the yarn. Depending on the processing methods and thermal history poly (ethylene terephthalate) is among the few polymers which may exist both as an amorphous and a semi-crystalline form [78].

The availability of poly (ethylene terephthalate) polymer in different forms leads to the production of various types of PET fibers.

Nowadays, a variety of PET morphology and structure can be created by varying the process conditions (Figure 11); because of this, PET is considered as a model polymer for scientific research on structure–property relationship. The wide application areas of PET yarn place different demands on the property of the yarn, these properties are determined by the multiscale structural parameters of the fiber morphology. Over the past several decades, the effort to understand the relationship between the processing, structure, and properties of PET industrial yarns has been made by several scholars [75, 76, 79–85]. These studies concluded that the amorphous orientation of the yarn has more influence on the mechanical properties of PET industrial yarn. In addition, the structural characteristics of PET yarn are not simply determined by a single processing parameter of the yarn, to obtain the yarn with a specific desired structure or properties, a series of processing such as technological parameters on the spinning-drawing machine such as spinning speed, draw ratio, and heat-setting temperatures, should be taken into considerations.

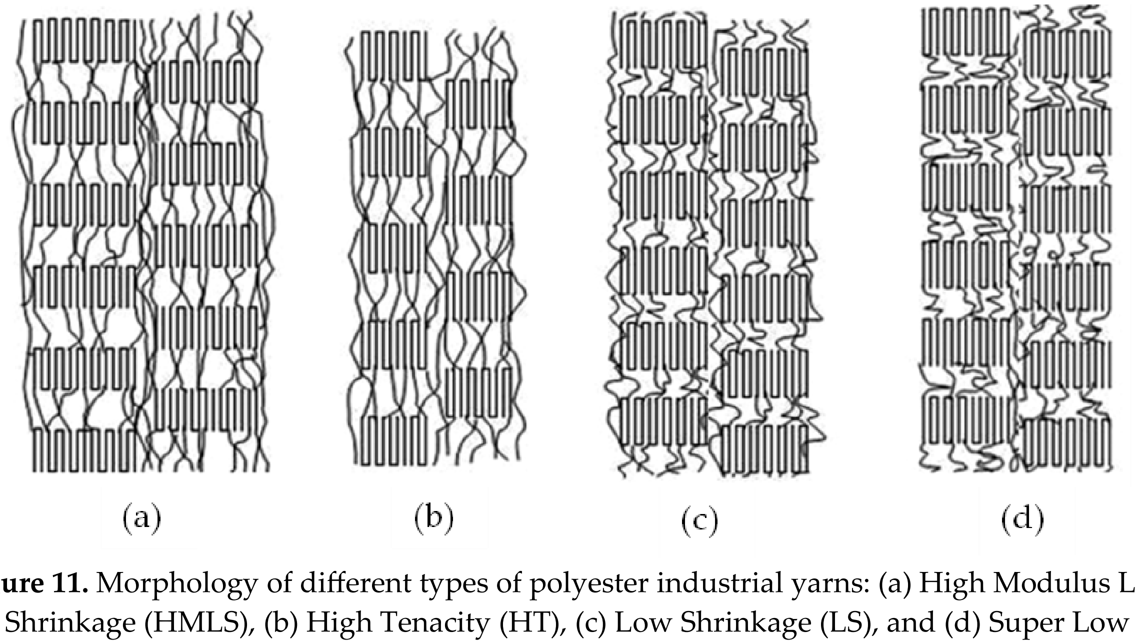

Figure 11. Morphology of different types of polyester industrial yarns: (a) High Modulus Low Shrinkage (HMLS), (b) High Tenacity (HT), (c) Low Shrinkage (LS), and (d) Super Low Shrinkage (SLS) [75].

2.6.4 Mechanical Properties of PET Industrial Yarns

The mechanical property of polyester industrial yarns is a crucial parameter that is needed in mechanical rubber reinforcement technologies. Tenacity and Elongation of PET yarns are the most significant mechanical properties of PET industrial yarns in conveyor belt applications. The tenacity of the yarn is obtained by exerting a force on a known unit of yarn and measuring the force required to break the yarn. Thus, tenacity is defined as breaking load divided by the linear density of the yarn. Tensile strength is the word used to describe the strength of a textile fiber or yarn when it is loaded along its length axis.

Previous findings proved that the tenacity of the polyester yarn is highly affected by the amorphous region of the yarn structure; it was shown that the highest amorphous orientation is found in high tenacity PET yarns while the lowest tenacity and amorphous orientation is found in the Super Low Shrinkage (SLS) type of PET yarns. Therefore, the tenacity of the PET yarn is primarily determined by the amorphous orientation in the yarn structure [77, 80]. For most yarns used to produce apparel and clothing applications, the high tenacity is not a big concern, and single yarns are used, but in the case of technical yarns, high strength and modulus, dimensional stability of the yarns are very crucial parameters, and to meet the mechanical property level required for the industrial applications most of the time ply or folded yarns are produced.

A folded yarn is produced by twisting two or more single PET yarns together as per the required mechanical property for the specified application. The twisting of two or more single yarns improves the binding-in of the fibers and increases the mechanical property of the yarn [86, 87].

2.6.5 Thermal Property of PET Industrial Yarns

Heat treatment of the PET fibers for a short duration (1.2 seconds) under the free-to-relax condition can form the micro-crystals in the amorphous region of the PET fiber structure, which leads to the change of PET fiber's mechanical behaviors [88]. The heat treatment of polyester yarns above the glass transition temperature decreases the tensile strength of the yarn [89]. Polyethylene yarns are susceptible to thermal aging, and the effect of temperature on the property of the yarn depends on the molecular weight of the polymers in the fiber structure, glass transition, and melting temperature of the polymers used to produce the fiber [90, 91].

2.6.6 Shrinkage Property of PET Industrial Yarns

Thermal shrinkage of PET industrial yarns is a highly relevant characteristic and is of great interest to industry because of the need for high dimensional stability of the rubber reinforcing material over a wide range of temperatures. Moreover, dimensional stability is required in the longitudinal direction of the belt to avoid belt slippage between the drive drum and belt during operation. Hence, PET yarns are mainly used as a warp yarn in the fabrics used to reinforce conveyor belts, and these yarns' shrinkage property directly influences the dimensional stability of the belt. The shrinkage of PET fibers or yarns depends on the drawing process of the filament. The undrawn PET filament has higher shrinkage than that of the drawn filament because the undrawn PET yarn is amorphous while the drawn is crystalline. The structure with low amorphous orientation has a lower shrinkage percentage, and vice versa [86].

2.6.7 Application Areas of PET Industrial Yarns

Industrial polyester yarns are used in various applications such as conveyor belts, v-belts, geotextiles, hoses, seatbelts, and tire cords due to their elevated mechanical, physical, and chemical properties and low cost [92].

2.7 Adhesion of Rubber to Textiles

The textile-reinforced conveyor belt is the combination of two distinct materials, which are textile and rubber. Therefore, adhering these materials together is crucial to obtain a conveyor belt with the necessary physical and mechanical properties. However, establishing chemical or physical adhesion between these materials has been challenging over the years [93, 94]. Nonetheless, researchers tried to develop an adhesive chemical to solve the adhesion issue between rubber and textiles. The Adhesive chemical, Resorcinol Formaldehyde Latex (RFL), developed by William H. Charch and Dorothy B., was successfully used in textile-rubber reinforcement technologies to impart adhesion to textile materials [95]. Even though RFL adhesives have been utilized over the years in textile-rubber reinforcement technologies, the chemical is toxic and can cause health concerns. Because of this, in 2014, the European Union categorized it under carcinogenic and mutagenic chemicals. Therefore, researchers have been trying to develop alternative methods for the adhesion of textiles to rubber, such as plasma treatments [96–99]. Nonetheless, there is no effective adhesion method developed that overtakes the RFL.

The textile materials are dipped in the Resorcinol Formaldehyde Latex solution either at yarn or fabric level. The fabric or yarn immersed in the RFL solution undergoes a curing process at a temperature of 180 °C for a short time which depends on the type of textile fiber, the thickness of the fabric, and the yarn's linear density [100, 101].

2.8 Property Requirements of Multi-Ply Conveyor Belts

The conveyor belts are expected to meet the following basic requirements:

High strength – the conveyor belt must have optimal tensile strength required to withstand the maximum force exerted on the belt by the material being conveyed throughout its service life. The required strength varies with the size and type of material to be transported, belt splicing, method of loading, and condition of the conveyor installation. In general, the maximum working load of the conveyor belt is about 10-15 percent of the belt's breaking load, and the safety factor of the conveyor belt system is 6-10, depending on the conveyor belt type. Conveyor belt tensile strength primarily depends on the properties of component materials; these properties are specified in the description of the conveyor belt [102].

Low elongation – to avoid slippage during operation between the driven pulley and the belt and maintain dimensional stability, the belt with low elongation in a longitudinal direction is required. The belt elongation is determined by the type of reinforcement, fabric construction, yarn types used for the fabric construction, and thermal properties of the fabric used for the reinforcement [103].

High impact resistance – the conveyor belt is required to absorb the impact load exerted on the belt by the material being transported during the operation. The belt's impact load is determined by the construction of the top cover and the stress-strain behavior of the reinforcing material. During operations, conveyor belts are frequently vulnerable to damage due to the impact load levied on the belt surface by the material being transported. This damage results in the need for the replacement of the damaged belt and downtimes that can lead to severe financial loss [104, 105].

Good troughability – the empty belt is required to have sufficient contact with the center roller, as shown in Figure 12b, to avoid belt damage during the operation and increase the loading of a conveyor belt. The troughability of the belt is determined by the rigidity of the belt in a transverse direction [36].

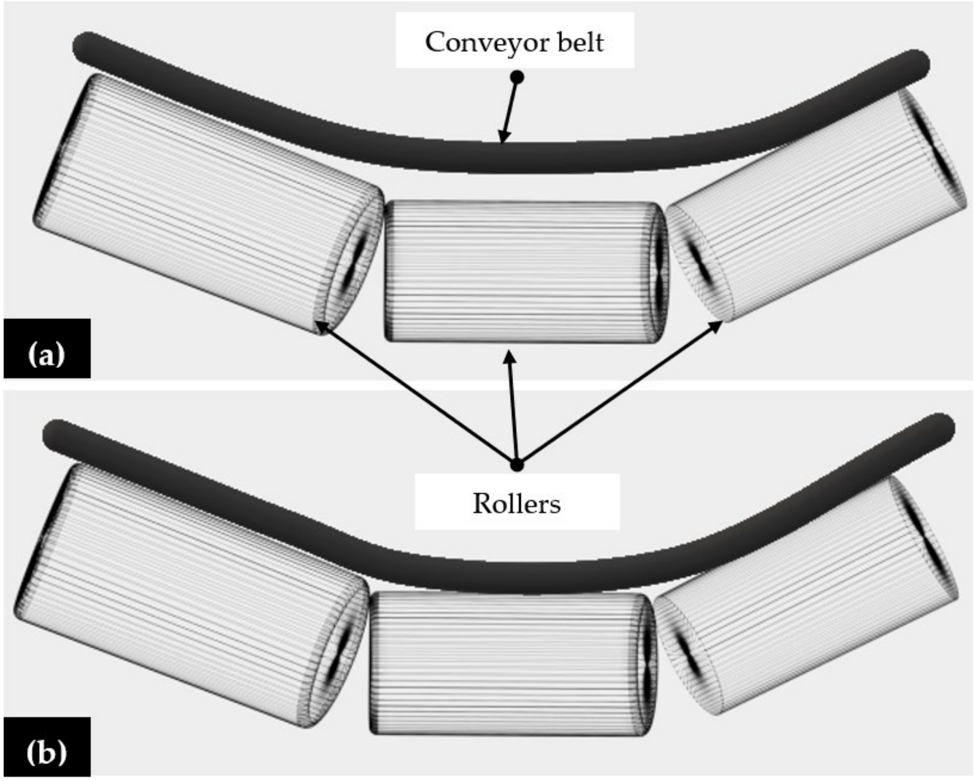

Figure 12. Troughability. (a) Incorrect troughing, (b) Correct troughing [36].

In the case of the fabric-reinforced conveyor belts troughability of the belt is influenced by the fabric construction (weave type), weft yarn type, number of plies, and distance between the plies. Bahrun et al. developed a mechanical model of a conveyor belt to prevent the slippage of the conveyor belt and ensure the stability of belt during the transportation of bulk materials [106]. In fabric-reinforced conveyor belts, bending resistance and buckling properties are determined by the modulus and crimp percentage of the warp yarn and the distance between the number of conveyor belt plies.

Good adhesion – during operation, the conveyor belts are subjected to continuous flexing both in the transverse and longitudinal directions. Therefore, the adhesion between the conveyor belt components is crucial to prevent the stripping of ply or cover separations [107].

Resistance to atmospheric conditions – conveyor belts are required to be resistant to atmospheric conditions such as moisture, light, heat, mildew, etc. The design of cover materials needs to consider the atmospheric conditions under which the conveyor belt operates [108].

However, additional requirements are dependent on the product being conveyed, the application area, and the environment under which the conveyor belt operates.

2.9 Application Areas of Conveyor Belts

The main application areas of conveyor belts are the mining industry (both underground and surface mining), the food industry, the sugar industry, the glass industry, the recycling industry, logistic centres, and parcel services, shown in Figure 13.

Figure 13. Some application areas of textile-reinforced conveyor belts [31, 109, 110].

2.10 Conveyor belt's Vulcanization Process Parameters

Vulcanization is a vital process during the production of conveyor belts to strengthen and harden the rubber materials and to adhere the conveyor belts' reinforcement together. This process is carried out under a specific temperature, pressure, and duration depending on the types of material composed in the conveyor belt's reinforcement [111]. Despite the cruciality of these parameters, not enough scientific research has been conducted in the vulcanization parameters needs to be fulfilled for the textile-reinforced conveyor belts.

2.11 Summary of Literature Review

The work of various researchers was analyzed in the area of conveyor belts, primarily in textile reinforced conveyor belts. The research so far conducted mainly focused on the design of conveyor belts, fiber and yarn types, weave structures, splicing methods, and adhesion chemicals used to produce durable conveyor belts. Therefore, the effect of vulcanization parameters on the components of the conveyor belt was not got attention from the researchers. In this work, the effect of vulcanization parameters on the carcass of textile-reinforced conveyor belts was taken as a main concern and investigated.

3. MATERIALS

The thesis aimed to investigate the influence of material properties and processing parameters on the physio-mechanical properties of textile-reinforced conveyor belts. To achieve this goal, high-tenacity polyester yarns, woven fabrics, and rubber were used for the investigation. Furthermore, textile-reinforced conveyor belts were produced from these materials. The detailed parameters of materials utilized for the research are provided in this section.

3.1 High Tenacity Polyester Yarns

In order to improve the adhesion property of the yarns or materials produced from these yarns during the conveyor belt manufacturing process, a pre-activated high tenacity polyester yarn with the linear densities of 110, 220, 440, 660, and 990 tex was used for the experiment. The polyester multi-filament yarn samples were obtained by doubling method of the basic yarn (110 tex) with a factor of two, four, six, and nine with a minimum twist in the S-direction imparted to the doubled yarns in order to keep the yarns together. The 220, 440, 660, and 990 tex yarn samples had a twist value of the 90s, 60s, 60s, and 60s turns per meter, respectively. The properties of the basic yarn sample (110 tex-yarn) are provided in Table 1.

Table 1: Properties of high tenacity polyester yarns.

Yarn type	**Property**				
	Linear density (tex)	Breaking force (N)	Breaking tenacity (cN/tex)	Elongation at break (%)	Turns per meter (TPM)
High Tenacity Polyester	110	89.90	81.00	13.50	2

The yarn samples were supplied by Kordárna Plus a.s. company in the Czech Republic. Kordárna is the leading fabric supplier for the Sempertrans Ltd. conveyor belt producing company.

The pictures of yarn samples supplied by Kordárna Plus a.s. company are presented in Figure 14.

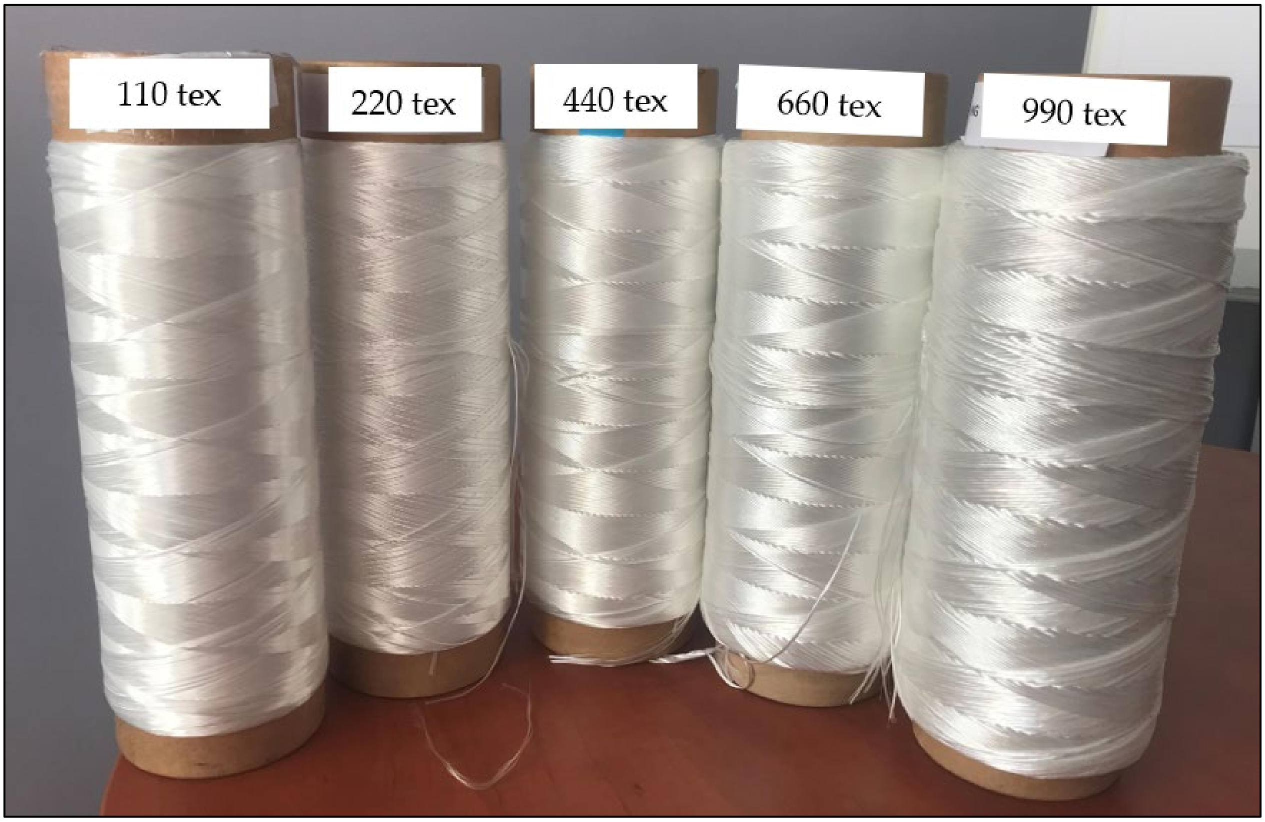

Figure 14. High tenacity polyester yarn samples with different linear densities.

3.2 Industrial Woven Fabrics

A plain weave structure fabric woven from high tenacity polyester yarn in the warp direction and polyamide 6.6 yarn in the weft direction was provided by Kordárna Plus a.s. company, Czech Republic. The Industrial woven fabric with polyester and polyamide in the warp and weft directions, respectively, is known by the acronym of EP fabric (E - stands for polyester warp yarn and P- polyamide 6 weft yarn) in the mechanical rubber reinforcing industries. The woven fabric samples were supplied in a greige and dipped form. Rubber and textile are two distinct materials; adhering them together by creating a direct bond between the rubber and textile is impossible because of their chemical nature.

However, various types of adhesive chemicals are widely used to adhere these materials together. Therefore, to adhere textile fabric and rubber materials, EP fabrics were dipped in a resorcinol-formaldehyde-latex (RFL) solution. The fabric dipped in adhesive solution is referred to as dipped fabric, shown in Figure 16.

Woven fabric samples without any finishing treatments are called greige fabric, and throughout the document, the greige fabric represents fabric before dipping, shown in Figure 15.

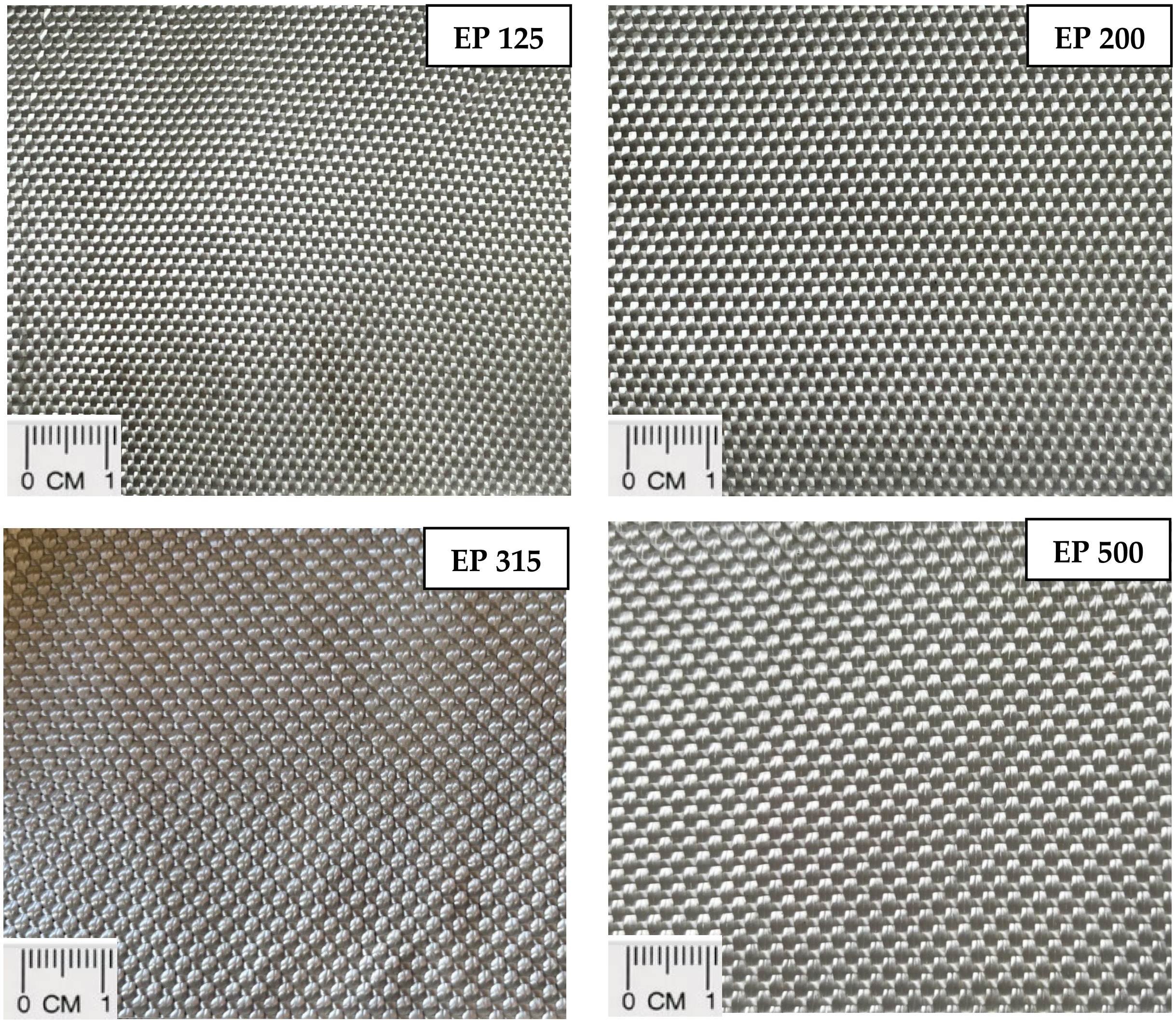

Figure 15. EP fabric samples with different nominal tensile strength before adhesive chemical treatment (Greige fabric).

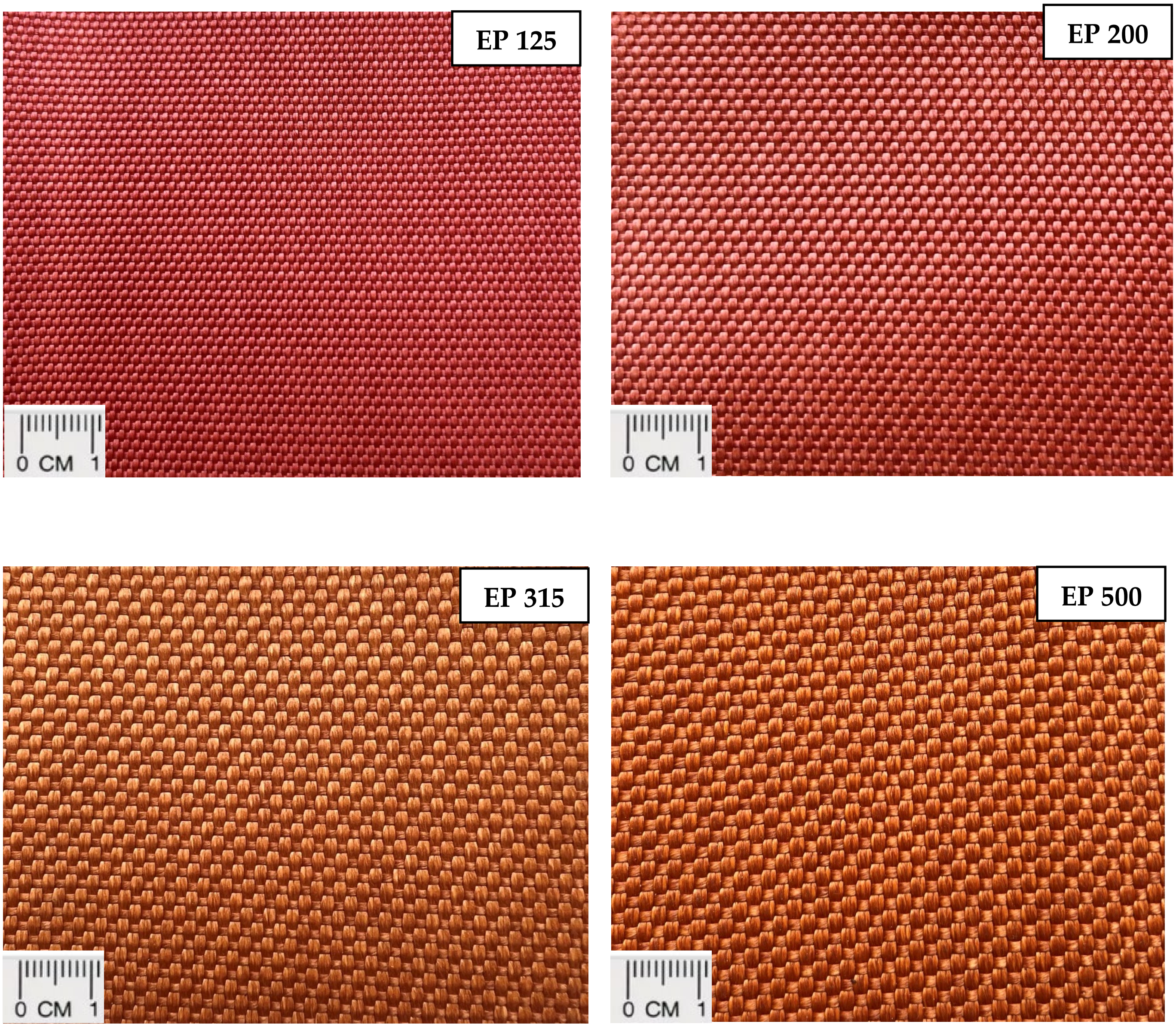

Figure 16. Resorcinol Formaldehyde Latex dipped EP fabric samples with different nominal tensile strengths (Dipped fabric).

The yarns provided in section 3.1 were used as a warp yarn for all the fabric samples in Figures 15 &16. The fabric samples were coded based on their nominal tensile strength. This sample coding method is popular and well-known in industrial fabric producing companies and conveyor belt manufacturers. The properties of RFL treated EP fabric samples are provided in Table 2.

Table 2. Properties of RFL treated EP woven fabric samples.

Fabric type	Fabric properties								
	Warp yarn	Weft yarn	Warp yarn count (tex)	Weft yarn count (tex)	Ends/cm	Picks/cm	Thickness (mm)	Mass per unit area (g/m2)	Crimp of warp (%)
EP 125	PET	PA 66	110 x 2	94 x 2	12 ± 2	6 ± 2	0.70 ± 0.15	450 ± 25	2.50
EP 200	PET	PA 66	110 x 4	94 x 3	9 ± 2	5 ± 2	0.90 ± 0.15	631 ± 10	2.50
EP 315	PET	PA 66	110 x 6	94 x 4	11 ± 2	4 ± 2	1.40 ± 0.15	1040 ± 40	2.50
EP500	PET	PA 66	110 x 9	94 x 6	11 ± 2	3 ± 2	1.95 ± 0.15	1555 ± 50	2.50

3.3 Styrene Butadiene Rubber

The styrene butadiene rubber (SBR) is a synthetic rubber used for the cover and skim components of the conveyor belt samples produced in this work.

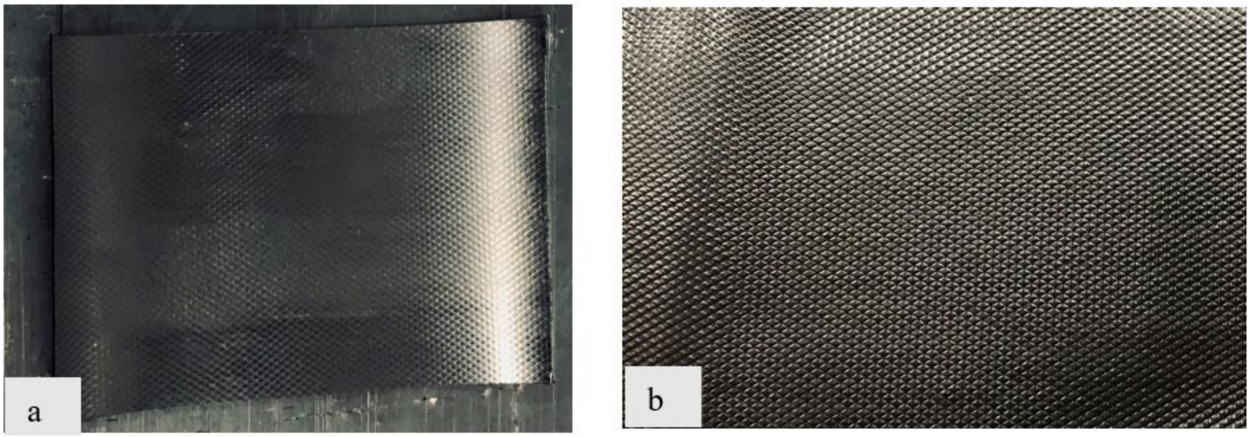

Figure 17. Styrene butadiene rubber samples. (a) Rubber for the cover parts, (b) Rubber for the skim parts.

Table 3. Properties of styrene butadiene rubber.

Rubber type	Component type	Rubber properties		
		Thickness (mm)	Tensile strength (N/mm^2)	Elongation (%)
SBR	Skim	1.0	9.35	680.93
	Bottom cover	4.0	9.35	680.93
	Top cover	4.0	9.35	680.93

4. METHODOLOGY

4.1 Experimental Design from Yarn to Conveyor Belt

Experiments were designed to determine the physio-mechanical properties of textiles and textile-reinforced conveyor belts. The investigations were conducted on high tenacity polyester yarns, EP woven fabrics, and textile-reinforced conveyor belts under various processing parameters. To identify the effect of thermal aging on textile materials, high tenacity polyester yarns and fabrics were subjected to various experiments at different stages. Subsequently, the conveyor belt reinforced with the EP woven fabric was produced and subjected to mechanical property tests.

Physical and mechanical investigations were carried out on the polyester yarns at the greige and dipped levels of pre-and post-thermal aging under the designated thermal aging parameters. The experimental design for polyester yarn was shown on the left-hand side of Figure 18. The arrows in light blue indicate the flow of yarn experimental tests starting from the sample type to the tests performed on the high tenacity polyester yarn.

Following the yarn experimental tests, woven fabrics were subjected to experimental investigations. The fabrics were tested at a greige level and after dipping with resorcinol formaldehyde latex adhesive chemical, pre- and post-thermal aging. The experiments carried out on the woven fabric at different levels are shown in the middle part of Figure 18, and the investigation processes are marked with black arrows.

The results obtained from polyester yarns at different thermal aging parameters were used as a precursor to determine the thermal aging parameters of the woven fabrics. Subsequent to the fabric experimental tests, the textile-reinforced conveyor belts were produced and subjected to mechanical property investigations.

The textile-reinforced conveyor belt sample preparations and experimental investigations carried out on the conveyor belt are shown on the right-hand side of Figure 18, with the experimental flows marked in brown. The experiments which combined yarn, fabric, and conveyor belt were shown in blue arrows.

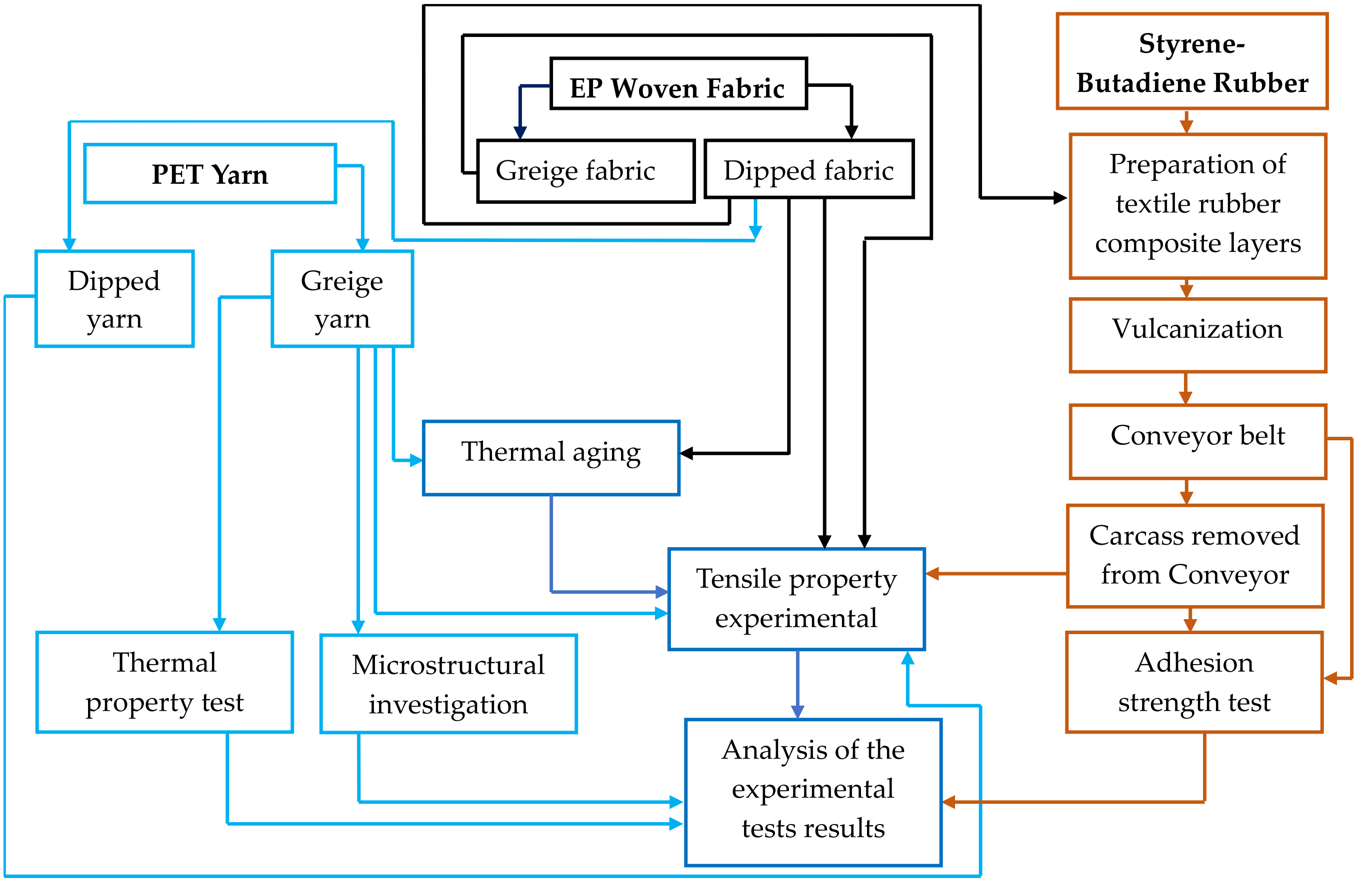

Figure 18. Experimental design flowchart.

4.2 Thermal Aging of High Tenacity Polyester Yarn

Textile yarns are not directly involved in reinforcing conveyor belts; however, fabrics made of these yarns are used as a belt carcass. Therefore, it was crucial to study the physio-mechanical properties of the yarns by subjecting the polyester yarn samples to a similar temperature under which the textile reinforced conveyor belt vulcanizing process is performed.

Therefore, industrial high tenacity polyester yarn samples, shown in Figure 14, were prepared in the form of a hank (Figure 19) to facilitate the thermal aging of the yarn samples.

The polyester yarn samples were subjected to thermal aging in an industrial oven (temperature chamber) of Model VT 7011 produced by Vötsch Industritechnik GmbH, Germany, shown in Figure 20a. The experiment's main objective was to determine how the thermal aging temperature and aging duration can affect the mechanical and structural properties of the high tenacity polyester yarn. Achieving this objective was vital due to the fact that the result will be used as input for the next section of the work in order to deeply analyze the effect of vulcanization process parameters on the textile materials that are used as a reinforcement of the conveyor belt and how these parameters can affect the textile materials at different production stages.

Figure 19. High tenacity polyester yarn samples prepared in a hank form.

The aging temperature of polyester yarn samples was chosen based on two essential things. These were on the polyester fiber’s glass transition temperature (Tg) and the temperature ranges used for the vulcanization of textile reinforced conveyor belts in conveyor belt producing companies for heavy-duty conveyor belts with three layers of fabric carcass. The aging time was also chosen by considering vulcanizing duration adapted in conveyor belt producing companies for the textile reinforced conveyor belts with three layers of fabric.

Figure 20. (a) Industrial temperature chamber (Industrial oven), (b) Temperature monitoring part of the oven.

Depending on the above-mentioned parameters, the aging temperature of 140, 160, 200, and 220 °C was chosen for the thermal aging of high tenacity polyester yarns in the industrial oven under no applied pressure. Also, the duration of six, twelve, and thirty-five minutes of thermal aging of yarns in the oven was designated for the experiment. The aging duration of six minutes was added to the experiment only for the yarn samples that underwent thermal aging at 220 °C.

The main target of aging the yarn for such short duration at elevated temperature was to evaluate the tensile property of the yarn under these conditions in case the conveyor belt producers decide to shorten the vulcanization process duration at the same time by increasing the vulcanization temperature.

Prior to the thermal aging of each high tenacity polyester yarn sample, the industrial oven was heated above the designated temperature for the thermal aging to avoid the possibility of temperature drop while placing the yarn samples in the oven. Once the yarn sample was put in the oven, the oven was firmly closed, and the samples were fully aged based on the specified aging duration. This method was repeated for each sample based on the aging design provided in Table 4. Post-thermal aging, the yarn samples were conditioned for further experimental tests at the standard laboratory temperature of 20 ± 2 °C and 65 % relative humidity for 24 hours.

Table 4. Design of high tenacity polyester yarn samples thermal aging parameters.

Aging temperature	High tenacity polyester yarn samples with different linear densities														
	110 tex			**220 tex**			**440 tex**			**660 tex**			**990 tex**		
140 °C	Ø	X	Ø	Ø	X	Ø	Ø	X	Ø	Ø	X	Ø	Ø	X	Ø
160 °C	Ø	X	X	Ø	X	X	Ø	X	X	Ø	X	X	Ø	X	X
200 °C	Ø	X	X	Ø	X	X	Ø	X	X	Ø	X	X	Ø	X	Ø
220 °C	X	X	X	Ø	Ø	Ø	Ø	Ø	Ø	X	X	X	Ø	Ø	Ø
	6	**12**	**35**	**6**	**12**	**35**	**6**	**12**	**35**	**6**	**12**	**35**	**6**	**12**	**35**
	Thermal aging duration, min														

Ø- *signifies that the yarn sample was not aged at the given temperature for the specified aging duration, and* ***X*** *– signifies that the yarn sample was aged at the given temperature for the specified aging duration.*

4.3 Thermal Aging of Woven Fabric

The industrial EP woven fabric samples were thermally aged under different conditions, shown in Table 5. The thermal aging of fabrics were conducted in an industrial oven of model VT 7011 produced by Vötsch Industritechnik GmbH, Germany, as shown in 20a, at the temperature of 140, 160, and 220 °C for an aging duration of six and thirty-five minutes. The thermal aging conditions were designated based on the results obtained from polyester yarn samples, vulcanization conditions adapted for producing textile-reinforced conveyor belts in the companies, glass transition temperatures of fibers in the weft and warp yarns of the woven fabric, and stability of adhesive chemicals used for the dipping of EP woven fabric. Following the thermal aging process, fabric samples were conditioned for 24 hours at the standard laboratory conditions of 20 ± 2 °C and 65 % relative humidity before subjecting the samples to further experimental investigations. The thermal aging conditions of dipped EP woven fabric samples are designated as presented in Table 4.

Table 5. Thermal aging conditions of RFL dipped EP woven fabric samples.

Aging temperature	RFL dipped EP woven fabric samples							
	EP 125		EP 200		EP 315		EP 500	
140 °C	X	X	X	X	X	X	X	X
160 °C	X	X	X	X	X	X	X	X
220 °C	X	X	X	X	X	X	X	X
	6	35	6	35	6	35	6	35
	Thermal aging duration, min							

***X** – signifies that the woven fabric sample was aged at the given temperature for the specified aging duration.*

Resorcinol- Formaldehyde-Latex dipped EP woven fabric sample aged at 220 °C for 35 min is shown in Figure 21 while the sample was in the industrial oven and after the aged sample was conditioned for 24 hours in the standard laboratory conditions.

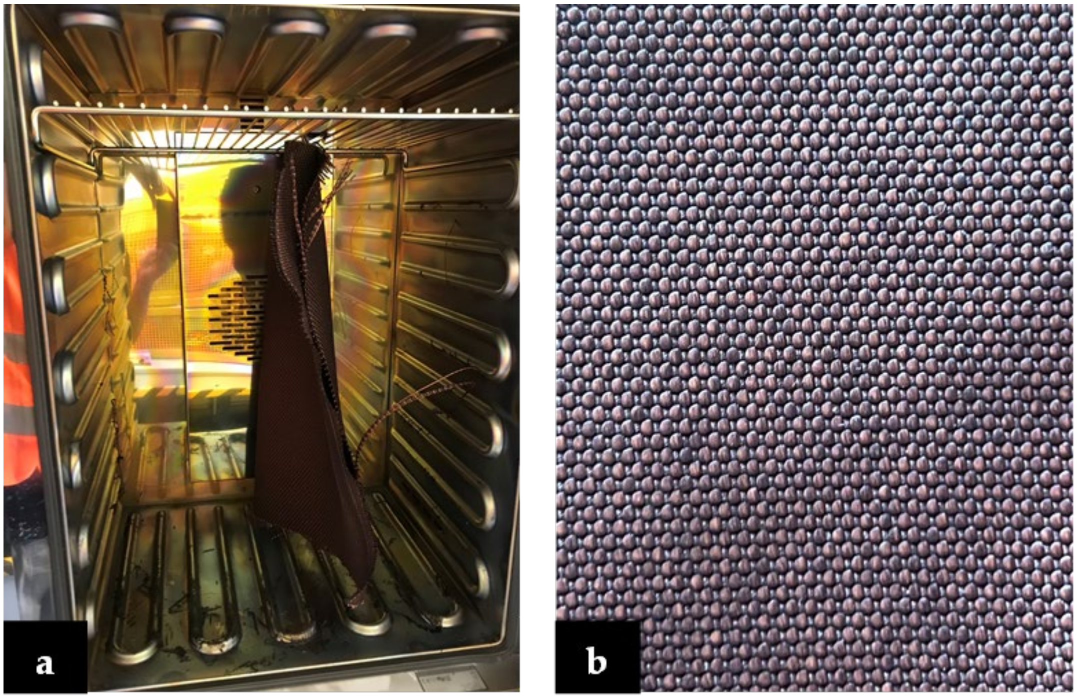

Figure 21. (a) Dipped woven fabric post thermal aging in the oven, (b) Thermally aged EP fabric after conditioning.

4.4 Modeling and Vulcanization Parameters of Textile-Reinforced Conveyor Belts

The textile-rubber reinforced composite model was prepared, as shown in Figure 22. The heavy-duty conveyor belt model has three layers of EP woven fabric carcass with a nominal strength of 200 kN/mm per fabric layer in the longitudinal direction. In total, the nominal strength of the conveyor belt carcass was 600 kN/mm. The tensile strength of the conveyor belt or fabric used for conveyor belt reinforcement is expressed either in kN/mm or N/m; due to the fact that the strength of the material is measured by the ratio of force exerted on the conveyor belt or fabric carcass per width of the conveyor belt or fabric. This provides a more perceptive comprehension of the belt’s strength, as it directly relates to the amount of force that the belt can withstand across its width. Because of this, the current work was focused on the longitudinal direction of the belt and fabric. This technic of measuring and expressing the tensile result of industrial fabrics and conveyor belts is well-known by technical fabric producers and conveyor belt manufacturers.

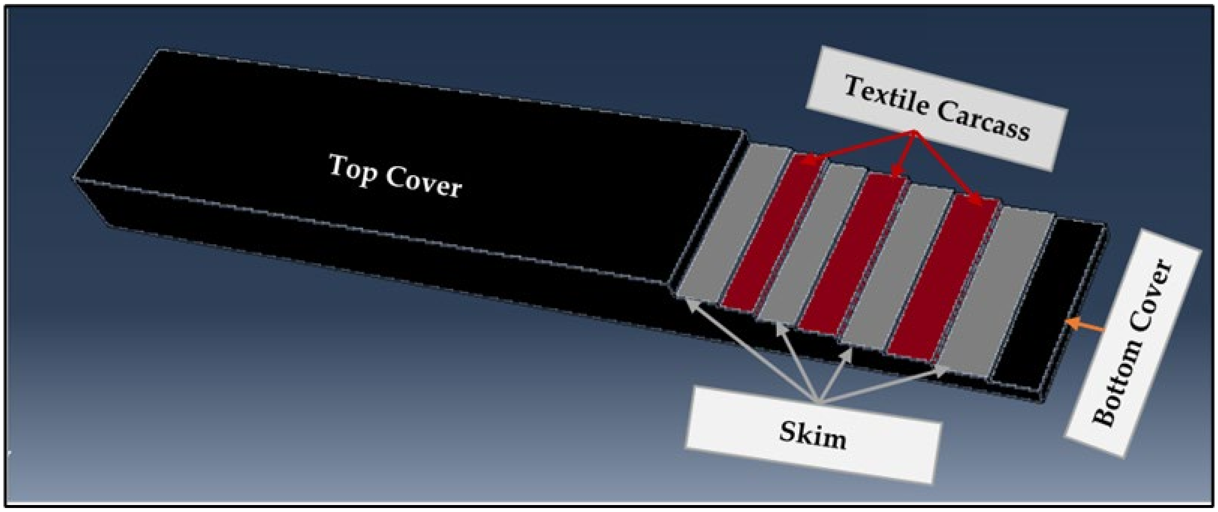

Figure 22. Three-Dimensional (3D) model of textile reinforced multi-ply conveyor belt [112].

Subsequent to modeling of the arrangement of constituent materials in the reinforcement, conveyor belt samples were produced under different vulcanization conditions, presented in Table 6. The vulcanization of the conveyor belt was conducted on a press machine (Figure 23c) at the research and development department of Sempertrans Ltd. conveyor belt producing company. Except for vulcanization temperature and duration, other parameters used were taken from the production line of the Sempertrans conveyor belt producing company.

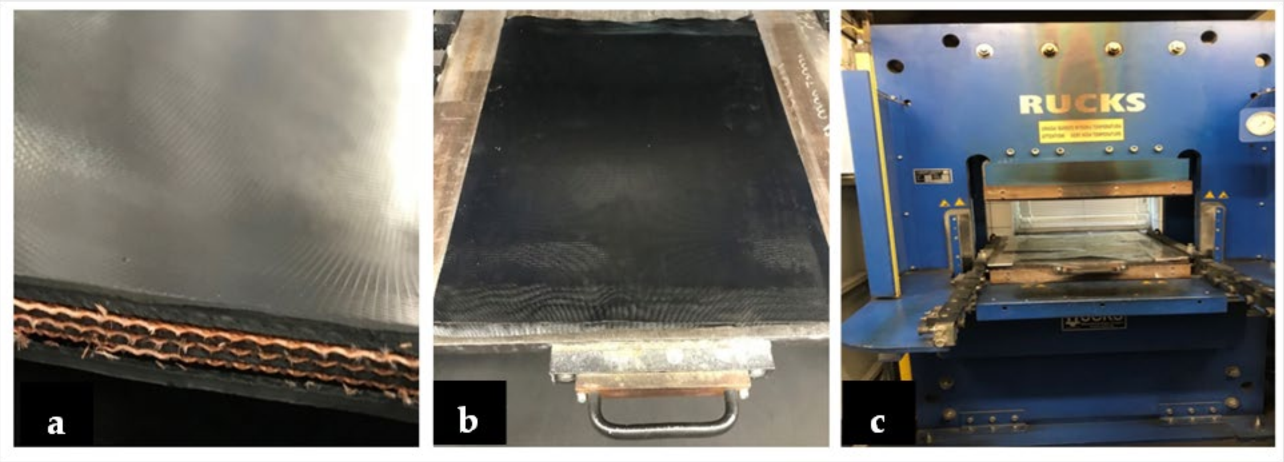

Figure 23. Vulcanization of textile reinforced conveyor belt samples. (a) Side view of the reinforcement, (b) Textile-rubber reinforcement prepared for vulcanization, (c) Hot-press machine utilized for vulcanizing textile-rubber reinforcement.

Conveyor belt samples were produced under various vulcanization parameters, as shown in Figure 24.

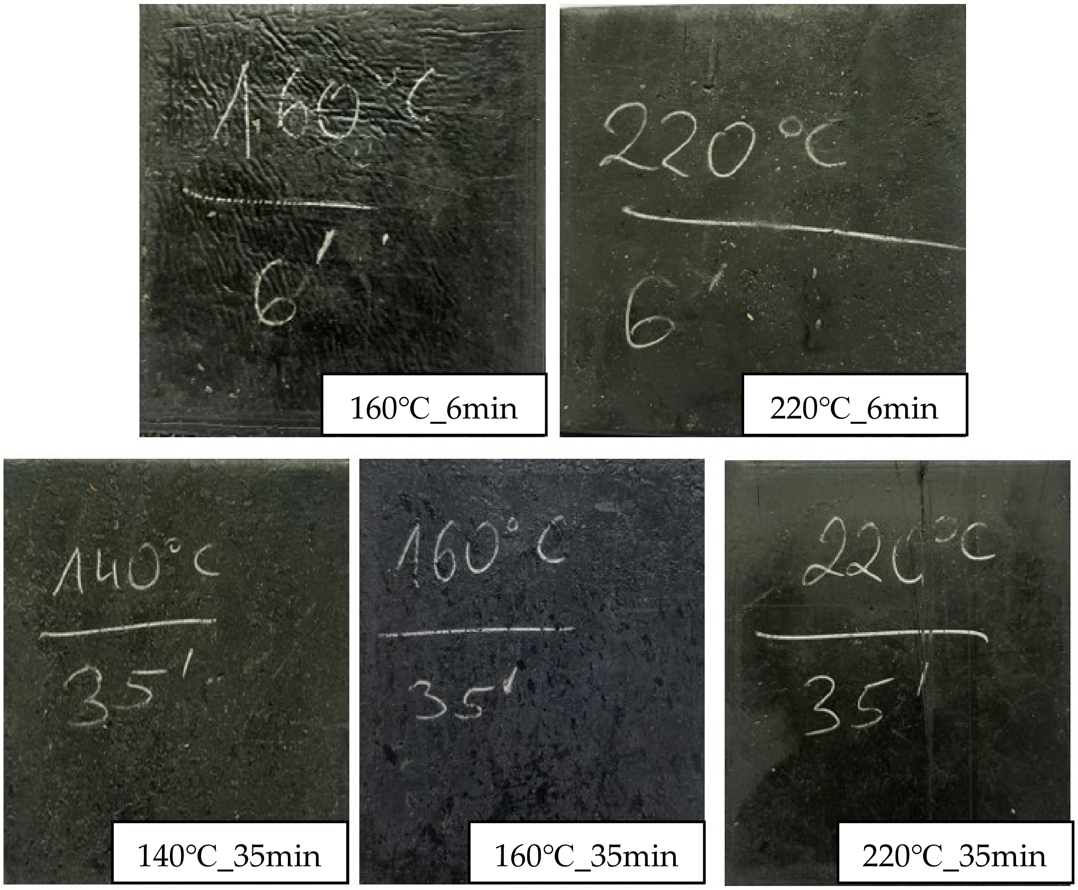

Figure 24. Textile-reinforced conveyor belt samples produced under different vulcanization parameters.

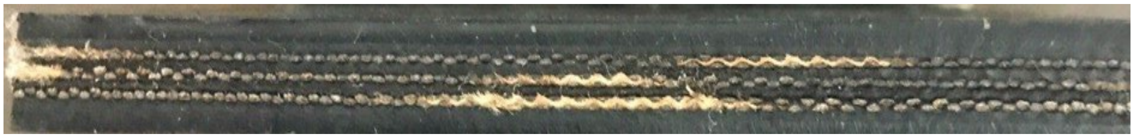

Figure 25. Side view of EP fabric reinforced conveyor belt with three-layers and produced with the vulcanization parameters of 160 °C for 35 min.

The pressure used for vulcanization was similar to the amount of pressure (200 Bar) adapted in the production line of 3-layer textile-reinforced conveyor belts of Sempertrans company.

The vulcanization temperature and duration were modeled based on different scenarios, such as the property of EP woven fabric mentioned in the yarn and fabric thermal aging sections and the vulcanization temperature adopted at the company. In addition, the safety of workers during the vulcanization process, the maximum temperature which can be operated on the vulcanizing machine without any hazardous issues, and the maximum thermal property of the rubber material used as a skim and cover of the conveyor belts were taken into consideration.

Table 6. Textile-reinforced conveyor belt vulcanization parameters.

	Conveyor belt constituent materials		**Vulcanization Conditions**			
Sample	Carcass type	Rubber type	Temperature (°C)	**Duration (min)**	**Pressing force of the press machine (kN)**	**Cooling method**
I	EP 200 fabric	SBR	140	6	1020	Natural
II	EP 200 fabric	SBR	140	35	1020	Natural
III	EP 200 fabric	SBR	160	6	1020	Natural
IV	EP 200 fabric	SBR	160	35	1020	Natural
V	EP 200 fabric	SBR	220	6	1020	Natural
VI	EP 200 fabric	SBR	220	35	1020	Natural

5. EXPERIMENTAL TESTS

5.1 Experimental Investigations of High Tenacity Polyester Yarn

The high tenacity polyester yarn samples were subjected to experimental tests in order to evaluate how the thermal, mechanical, and structural properties of the yarn samples were affected by the aging temperatures and duration of aging.

5.1.1 Thermal Property Test of High Tenacity Polyester Yarn

The thermal properties of high-tenacity polyethylene terephthalate yarn were investigated using Differential Scanning Calorimetry (DSC) and Thermogravimetric Analysis (TGA), shown in Figures 26 & 27, respectively. These experimental tests were conducted at the University of Borås in Sweden.

The Differential Scanning Calorimetry of Model DSC Q 2000 was used to analyze the thermal transition of high-tenacity polyethylene terephthalate yarn as a function of temperature and time. The results obtained from this investigation were used to determine the ideal processing temperature of the high-tenacity polyethylene terephthalate yarn under exposure of high temperatures.

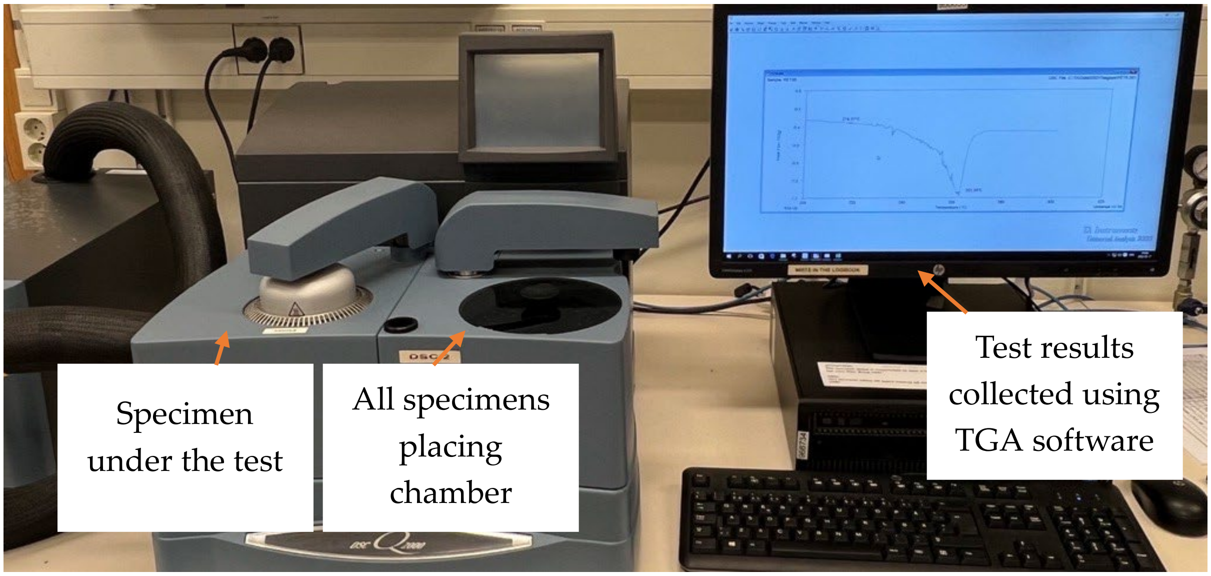

Figure 26. Differential Scanning Calorimetry.

For the DSC experimental tests, polyethylene terephthalate yarn samples of 5-10 milligram weight were folded in an aluminum pan. Ten runs were conducted at running a temperature up to 360 °C while heating 10 °C/min with a nitrogen atmosphere flow of 50 mL/min. From the experimental results, the melting and re-crystallization temperature of the fiber was obtained.

Thermogravimetric Analysis (TGA) of model TGA Q500 was used to analyze the thermal decomposition of polyethylene terephthalate yarn by subjecting the samples to thermal heating of up to 600 °C. From the TGA test results, the weight loss of the high-tenacity polyethylene terephthalate yarn in relation to the temperature and duration of heating was analyzed.

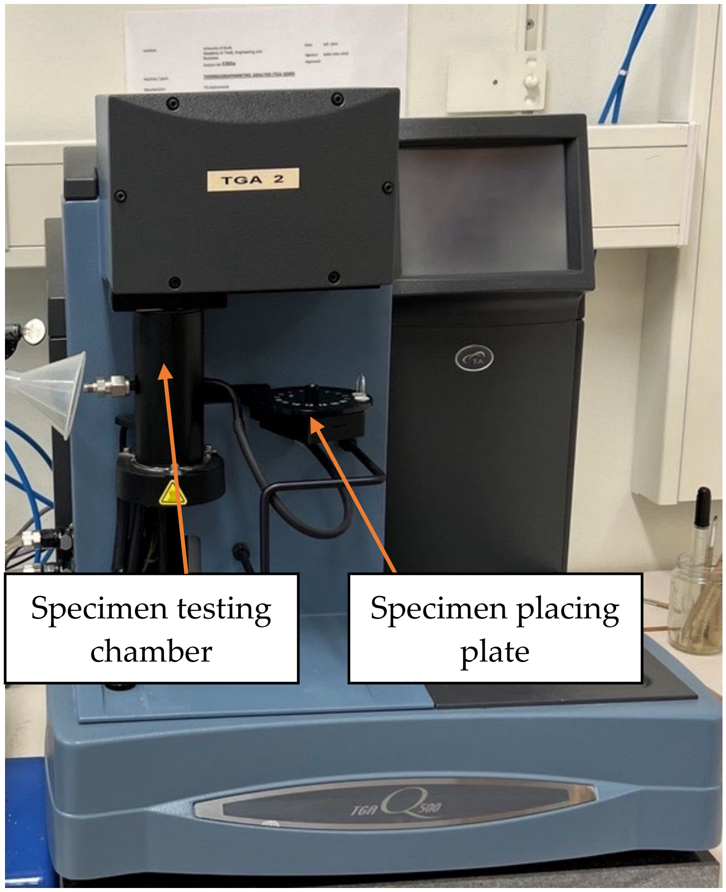

Figure 27. Thermogravimetric Analysis Machine.

5.1.2 Tensile Property of High Tenacity Polyester Yarn

A tensile test is commonly used to assess the materials' mechanical properties. The results of tensile tests are essential for selecting appropriate materials for various engineering applications. In conveyor belt producing companies, the strength of the conveyor belt is a primary concern. Thus, the quality of the conveyor belt is predominantly decided by the tensile property results. Tensile tests are mostly performed either to understand the maximum stress necessary to cause plastic deformation or to evaluate the maximum stress that the given material can withstand. The tensile test of high tenacity polyester yarn was performed to analyze the effect of aging temperature and duration on the tensile strength of the industrial polyester yarns. To have a comprehensive tensile property analysis, the tensile test was performed on the yarn specimens of the HT polyester yarn samples pre-and post-thermal aging for all samples listed in section 3.1.

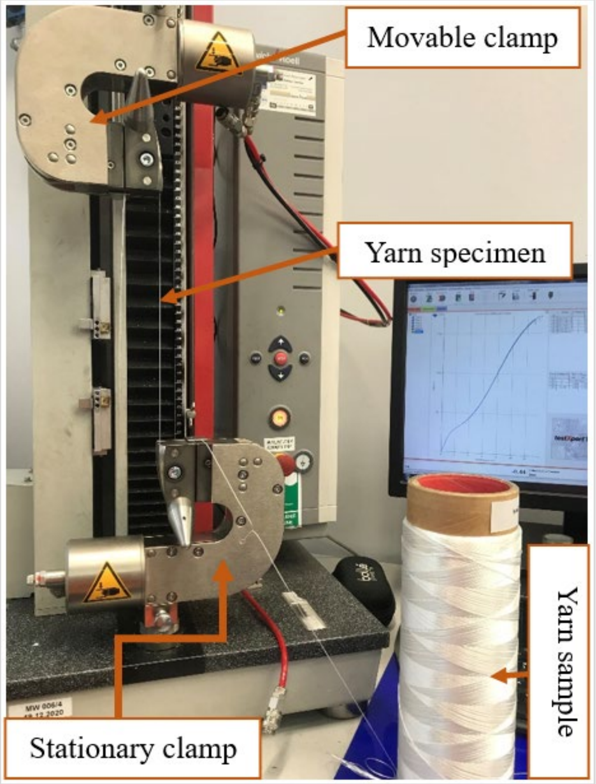

Figure 28. Zwick/Roell tensile testing machine.

The tensile tests of HT polyester yarn specimens were measured on a Zwick/Roell tensile testing machine (Figure 28) of 2.5 kN load cell, Constant Rate of Extension (CRE), crosshead speed of 250 mm/min, and a gauge length of 250 mm. For the tensile yarn specimen testing, an S-type clamp was used to firmly grip the specimens without any slippage or cutting of the specimens at the jaws.

The yarn samples were pre-conditioned according to ISO 139 [113], and the tensile test was performed at standard laboratory conditions. The yarn samples were categorized as pre- and post-thermal aging, and twenty specimens were tested from each sample. The tensile test data were collected using testXpert II software linked to the tensile testing machine. All the yarn sample tests were conducted, and results were analyzed in accordance with ISO 2062:2009 [114].

5.1.3 High Tenacity Polyester Yarn Shrinkage Test

The decrease in yarn length due to the thermal heating of the sample is described as shrinkage. Analyzing the thermal shrinkage of industrial polyester yarns mainly used for the reinforcement of mechanical rubber goods purpose is critical to ensure the dimensional stability of the yarns and fabrics made of these yarns. The shrinkage property of the yarn also affects the ability of belts to maintain tension while running. Therefore, ascertaining the shrinkage level of the yarns is significant to ensure the final product uniformity. The shrinkage percentage of the yarn was found by measuring the yarn length pre-and post-heating of the yarn specimen under specific stress and expressing it as a percentage of the pre-heating (initial yarn) length. The shrinkage result is used to predict the dimensional stability of the yarn under high temperatures. The shrinkage of the skein or single-end yarn can be determined manually or automatically, either in dry-hot air according to ISO 18067 [115] or in boiling water in accordance with ISO 18066 [116].

The dry-hot air method was chosen for the shrinkage test of high tenacity polyester yarn samples, and the test was conducted according to the standard.

For the yarn shrinkage test, the samples and testing conditions were designated as provided in Table 7 to evaluate the effect of temperature and testing duration. Also, for the shrinkage test, the yarn sample of 220 tex was selected, and 20 specimens at each testing parameter were conducted.

Table 7. High tenacity polyester yarn shrinkage testing conditions.

Yarn type			High tenacity polyester yarn				
Testing conditions	Temperature (°C)		140	160	177.7	200	220
	Duration (min)	2	X	X	XX	X	X
		5	X	X	X	X	X

*X – denotes that the shrinkage test was performed at the given condition, and **XX** – denotes the standard temperature and testing duration for the hot-air yarn shrinkage.*

The polyester yarn shrinkage test was performed by using Testrite Yarn Shrinkage testing equipment, shown in Figure 29, with a 50-gram pretension of weight.

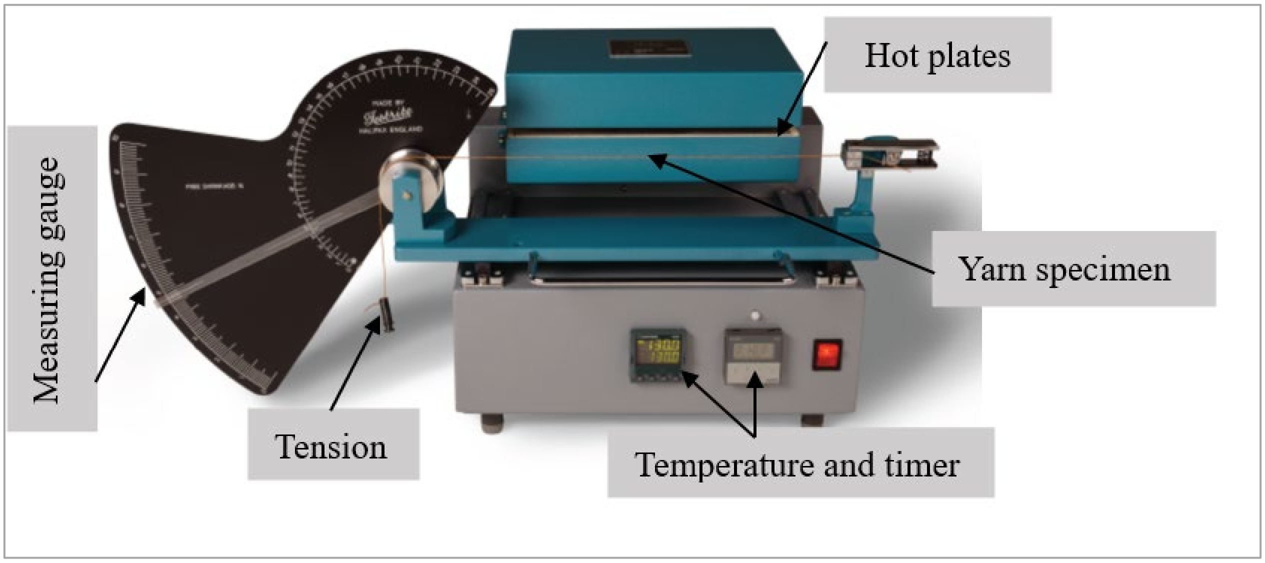

Figure 29. Testrite yarn shrinkage tester.

5.1.4 Surface Structural Examination

It is essential to understand how high tenacity polyester yarn surface structure was influenced by the thermal aging parameters as the structural arrangement determines the properties of the yarn. Therefore, the surface structure of high tenacity polyester yarn specimens pre- and post-thermal aging was investigated using a scanning electron microscope (SEM).

5.2 Tensile Property Experimental Test of Industrial Woven Fabric Samples

Woven fabrics used as a carcass of the conveyor belt reinforcement are primarily subjected to forces acting in the longitudinal directions of the belt. Therefore, tensile strength tests along the warp direction were performed to determine the effects of forces acting on the fabric.

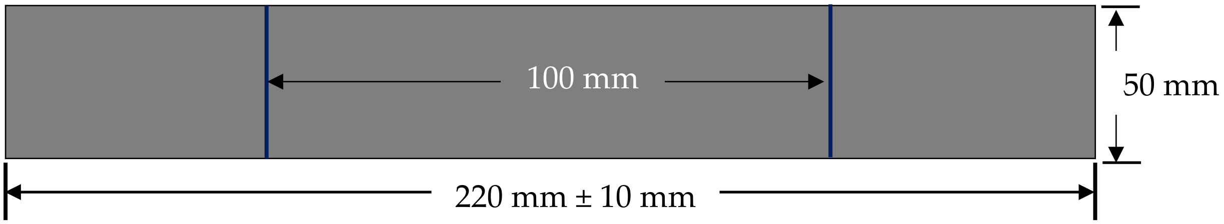

Figure 30. Fabric specimen dimension for tensile test

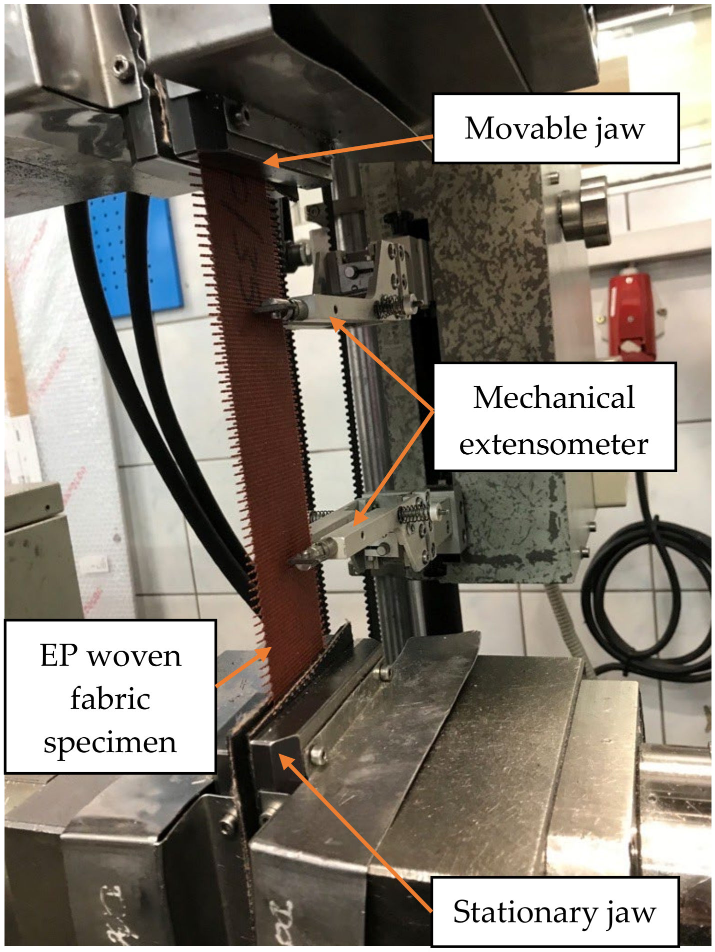

Figure 31. EP fabric specimens under tensile test.

The tensile property experimental investigation of industrial woven fabric samples presented in Table 2 of section 3.2 was conducted in-depth on the greige and dipped fabric samples pre- and post-thermal aging. The tensile property test of industrial woven fabric samples was performed according to ISO 13934-1:2013 [117]. Ten specimens from each fabric sample with 50 mm fabric width and 250 mm length between the jaws of the tensile testing machine were prepared by the strip method.

The specimens were subjected to tensile property testing using a Zwick/Roell tensile machine of a 150 kN load cell with a testing speed of 100 mm/min (Figure 31). The fabric specimen was gripped in the stationary lower jaw and movable upper jaw of the machine, and initial tension was applied to avoid unnecessary fabric slippage during the test, which may cause inaccurate results of the tensile property test. To determine the extension property of the EP industrial fabric specimens, a mechanical extensometer was used. The experimental test results were collected using the testXpert II software mounted to the testing machine.

5.3 Textile Reinforced Conveyor Belts

5.3.1 Tensile Property of Textile Reinforced Conveyor Belts

The tensile properties of textile reinforced conveyor belt samples were tested using a Zwick/Roell tensile machine with mechanical extensometers and a load cell of 150 kN in compliance with ISO 283:2015 [118]. The dimensions of the conveyor belt specimens were prepared according to the norm, as shown in Figure 32.

Figure 32. Conveyor belt specimens for tensile test prepared from samples vulcanized at 160 °C for 35 minutes.

The conveyor belt specimen was gripped between the stationary bottom jaw and the movable upper jaw of the tensile testing machine (Figure 33). The experimental test was conducted in standard laboratory conditions and a machine testing speed of 100mm/min. The statistical tensile property test results were collected by testXpert II software.

Figure 33. Conveyor belt specimen under tensile load.

5.3.2 Adhesion Strength of Textile Reinforced Conveyor Belts

The adhesion of the conveyor belt's constituent materials plays a significant role in determining the tensile strength and duration of the conveyor belt. Therefore, investigating the adhesion strength between the plies of the conveyor belt is crucial. Adhesion strength is the mean force required to strip the plies of the conveyor belt from each other. The conveyor belt samples were subjected to an adhesion strength test after 24 hours post-vulcanization; this period also included the conditioning of the conveyor belt samples. In order to investigate the adhesion strength between the plies of conveyor belts, the specimens were prepared and tested in accordance with ISO 252:2007(E) [119].

The specimen's adhesion strength tests were conducted on the longitudinal directions of the samples, and the test was performed using the Zwick/Roell machine of 2.5 kN load cell and testing speed of 100 mm/min, shown in Figure 34. The adhesion strength results were evaluated according to ISO 6133:2015(E)[120].

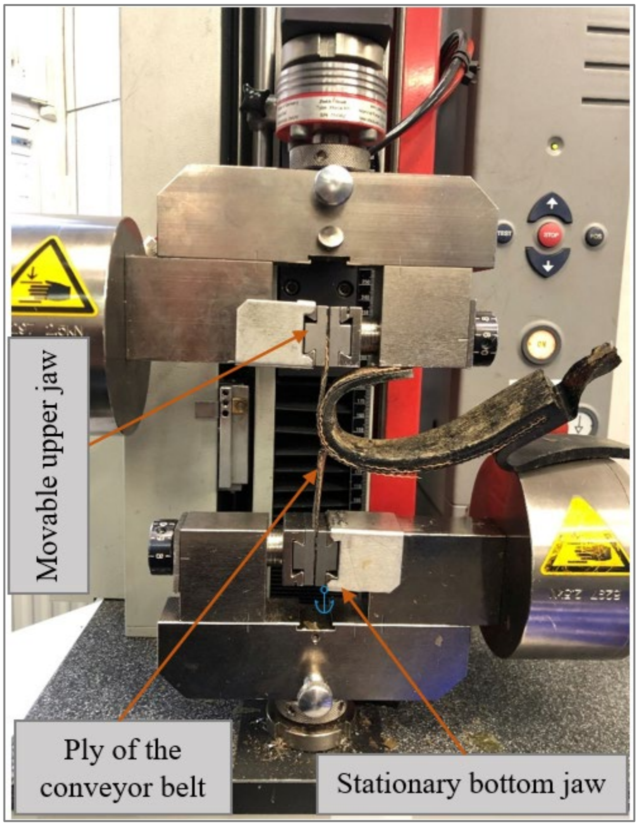

Figure 34. Adhesion strength test of textile-reinforced conveyor belt specimen.

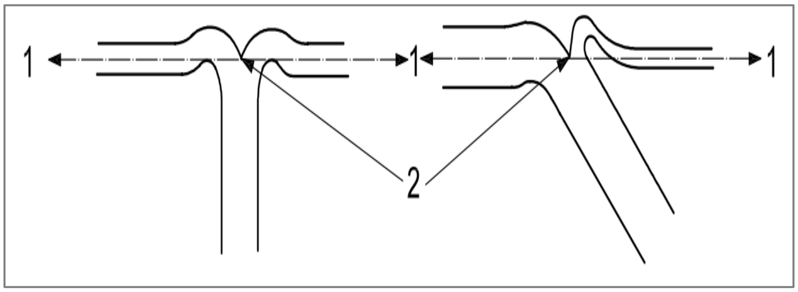

Figure 35. Position of line separation of plies, where 1- signifies plane through axes of the components of test piece held between grips, 2- shows the line of separation properly aligned with plane through axes [119].

6. RESULTS AND DISCUSSION

6.1 High Tenacity Industrial Polyester Yarn's Experimental Test Analysis

In this section, the experimental test results of high tenacity polyester yarns are presented, and the findings are thoroughly discussed from the perspective of the usage of the material in the conveyor belt application.

6.1.1 Thermal Property Test Results of High Tenacity Polyester Yarn

Thermal properties of the high tenacity polyester yarns were investigated using a Thermogravimetric Analysis (TGA) and Diffraction Scanning Calorimetry (DSC).

TGA is a thermal analysis that was used to determine the decomposition behavior and thermal stability of the high tenacity polyethylene terephthalate yarn by measuring the changes in the weight of the sample. As shown in Figure 36, the thermal properties of the PET yarns are presented in the form of a weight loss curve, which shows the changes in the yarn sample weight over time, and the derivative curve, which shows the rate of change in weight.

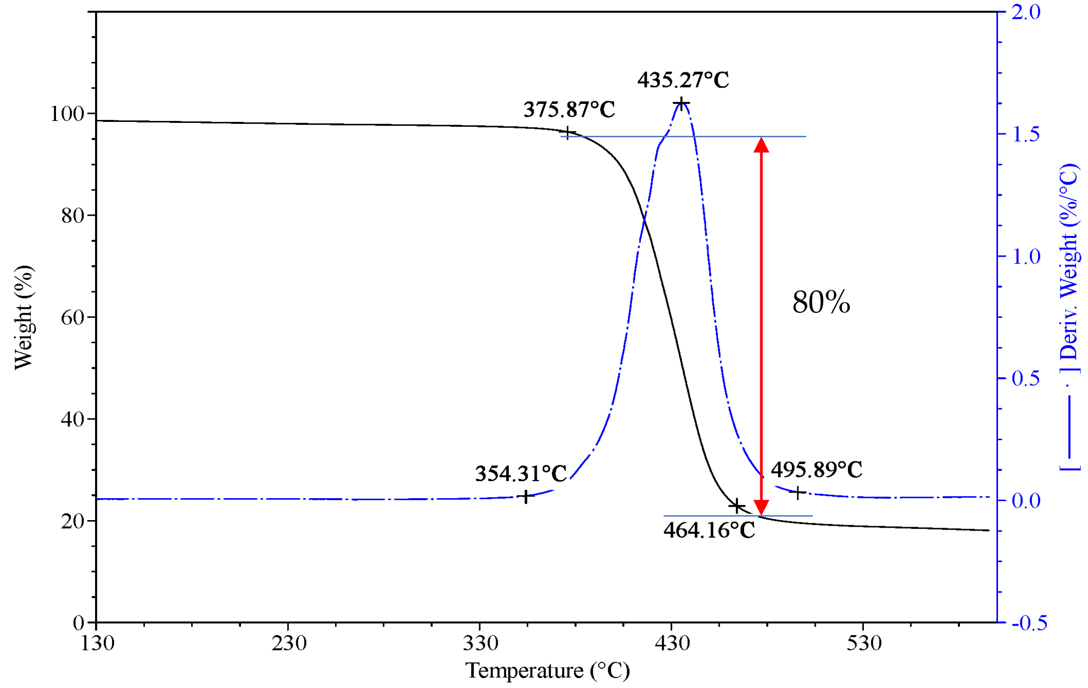

Figure 36. Thermal property of high tenacity polyester yarn obtained from TGA.

The experimental result conducted on the high-tenacity PET yarn indicates the weight loss of the sample occurred at the temperature of 375.87 °C, and the weight of the sample was significantly reduced (≈ 80%) until the temperature reached around 464.16 °C. However, after the temperature reached 464.16 °C, the weight of the sample remained constant. In addition, the peak of the sample decomposition rate was observed at the temperature of 435.27 °C. At this temperature, the yarn was decomposed at the rate of 1.627 %/°C.

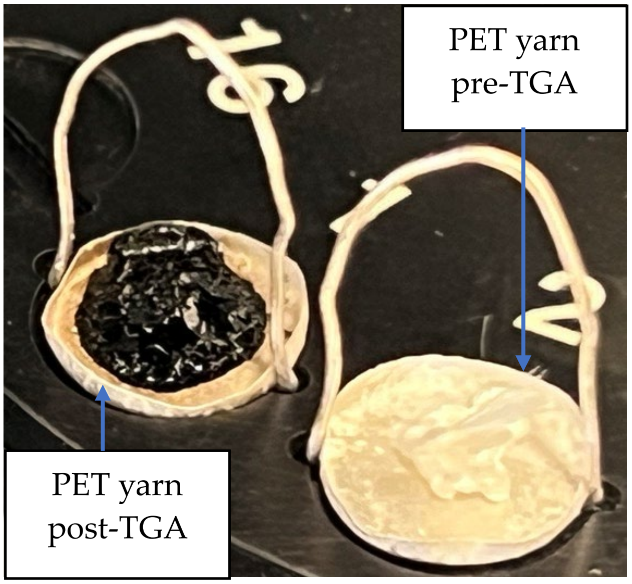

Figure 37. PET yarn samples pre-and post TGA testing.

Even though the TGA results showed the yarn decomposition temperature, it was essential to know the exact temperature at which the PET melts to limit the aging temperature of the polyester yarns. Therefore, the samples were tested using the DSC equipment, and the results obtained from the experimental results are provided in Figure 38. DSC measures the heat flow difference between the sample and reference sample as a function of time and temperature. From the DSC curve, the thermal properties of the PET sample were determined. The result illustrates that the melting point of polyester was 262.38 °C, which is in line with the typical melting temperature of polyester (≈260 °C)[121]. Furthermore, the re-crystallization temperature was obtained at 211.59 °C.

The results obtained from the Thermogravimetric Analysis (TGA) and Diffraction Scanning Calorimetry were significant in determining the optimum vulcanization temperature for the conveyor belts reinforced by fabrics made from polyester yarns in the following sections of the work.

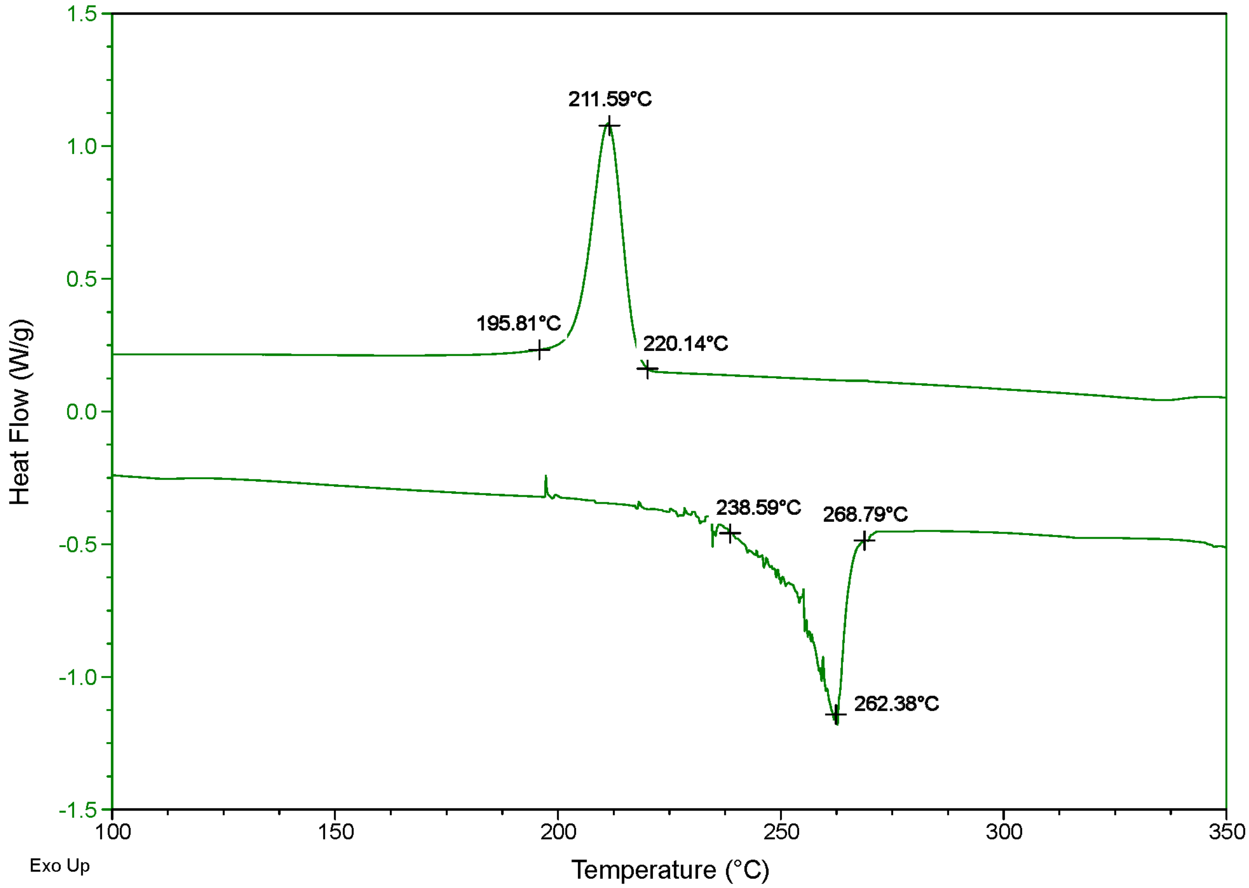

Figure 38. Thermal properties of high tenacity polyester yarn obtained from the DSC machine.

6.1.2 Analysis of the Tensile Test Results

A comprehensive analysis was conducted on the tensile property test results obtained under various conditions of experimental tests performed on the high tenacity polyester yarn samples. These results are described in graphical forms and explicitly elucidated from a scientific viewpoint of polyester yarns for the use of mechanical rubber goods, mainly for conveyor belt application.

(a) Effect of Yarn Linear Density on the Breaking Strength of High Tenacity Polyester Yarn

The polyester yarn samples provided in section 3.1 were created from the 110-tex yarn (referred to as a basic yarn in this document) by multiplying the yarns by a factor of two, four, six, and nine.

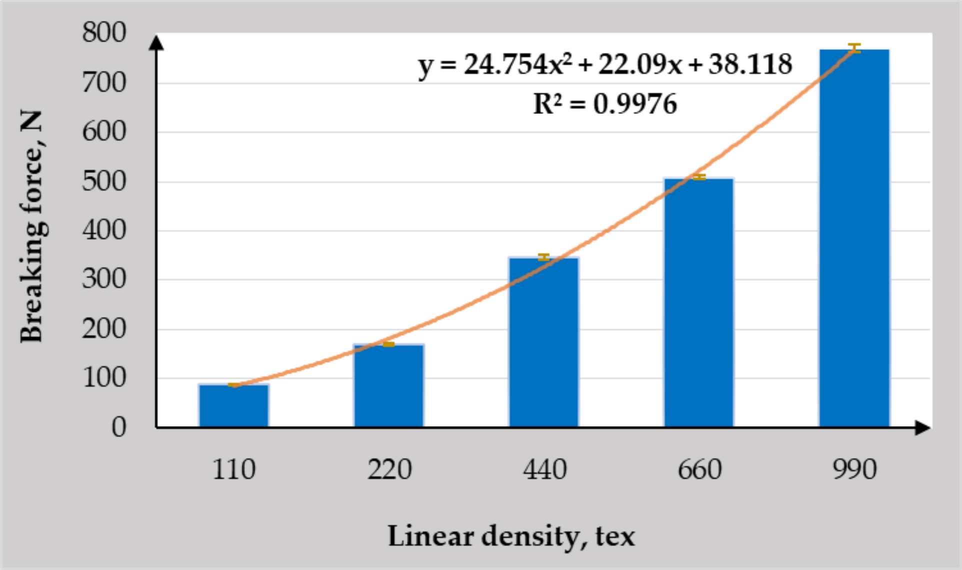

Figure 39. Breaking force of high tenacity polyester yarn samples of different linear densities.

In Figure 39, the linear density's effect on the yarn's tensile property was analyzed. The experimental test was conducted before subjecting the yarn samples to the thermal aging process, and these yarns are referred to as unaged yarn in this graph and the subsequent sections of the document.

The ability of yarn to withstand the exerted tensile load was dependable on the linear density of the yarn samples. As shown in Figure 39, the yarn with high linear density needs more force to break the yarn specimen. Even though the yarn samples' linear density was increased by multiplying 110 tex in factors of two, four, six, and nine, the breaking load of these samples was not in the linear order of the factors by which yarn samples were multiplied. Nevertheless, the two-degree polynomial regression rate shows 0.99, which is almost analogous.

Additionally, the increase in the linear density of the yarn has no significant change in the tenacity of the yarn (± 1 cN/tex), as shown in Figure 40. The stress-strain curve of all high tenacity polyester yarn samples under applied axial load was relatively similar in the elastic range of the curve. However, in the plastic range, the percentage elongation at break for the yarn samples varied based on the linear density of yarns.

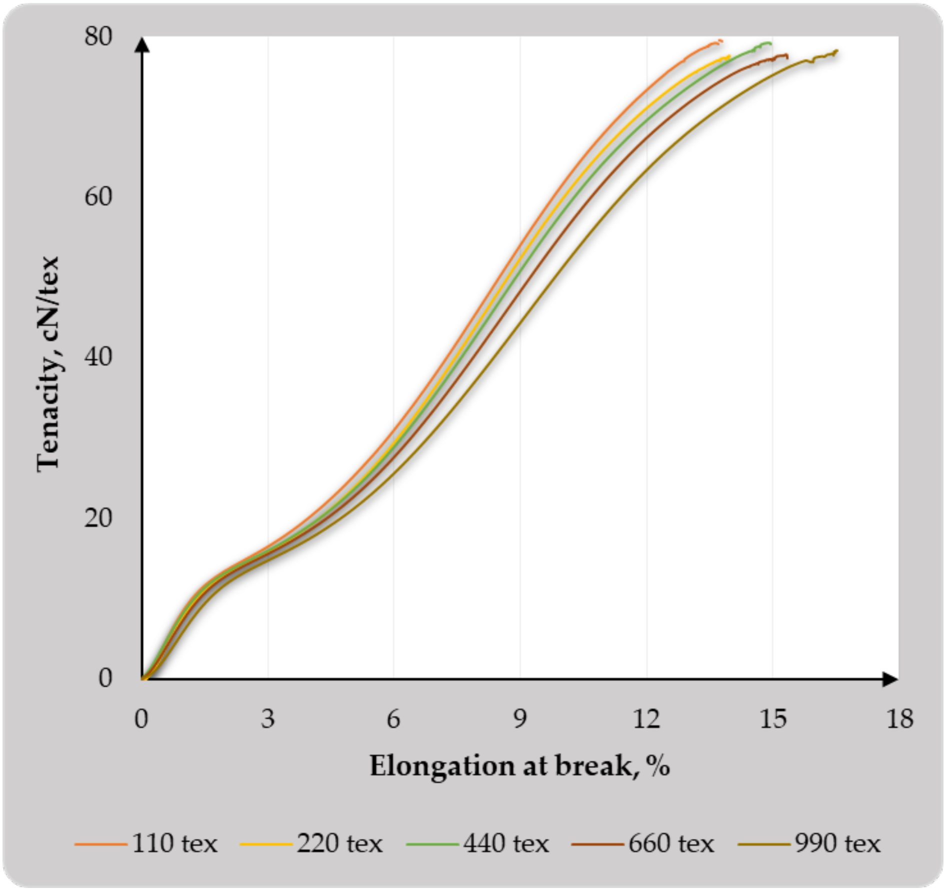

Figure 40. Tenacity Vs elongation at break of unaged PET yarn.

The percentage elongation at break for the yarn sample with lower linear density was slightly lower. The percentage elongation of the samples increased with the increase of linear density; however, the difference was insignificant (± 2%). It can be noted that the twist imparted to the yarn samples derived from the basic yarn (110 tex) has contributed to the elongation of the yarn samples. An increase in the twist level of the yarn puts additional stress on the yarn and increases fiber-to-fiber friction. An increase in the yarn twist increases the force in the direction of the yarn axis, which results in lowering the yarn tenacity and increases elongation at break [122].

(b) Effect of Aging Temperature on the Tensile Properties of HT Polyester Yarn

The main target of this work was to investigate how the tensile properties of textile materials used to reinforce conveyor belts can be influenced by the processing temperature.

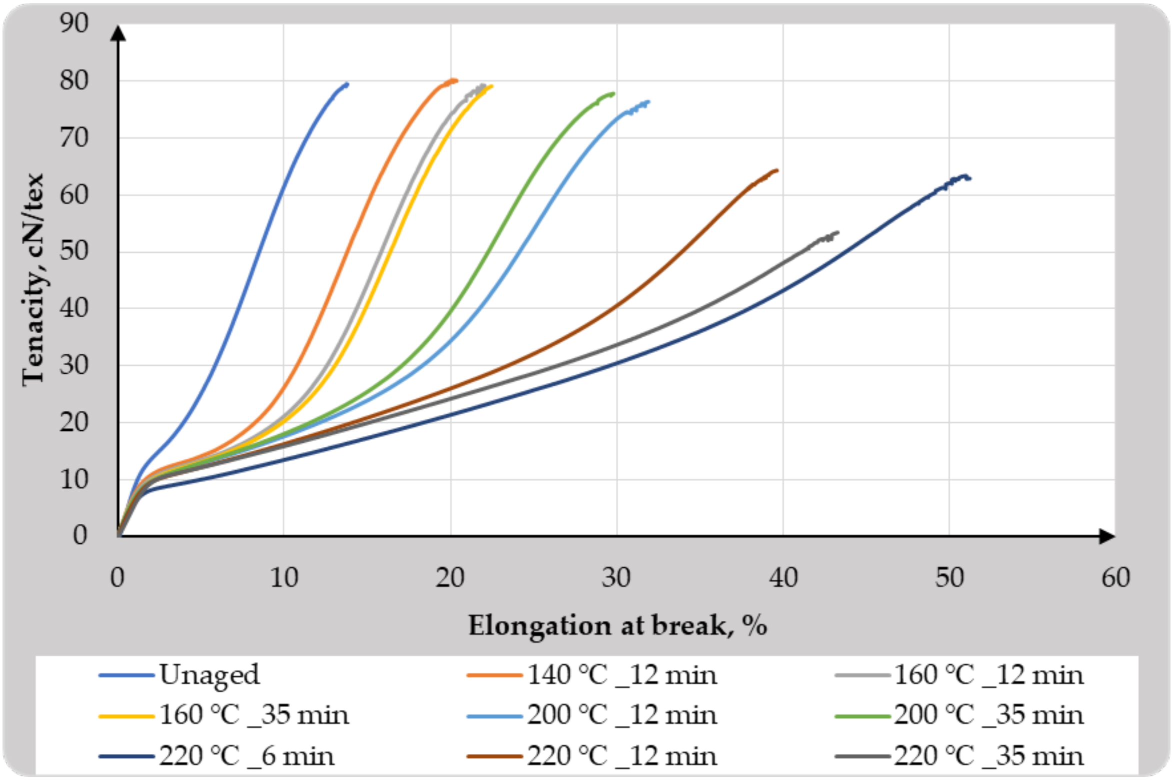

Figure 41. General overview of tensile property behavior of 110 tex-basic yarn under various thermal aging conditions [123].

In order to analyze the effect of aging temperature and duration of aging on the tenacity and percentage elongation at break of the high tenacity polyester yarns, the graph shown in Figure 41 was plotted from the tensile strength test result analysis of the basic yarn (110 tex) sample aged under various aging conditions. The graph in Figure 41 provides the changes that occurred because of thermal aging on the tensile property of the yarn.

It is interesting to see the tenacity Vs percentage elongation graph of 110 tex PET yarns under various thermal aging conditions. From the curve, it is clear that the aging temperature and duration of aging have influenced the tenacity, modulus, and percentage elongation at the break of the yarn. The tensile characteristics of high tenacity polyester yarn can be described by categorizing the tenacity Vs elongation curves of the yarn samples into two regions: the elastic region and the plastic deformation region of the curve. The elastic region is where the polyester yarn sample can be deformed under the applied tensile load and returned to its original configuration upon removing the load. In the elastic region, the stress is proportional to strain, which obeys general Hooke’s law, and this region determines the modulus of the yarn sample. The point at which the elastic region changes to the plastic region is called the yield point. The region from the material's yield point to the breaking point is called the plastic deformation region. Unlike the elastic region, plastically deformed yarn does not return to its original structure upon removing the applied load.

In Figure 41, regardless of the aging parameters, all high tenacity polyester yarn of 110 tex exhibited similar elastic behavior. However, the tensile property of the high tenacity polyester yarn was varied with the thermal aging conditions in the plastic region of the curve. For the yarn samples aged below 200 °C irrespective of the aging duration, there were insignificant tenacity differences obtained. However, the elongation and tenacity of yarn samples aged at 220 °C, regardless of the aging duration, showed lower tenacity and higher yarn elongation.

The following sections of the thesis discuss the reason behind the tenacity and percentage elongation of high tenacity polyester yarns under various aging conditions.

(c) Influence of Thermal Aging Parameters on the Tenacity of Industrial Polyester Yarn

The tenacity of industrial high tenacity PET yarn samples was investigated under thermal aging, and the influence of the temperature on the tenacity of yarn was analyzed. As shown in Figure 42, the samples were aged under different temperatures for a constant aging duration of twelve minutes. Also, to easily observe the change that occurred due to thermal aging yarn sample before aging is included in the graph. The graph illustrates how yarn samples with different linear densities can behave under various aging temperatures.

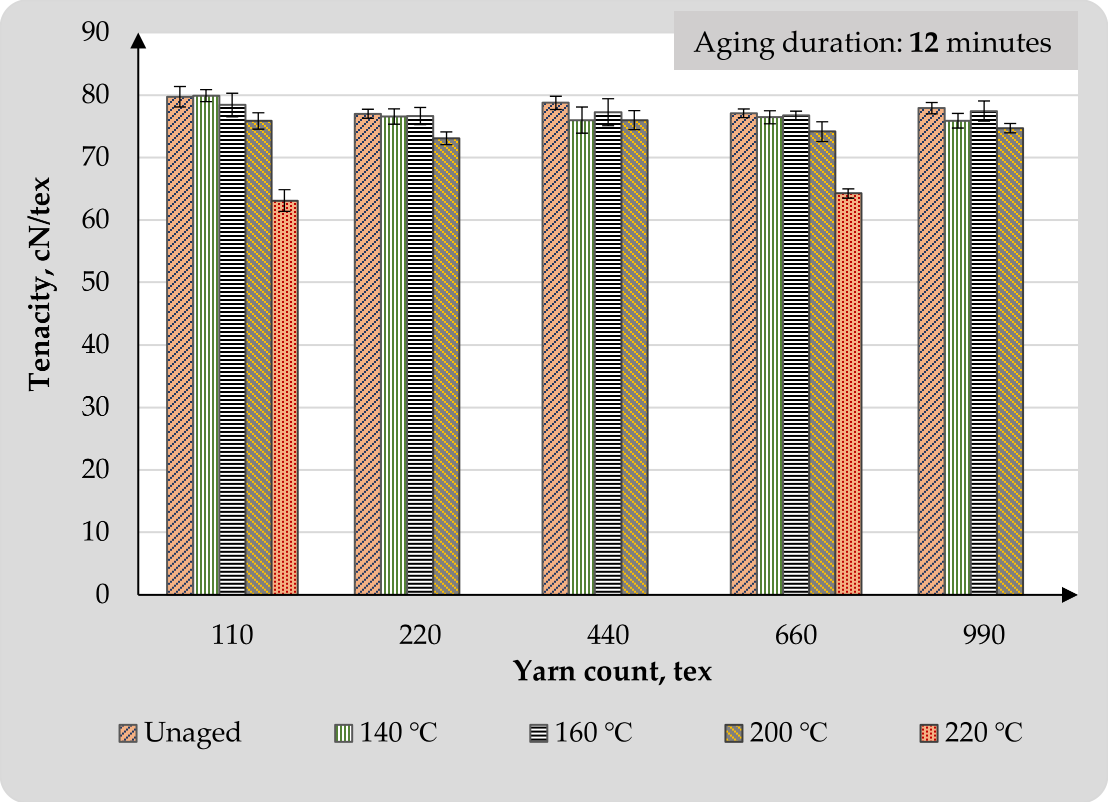

Figure 42. Influence of aging temperature on the tenacity of PET yarn with different linear densities.

The polyester yarn samples aged at 140 and 160 °C for twelve minutes showed a similar level of tenacity, with an average difference of ± 2.14%, irrespective of the yarn's linear density. Additionally, for the samples aged at 200 °C, inconsiderable yarn tenacity change was observed regardless of the yarn samples' linear density; only on average ±0.55 cN/tex tenacity loss was registered in comparison to the unaged yarn. However, as the aging temperature rose to 220 °C while the aging duration was unchanged (12 minutes), the tenacity loss of 20.84% and 16.67% were respectively observed for the yarn with a linear density of 110 tex and 660 tex compared to the unaged industrial polyester yarn.

It is an excellent insight to see how the aging temperature can affect the tenacity of industrial polyester yarns below the melting temperature of the polyester yarn (≈ 262 °C) and above the glass transition temperature (≈ 180 °C) under the graphs shown in Figures 42 & 43. The impact of thermal aging on the industrial polyester yarn samples' tenacity under the elevated aging duration of 35 minutes is shown in Figure 43. The yarn samples aged at and below 200 °C showed inconsiderable tenacity loss compared to the unaged polyester samples, regardless of the yarn's linear density. Also, as shown in Figure 43, the tenacity of yarn samples aged for the duration of 35 minutes gradually degraded as the aging temperature increased from 140 to 220 °C.

A significant loss of tenacity, 36.02% and 26.30% for 110 tex and 660tex yarn samples, respectively, compared to the unaged yarn samples' tenacity, was observed for samples aged at 220 °C for 35 minutes. The results presented in Figures 42 & 43 signify that the tenacity of industrial polyester yarns is dependable on the aging temperature. As the aging temperature increases beyond the glass transition temperature and beneath the melting temperature of the industrial polyester yarn, it causes structural rearrangement in the fiber structure of the industrial polyester yarn.

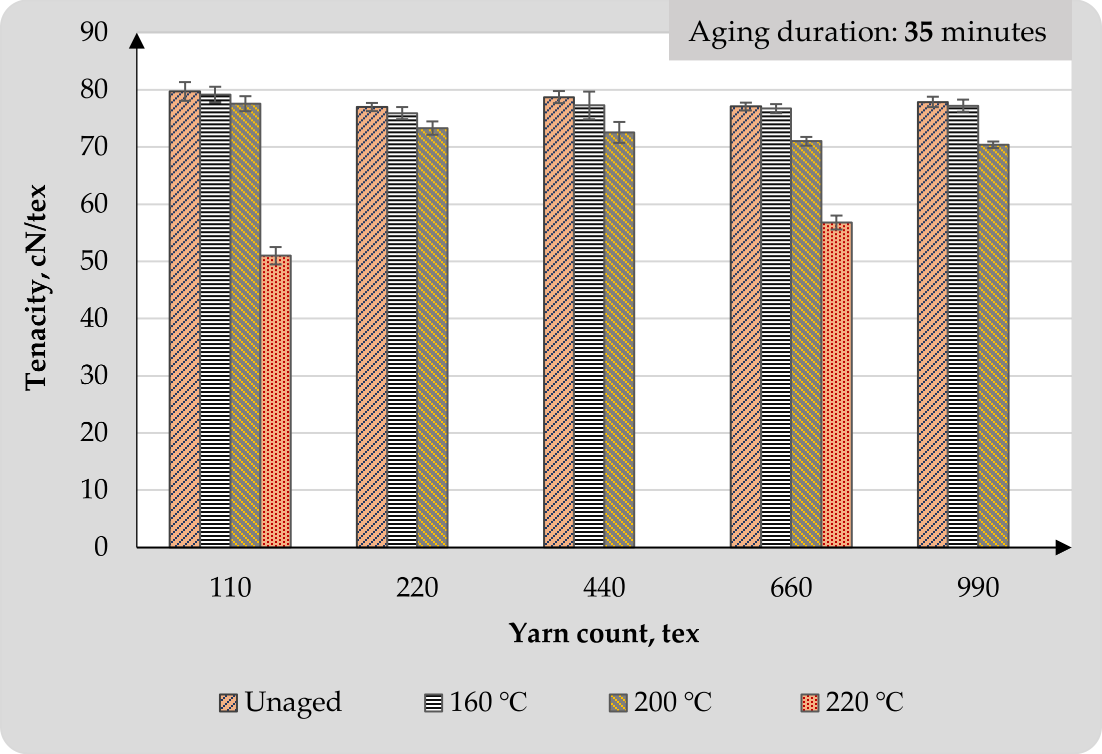

Figure 43. Influence of aging temperature on the tenacity of PET yarn with different linear densities.

The mechanism of the polyethylene terephthalate structural changes under thermal heating was studied by various researchers [124–127], and the findings consistently revealed that thermal aging causes fiber structure modification. Nevertheless, these studies did not further investigate how the fiber structure modification caused by thermal aging impacts the yarn's tenacity. ***This work shows that the findings are in line with the previous research and added one further step to the existing knowledge about the impact of thermal aging parameters on the mechanical properties of industrial polyester yarn.***

The experimental results obtained from the tensile strength test of the high tenacity industrial polyester yarn indicated that the tenacity of the yarn samples remains the same if the yarn undergoes thermal aging below its glass transition temperature. However, the aging of yarn above the glass transition temperature of the yarn gradually deteriorates the yarn’s tenacity, mainly if the aging temperature is above 220 °C, the tenacity loss is higher.

This signifies that the crystal sizes and fiber morphology rearrangements that can occur in the amorphous regions of the polyester fiber directly influence the mechanical properties of the yarn. The rearrangement of the polymeric structure in the fiber morphology causes the breakage of yarns under a meager external load.

From the tenacity result analysis shown in Figures 42 & 43, it is clear that the duration of thermal aging also plays a significant role in determining the tenacity of the yarn. The yarn subjected to thermal aging for a longer period (35 minutes) has shown lower tenacity at the elevated aging temperature (220 °C), irrespective of the yarn's linear density.

(d) Influence of Thermal Aging Parameters on the Percentage Elongation of Industrial Polyester Yarns

The effect of thermal aging on the percentage elongation of high tenacity industrial polyester yarn was investigated, and the analyses are shown in Figures 44 & 45.

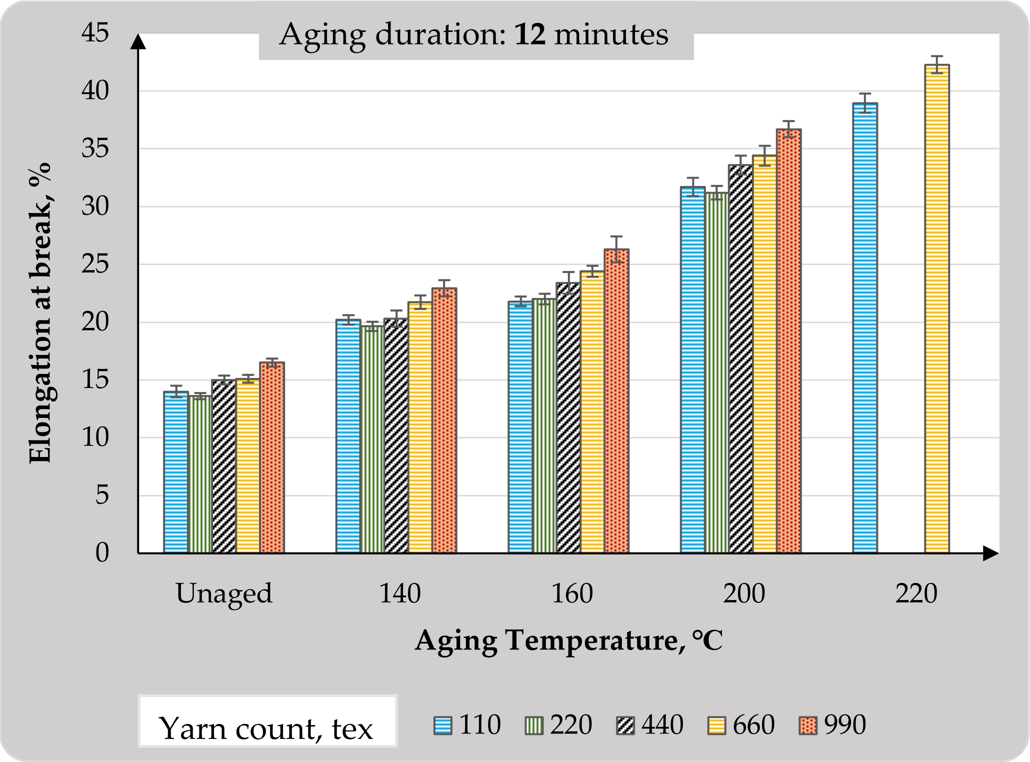

Figure 44. Influence of thermal aging parameters on the percentage elongation of PET yarn.

Figures 44 & 45 present the percentage elongation of the yarn aged at various aging temperatures for twelve and thirty-five minutes, respectively. The results indicate that the aging temperature immensely impacts the elongation of industrial polyester yarns. Irrespective of the aging duration and the linear density of the yarns, the percentage elongation of the industrial polyester yarn increased with the aging temperature. The analyses signified that the industrial polyester yarn was highly elongated when the sample was subjected to thermal aging at and above 200 °C. The samples with a linear density of 110 tex and 660 tex were subjected to high thermal aging at 220 °C, and the percentage elongation obtained was almost three times higher than the unaged yarn regardless of the aging duration and linear density of the yarn.

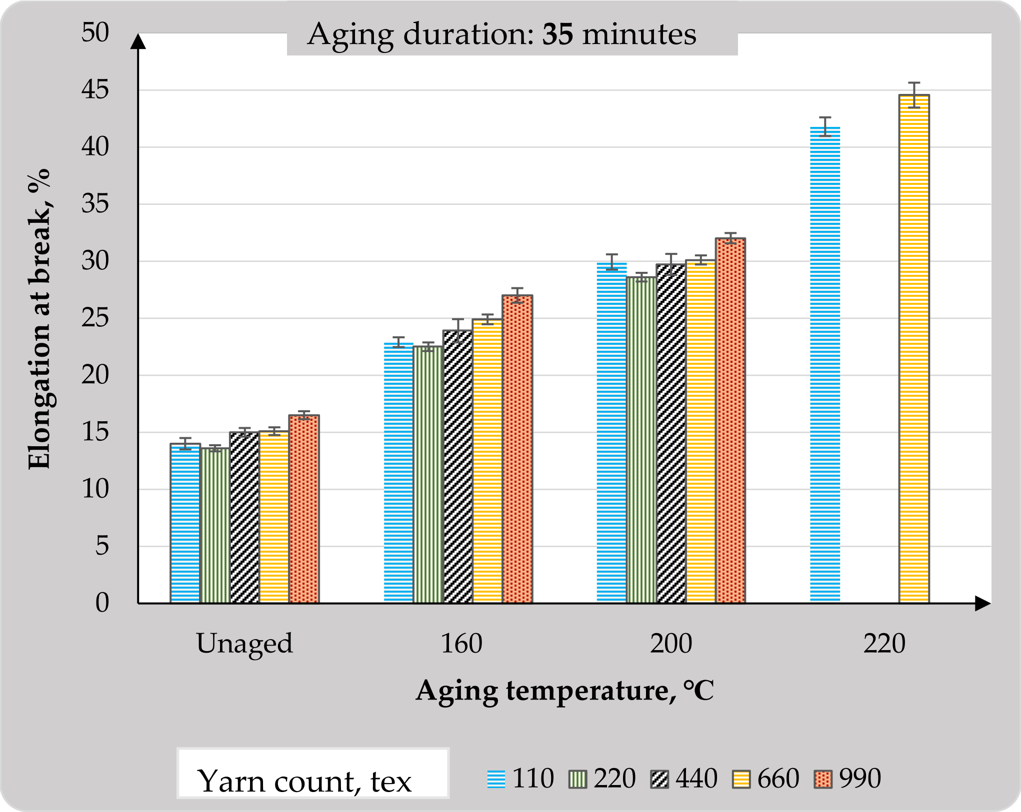

Figure 45. Influence of thermal aging parameters on the percentage elongation of PET yarn samples.

A textile material's elongation property is crucial in mechanical rubber reinforcement technology as it determines the dimensional stability of the mechanical rubber good. In addition, this property is highly reliable on the thermal aging temperature. Therefore, determining the optimum temperature for every textile rubber-reinforced mechanical rubber good is vital.

The science behind the elongation phenomena of industrial polyester yarn samples is linked to the structure of the polymer materials in the fiber structure. As can be seen from the elongation results, the thermal aging below, but close to the glass transition temperature of the polyester yarn, can cause minimal elongation of averagely ± 9.4% compared to the unaged yarn. However, as the aging temperature rose to 200 °C and 220 °C, the average percentage elongation of the yarn samples was 15.24% and 28.63%, respectively, compared to the unaged yarn. The incrementation in percentage elongation with thermal aging shows that as the aging temperature is closer to the melting temperature of the polymers in the fiber structure, the ability of molecules to freely extend under a minimum applied load is high. Sardag et al. and Gupta et al. [89, 127] also described the dependency of polyester fiber elongation on the annealing temperature in their papers. Nevertheless, the temperature at which the polyester yarn’s percentage elongation varies depends on the type of polyester fiber used for the experimental tests.

6.1.3 Influence of Weaving Process and Resorcinol-Formaldehyde-Latex (RFL) Dipping on the Mechanical Properties of Industrial Polyester Yarn

Industrial polyester yarns lack adhesiveness to rubber materials. In order to enhance the adhesiveness of these two distinct materials (rubber and textile), the polyester yarn has to be treated with adhesive chemicals such as resorcinol-formaldehyde-latex (RFL) solution. The treatment of polyester with an adhesive solution can be at the yarn or fabric level, depending on the mechanical rubber good intended to be produced.

In the case of conveyor belts, polyester yarns are not directly used for the reinforcement purpose; instead, they are used to produce a woven fabric which will be used for the reinforcement of the rubber. Therefore, the fabric is treated with RFL adhesive to increase the adhesion of the fabric with the rubber.

To evaluate the effect of RFL and the weaving process on the mechanical properties of the industrial high tenacity polyester yarn, the yarn samples were removed from RFL-dipped woven fabric and subjected to tensile property experimental tests. The result obtained from the experimental tensile test of polyester yarns removed from woven fabric was compared with the tensile property of yarn without any adhesive treatment, referred to as greige yarn in this document; these analyses are shown in Figure 46.

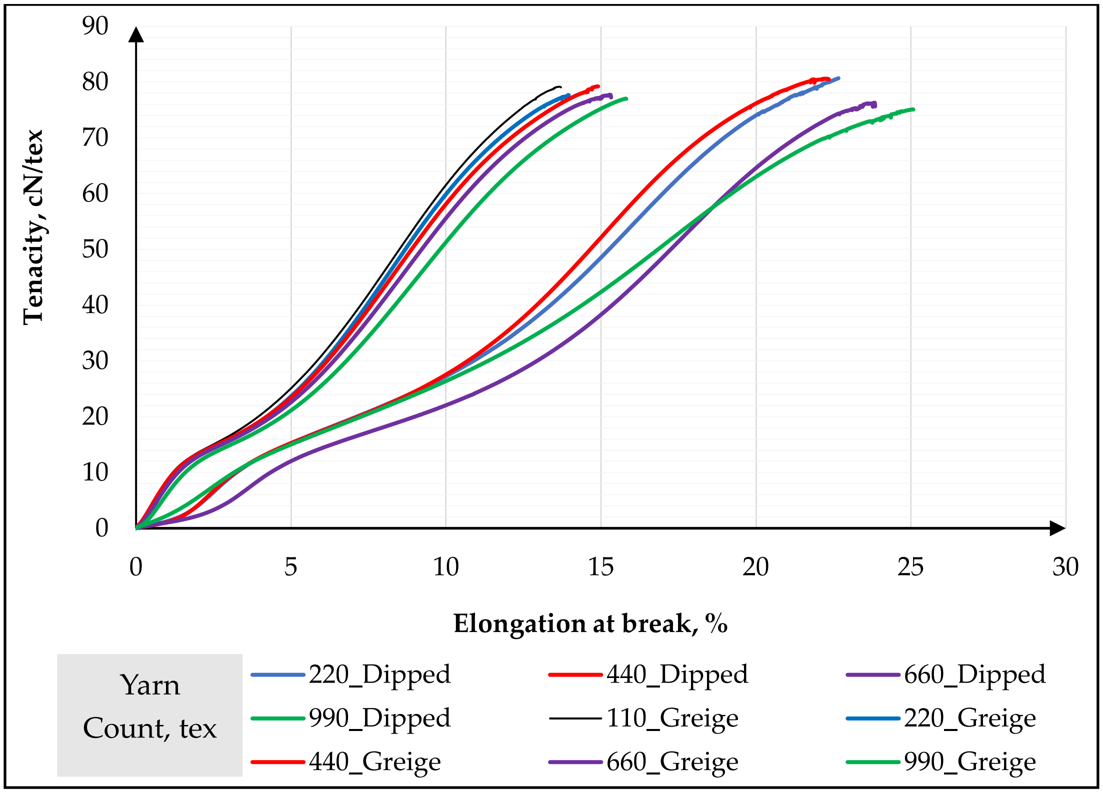

Figure 46. Comparison of dipped yarn removed from woven fabric Vs greige yarn samples.

The tenacity versus elongation percentage curve of the greige high tenacity polyester yarn and RFL dipped high tenacity polyester yarn raveled from the fabric structure signifies that the RFL and weaving process has an impact on determining the elongation and elastic modulus of the industrial polyester yarn. As shown in Figure 46, no significant change (±2.32%) was observed because of RFL treatment or weaving on the tenacity of industrial polyester yarn. However, many researchers found that the tensile strength of warp yarn is degraded during a weaving process [128–130], but in the result presented in Figure 46, no such change was observed. This signifies that even though the weaving process degrades the tensile strength of warp yarn, RFL adhesive chemical has the ability to maintain the strength of the yarn in addition to increasing the adhesion of the polyester yarn to the rubber materials, the influence of RFL on the fabric's mechanical property was deeply discussed in section 6.2.1 of this document.

In the curve shown in Figure 46, it is interesting to see how the elongation percentage of the yarn was changed after weaving and dipping in RFL solution. The greige yarn has lower elongation compared to the yarn removed from the woven fabric. In the tenacity-elongation curve of the yarn removed from the woven fabric, no visible linear correlation appeared between the tenacity and elongation of the yarn, meaning the elastic region of the yarn is insignificant. This phenomenon can be discussed under two scenarios, the first is the effect of the RFL dipping process on the properties of the yarn, and the second is the effect of warp crimp on the elongation property of the yarn.

The treatment of polyester fabrics or yarns with the RFL adhesion solution is called the dipping process. After the textile yarn or fabric is dipped in the RFL solution, it is subjected to a curing process at 185 °C to facilitate fabric adhesiveness to the rubber [131].

Therefore, during the curing process, the polyester yarn is subjected to thermal treatment, which is above its glass transition temperature; this slightly causes the rearrangement of polymer molecules in the fiber structure and facilitates the elongation of the yarn under minimum load, as shown in Figure 45.

The second scenario is that weaving involves the warp yarn and weft yarn interlacement based on the weave structure. The warp yarn is a thread that runs in the longitudinal axis of the fabric, and the weft yarn is a yarn that runs in the transverse axis of the fabric. These yarns create a curvature during the interlacement, as shown in Figure 47. This curvature is called a crimp.

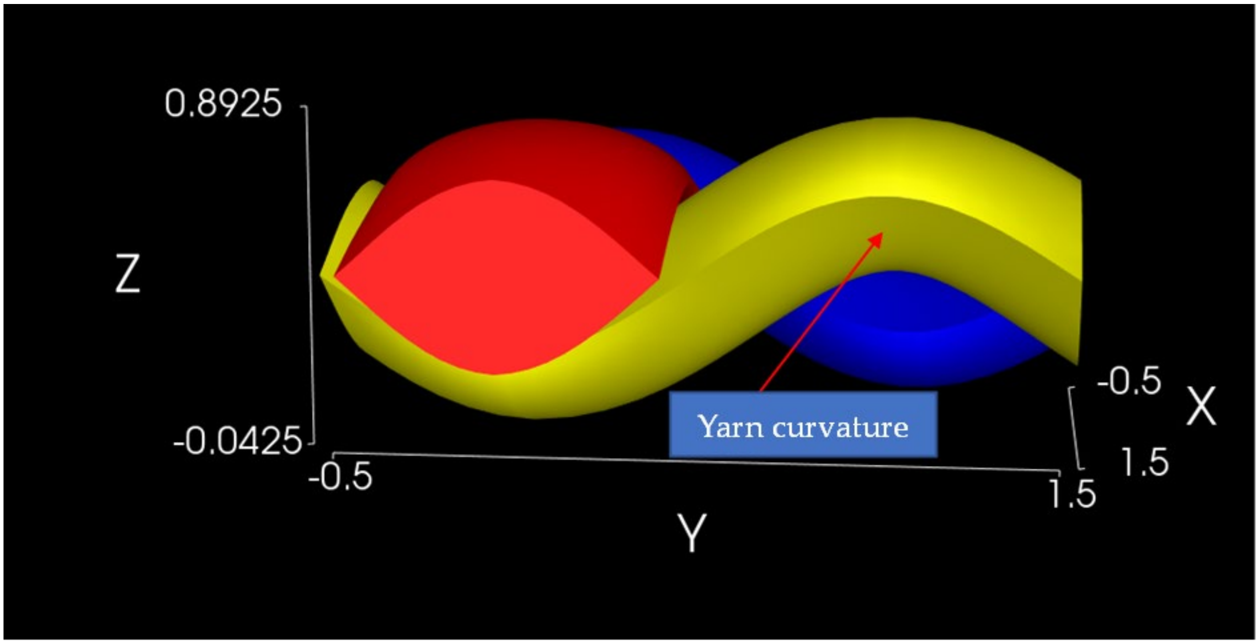

Figure 47. Yarn curvature created during the interlacement of warp and weft yarns.

The crimp decreases the length of the yarns [128]. However, when the yarn is removed from the fabric, the elongation of the yarn increases under a tensile load. Because of the above two scenarios, the elongation of the yarn removed from the fabric was higher than the greige or yarn tested directly from the bobbin.

6.1.4 Thermal Shrinkage Results of High Tenacity Polyester Yarns

The thermal shrinkage of industrial polyester yarn was investigated at different temperatures and time intervals to analyze the thermal shrinkage behavior of the yarns. High-tenacity polyester yarn with a linear density of 220 tex was chosen for the shrinkage test. The results of the shrinkage test analysis are presented in Figure 48. The result showed that the percentage shrinkage of high tenacity polyester yarn was increased with the temperature irrespective of the yarn's duration of thermal exposure.

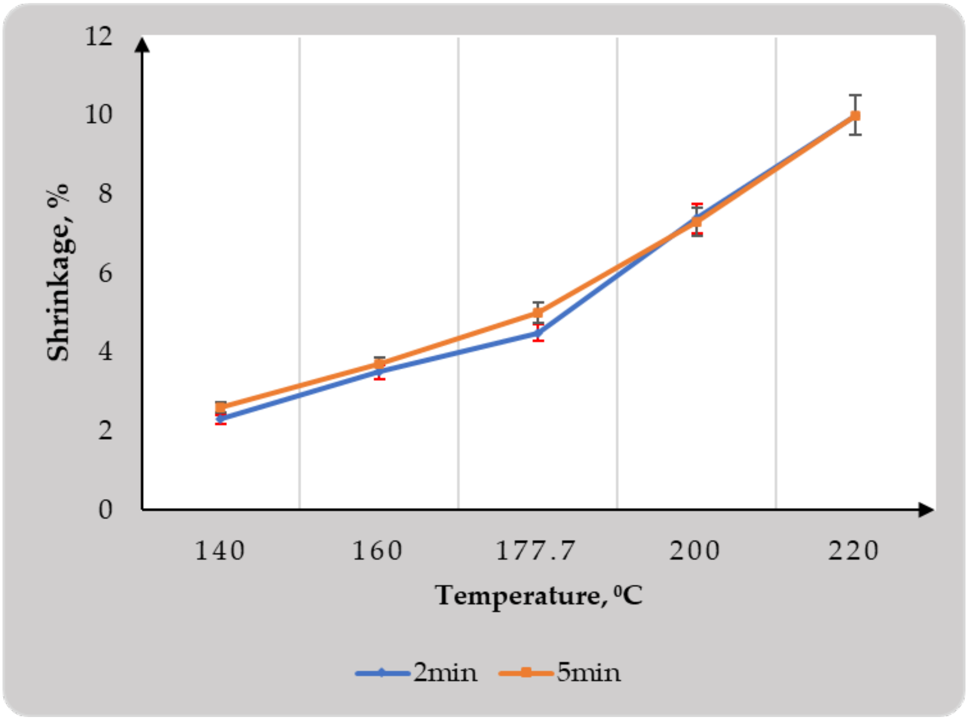

Figure 48. Effect of temperature and aging duration on the shrinkage property of high tenacity polyester yarn.

The shrinkage of polyethylene terephthalate was associated with the disorientation of fiber structures in the amorphous phase and followed by the crystallization during which the chain folding may occur [132, 133]. The disorientation, crystal decomposition, and shrinkage of the fiber depend on the aging temperature and time.

Therefore, the result revealed that subjecting the yarn to a higher temperature (220 ℃) for a longer duration facilitated the fiber structures' disorientation and caused a high percentage of the yarn shrinkage. This can result in dimensional instability of woven fabrics. Hence, the thermal aging should be kept at a lower temperature to have the fabric with better dimensional stability.

6.1.5 Effect of Thermal Aging on the Structural Properties of High Tenacity Polyester Yarn

The influence of thermal aging on the surface structural properties of the polyester fiber was investigated using a Scanning Electron Microscope (SME). The structural property of the high tenacity polyester yarns pre-and post-thermal aging and post-tensile property test was analyzed. The structural views of the yarn samples were conducted for all samples presented in section 3.1 and thermally aged under various conditions. However, no significant surface structural view was observed on the fiber surfaces because of the linear density difference; for that matter, the surface structural view of high tenacity polyester yarn of 660 tex at different thermal aging conditions is provided in Figure 49.

As shown in Figure 49(a-c), there was no considerable surface structural change observed between the unaged fiber and the fibers from thermally aged yarns at 220 ℃ for six and twelve minutes of aging duration. However, as the duration of aging increased to thirty-five minutes while the temperature remained the same (220 ℃), crack development (surface damage) was observed on the fiber surface (Figure 49d). This indicates that the aging of polyester yarns at a high temperature can cause an ultimate breakdown of chemical bonds in the fiber’s polymer structure and result in the degradation of polyester yarn. Furthermore, the fiber surface damage observed potentially leads to the mechanical property deterioration of high tenacity polyester yarns.

Therefore, it can be inferred that the thermal aging of polyester yarns over a long period (>35 mins) at high temperatures (≥ 220 °C) can lead to the deterioration of the physical, chemical, and mechanical properties of the yarn.

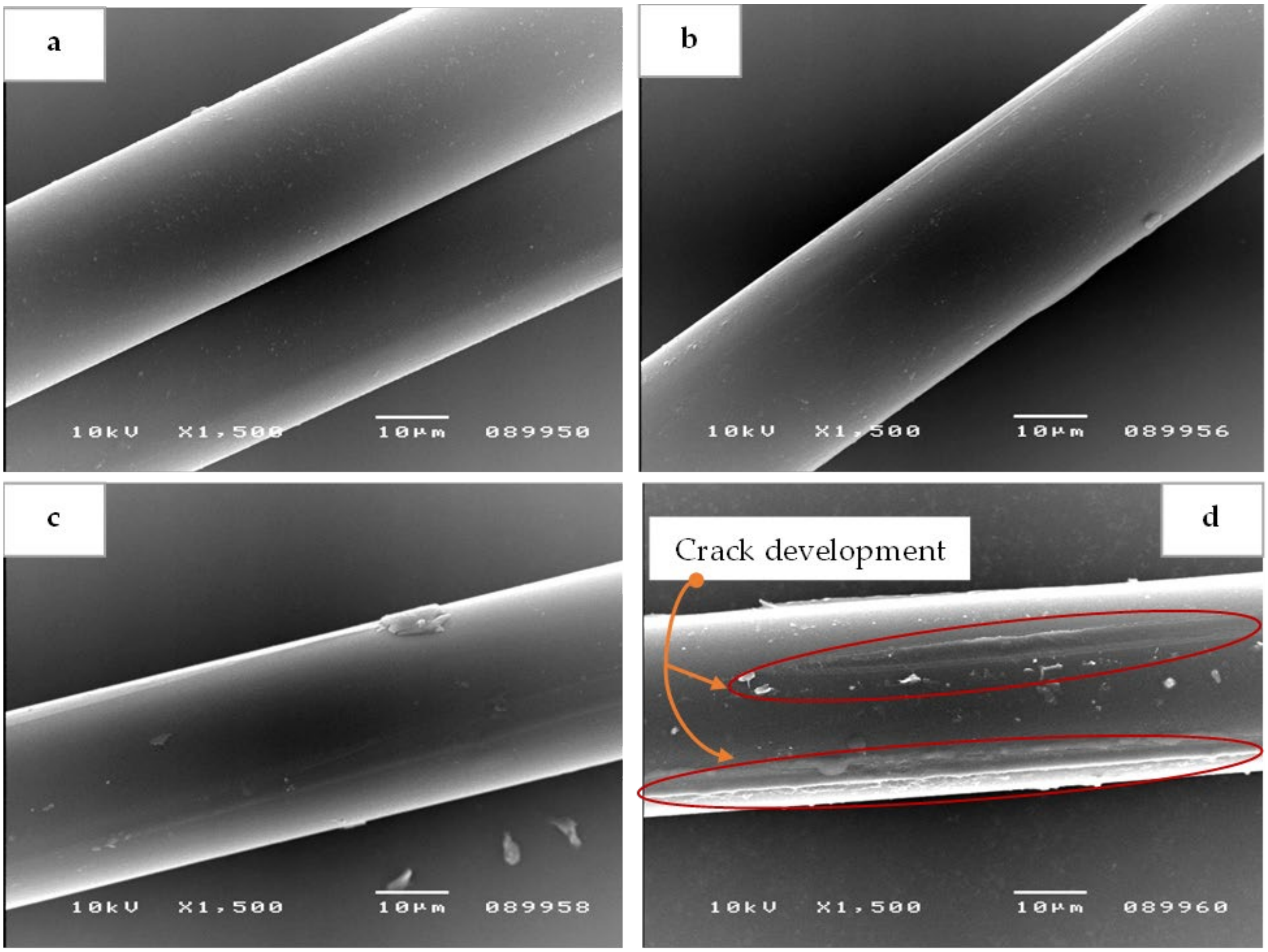

Figure 49. Surface structural view of high tenacity polyester fiber. (a) Pre-thermal aging, (b) Post-thermal aging at 220 °C for 6 minutes, (c) Post-thermal aging at 220 °C for 12 minutes, (d) Post-thermal aging at 220 °C for 35 minutes.

Furthermore, thermal aging can also affect the way polyester yarns behave under the tensile load. In Figure 50, the surface structure of polyester fibers after the tensile strength tests of high tenacity polyester yarns were shown. In Figure 50a, the surface structure of the broken end of polyester fiber from unaged polyester yarn post-tensile test was shown, and the image signifies the instant breakage of the fiber under tensile load.

However, fibers in the yarn structure aged at 160 °C for 12 minutes exhibited a different form of breakage rather than instant breakage, as shown in Figure 50b. This signifies that the thermal aging condition of 160 °C for 12 minutes has an influence on the way polyester fibers also behave under the tensile load. Therefore, the thermal aging of polyester fiber or yarn can cause the formation of irregular breakage, coiling, or necking on fiber breakage under the tensile load.

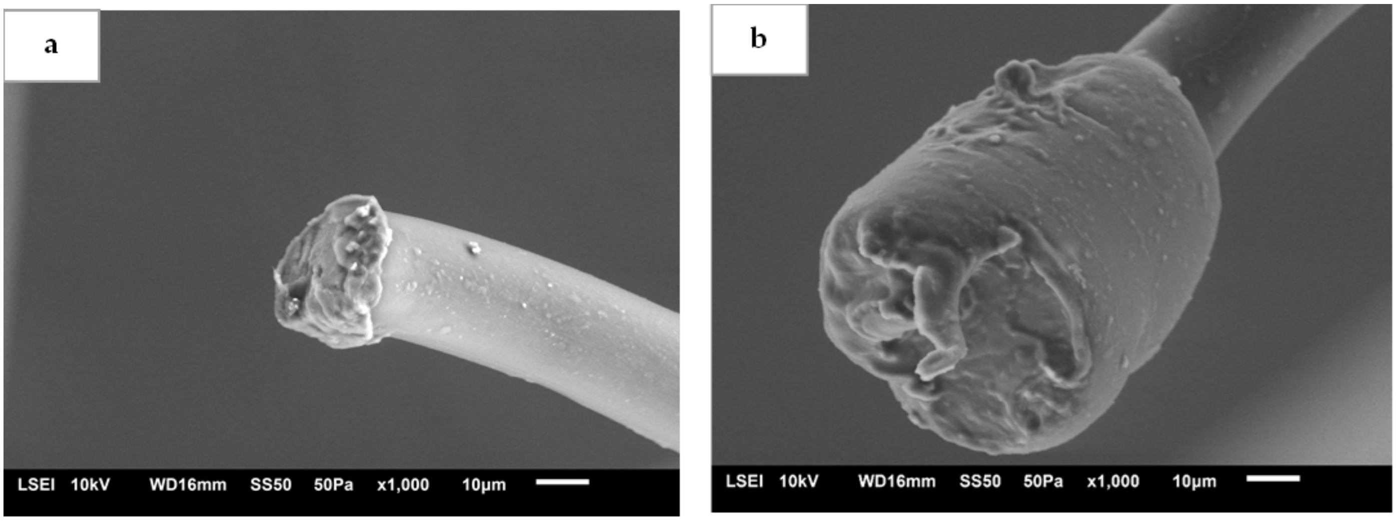

Figure 50. SEM structure of HT PET yarn after tensile test. (a) before thermal aging, (b) After thermal aging at 160 °C for 12 minutes.

6.2 Analysis of EP Woven Fabrics Experimental Test Results

6.2.1 Effect of RFL Dipping on the Tensile Properties of EP Woven Fabric

The influence of Resorcinol-Formaldehyde-Latex (RFL) adhesive solution on the tensile property of EP woven was analyzed by conducting experiments on the greige and dipped woven fabric samples with different nominal tensile strengths. The tensile property analysis was compared, as shown in Figure 51(a-d), and the results are elaborated.

Dipping EP fabrics intended to reinforce the conveyor belt in the RFL solution is not an option; instead, it is compulsory because EP fabric lacks enough adhesiveness to the rubber material. Without adequate adhesion between the conveyor belt's constituent materials, achieving a conveyor belt that withstands the external force exerted on the belt from the conveyed materials is impractical. Therefore, the greige EP woven fabric undergoes a dipping process, where the curing is carried out at around 185 °C following the dipping process of the fabric in RFL solution. The investigation revealed that, besides imparting adhesion to the EP fabric, the dipping process could also cause mechanical and physical property changes to the woven fabric.

The tensile property of the textile reinforced conveyor belt primarily depends on the tensile property of woven fabrics in the warp direction [112]. Thus, the tensile strength of greige and dipped woven fabric samples in the warp direction were investigated. The tensile strength results of EP woven fabric of 125 kN/m, 200 kN/m, 315 kN/m, and 500 kN/m shown in Figure 51 show that the tensile strength and elongation at break of the EP were changed due to the dipping of the fabric in RFL solution regardless of the nominal strength of the fabric.

The stress-strain curve shown in Figure 51(a-d) signifies that at the beginning of the curve, the elongation at the break of the greige fabric is higher than the dipped woven fabric, regardless of the sample type. However, as the stress increased, the elongation at break of dipped EP woven fabric surpassed the elongation of greige fabric.

Additionally, the tensile strength of the RFL dipped fabric samples are higher than the greige fabric samples for each EP sample type presented in Figure 51 (a-d).

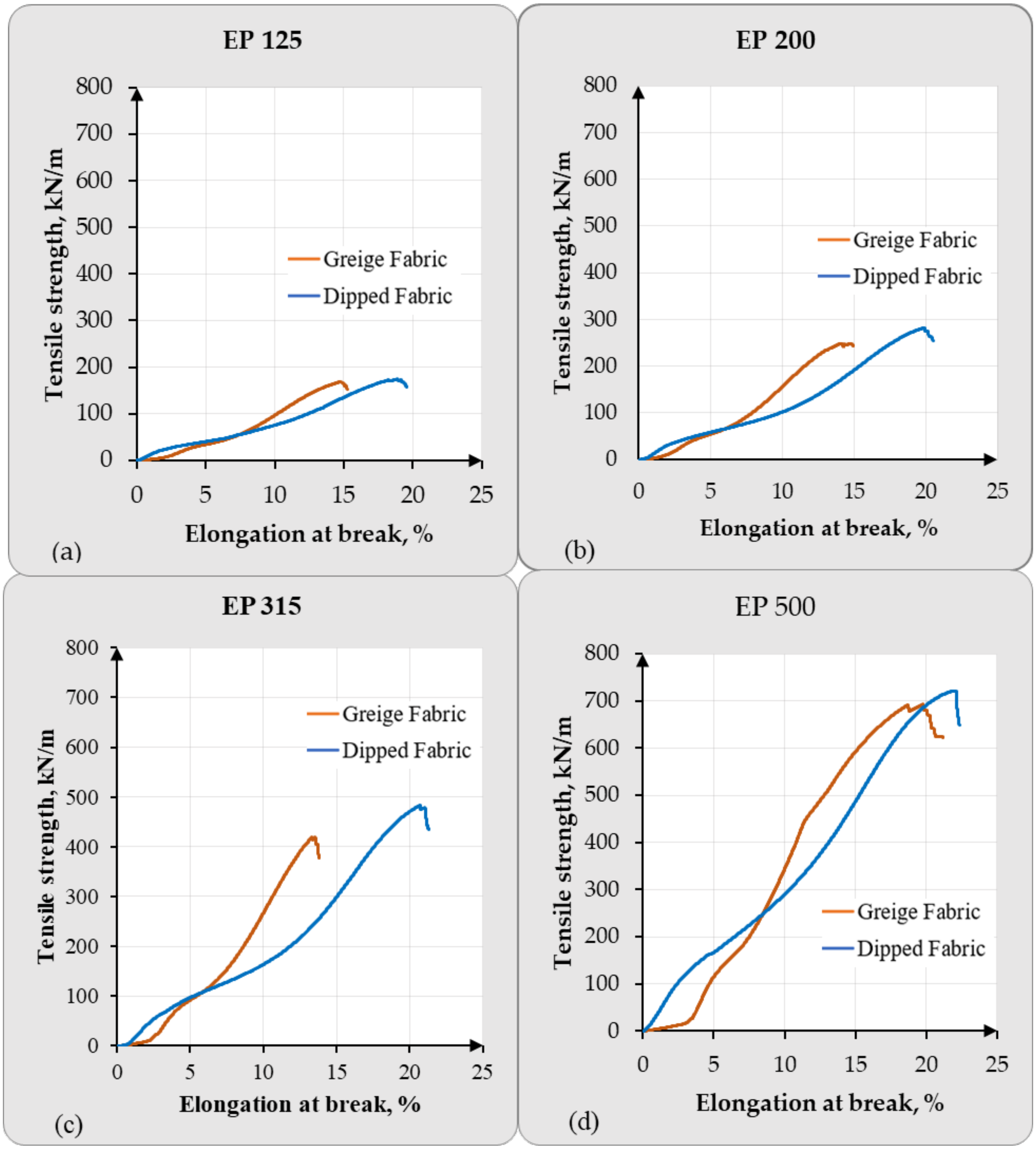

Figure 51. Effect of dipping on the tensile property of woven fabric samples. (a) EP fabric sample of 125 kN/m nominal tensile strength, (b) EP fabric sample of 200 kN/m nominal tensile strength, (c) EP fabric sample of 315 kN/m nominal tensile strength, (d) EP fabric sample of 500 kN/m nominal tensile strength.

This phenomenon happened due to two main factors: in the initial part of the curve, the greige fabric or fabric without any finishing treatment was more elongated under a minor external tensile load in contrast to the dipped fabric because of the warp yarn crimp. Nonetheless, as the stress level increased, the warp crimp of the greige fabric was removed; consequently, the greige fabric percentage elongation at break was reduced compared to the dipped fabric samples.

The other factor is that EP fabrics are made from thermoplastic yarns; after dipping in RFL solution and curing the fabric, the EP woven fabrics were stiffer, which can be observed in the first part of these curves shown in Figure 51(a-d). Consequently, elongating dipped EP fabric samples required a higher applied load than the greige fabric. As the applied load increased, the elongation of dipped fabrics was also incremented. Therefore, it can be concluded that the fabric crimp and dipping process immensely impact the mechanical properties of the EP woven fabric. This also affects the elastic modulus of the fabrics.

6.2.2 Effect of Thermal Aging on the Tensile Strength of EP Woven Fabric

The influence of thermal aging parameters on the tensile strength of RFL-dipped EP woven fabric samples of nominal strength 125 kN/m, 200 kN/m, 315 kN/m, and 500 kN/m was analyzed. In addition, the effect of aging temperature and duration of aging under no pressure on the fabric samples during aging were investigated, and these results were compared with the unaged RFL-dipped EP woven fabric (a fabric sample not subjected to thermal aging).

In Figure 52, the samples aged at 140, 160, and 220 °C for the duration of six minutes, and the unaged fabric sample results are shown. Compared to the unaged fabric, the samples aged at 220 °C for the duration of six minutes showed lower tensile strength. The tensile strength of EP 125, EP 200, EP 315, and EP 500 fabric samples decreased by 6.51%, 10.12%, 13.49%, and 13.96%, respectively.

From the analysis, it was noted that as the aging temperature increased from 140 °C to 220 °C the tensile strength of the fabrics gradually decreased by 5.35%, 8.74%, 10.71%, and 4.86% for EP 125, EP 200, EP 315, and EP 500 fabric samples, respectively.

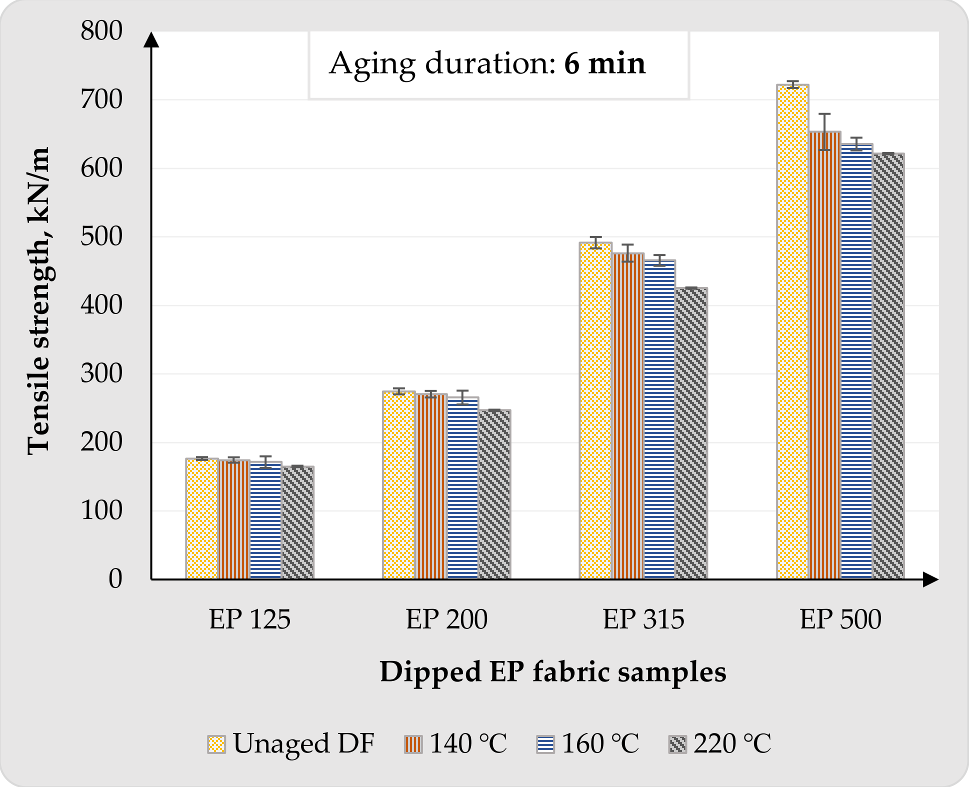

Figure 52. Effect of aging temperature on the tensile strength of RFL dipped EP woven fabric.

Moreover, the tensile strength of the EP fabric was diminished when the fabric samples were subjected to thermal aging for a longer aging duration (35 minutes), as shown in Figure 53. Compared to the unaged fabric, the tensile strength of samples aged at 220 °C for the duration of thirty-five minutes was decreased by 19.78%, 30.26%, 21.69%, and 19.86% for EP125, EP200, EP315, and EP500 fabric samples, respectively.

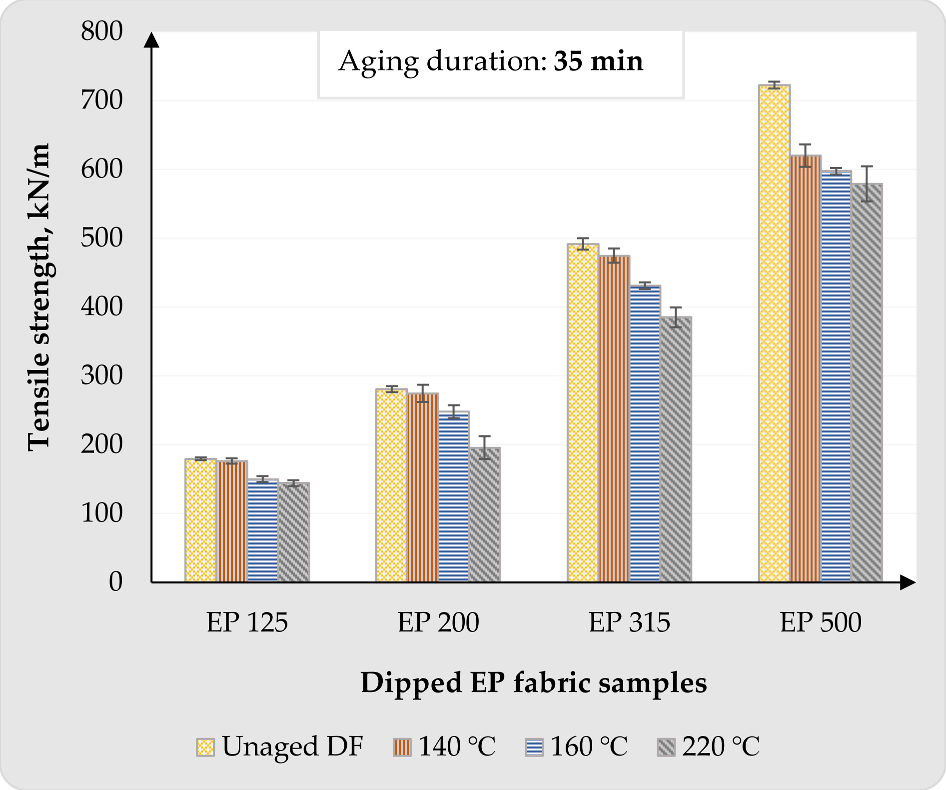

Figure 53. Effect of aging temperature on the tensile strength of RFL dipped EP woven fabric.

The above-presented analyses revealed that the aging temperature and duration of aging influenced the tensile strength of RFL-dipped EP woven fabric samples. The reduction in the tensile strength of the fabric samples was primarily linked to the properties of warp and weft yarns used to produce the fabric. Polyester and polyamide are synthetic polymers with different thermal properties. These synthetic polymers are susceptible to high temperatures and interact in complex ways under thermal aging. Polyester fibers are stiffer and more brittle under a high temperature, while polyamide fibers are weaker and more prone to rupture under a minor tensile load. Subjecting woven fabric created from these yarns to high temperatures can cause the polymer chain scission in the polyester and polyamide fibers, which leads to the reduction in the polymers' molecular weight as well as diminishes the tensile strength of the woven fabric under applied load.

Also, the thermal aging of polyester and polyamide can cause micro-structural changes in the fibers, mainly the crystallinity, which adversely influences the mechanical property of the woven fabric.

Additionally, at high aging temperatures, primarily above the glass transition temperature of the polyester and polyamide fibers, the polymer chains in the fibers become more reactive and create cross-links with other molecules. As a result, the polymer chains are less mobile, and the fabric's ability to stretch and deform under tensile load without breakage is decreased.

Overall, the aging temperature and duration of aging can significantly impact the tensile strength of EP woven fabrics regardless of the fabric thickness and mass per unit area of the fabric. However, the effect level varies depending on the specific thermal aging parameters the fabric samples were subjected to. Therefore, it is crucial to consider these impacts when selecting and designing textiles for mechanical rubber good reinforcements intended for applications where thermal aging is a factor.

6.2.3 Effect of Thermal Aging on the Percentage Elongation of EP Woven fabric

The elongation property of woven fabrics used to reinforce the conveyor belt determines the conveyor belt's dimensional change upon the initial installation of the belt during the start-up and operation of the conveyor belt. Therefore, it was necessary to investigate the percentage elongation of woven fabric pre-and post-thermal aging. The influence of aging temperature and duration on the elongation property of resorcinol-formaldehyde-latex dipped EP woven fabric samples were thoroughly analyzed.

Figure 54 presents the percentage elongation analyses of woven fabric samples aged at 140, 160, and 220 °C for six minutes and the elongation percentage of the fabrics' pre-and post-thermal aging. The analyses shown in Figure 54 indicated that the percentage elongation of the woven fabric samples irrespective of the sample type was significantly influenced by the aging temperature.

In addition, the change of percentage elongation for the fabric samples was in a similar pattern, meaning the percentage elongation of the fabric samples increased with the aging temperature.

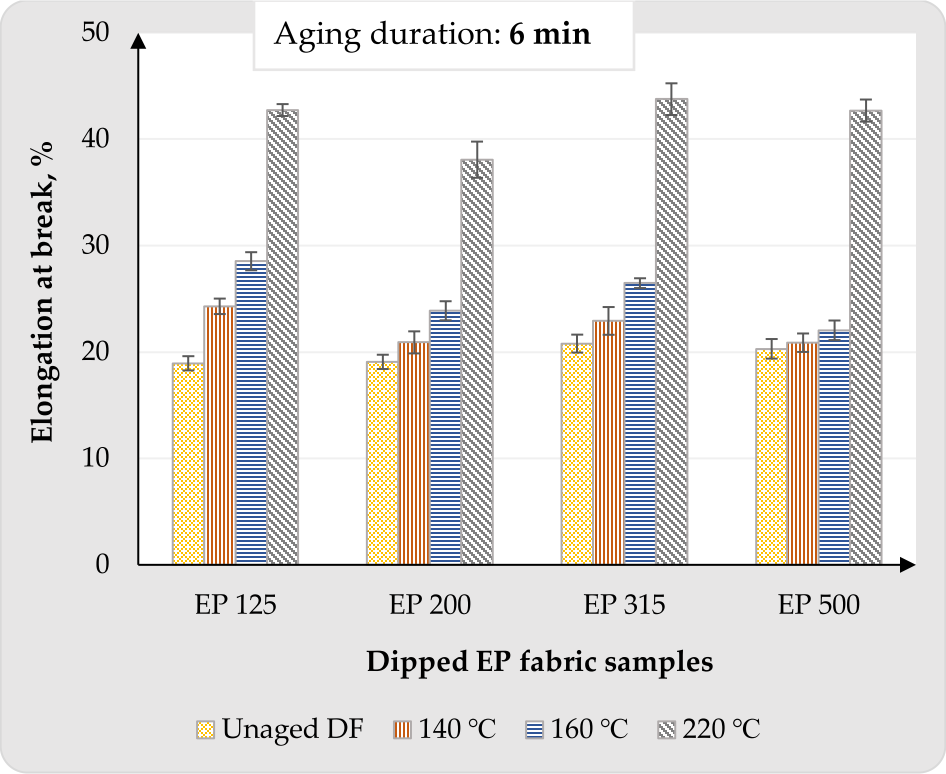

Figure 54. Effect of aging temperature on the percentage elongation of RFL dipped EP woven fabric.

The elongation difference observed between the unaged fabric and fabrics aged at 140 °C and 160 °C was insignificant compared to the percentage elongation changes observed for the samples aged at 220 °C.

Compared to the unaged woven fabric, the percentage elongation at break of the EP125, EP 200, EP 315, and EP 500 woven fabric samples aged at 220 °C were increased by 125.66%, 99.63%, 110.49%, and 110.30%, respectively. The effect of thermal aging on the elongation property of a polyester-polyamide woven fabric is complex and multifaceted.

Nevertheless, the elongation at break mostly depends on the constituent yarns' thermal properties, the fabric structure, the duration of thermal aging, and the temperature level. When the RFL dipped woven fabrics were subjected to thermal aging, the crosslinking created during the dipping process was potentially broken; as a result, post-thermal aging, the fabrics showed a high percentage elongation at break. Also, the high incrementation of elongation at break for the samples aged at 220 °C was indeed linked to the polymer structural change in the constituent yarns due to the thermal aging temperature, which was above the glass transition temperature of both polyamide and polyester yarns.

Additionally, as shown in Figure 55, the fabric sample aged for a longer duration indicated that the percentage elongation of the polyester-polyamide woven fabric samples increased with the temperature.

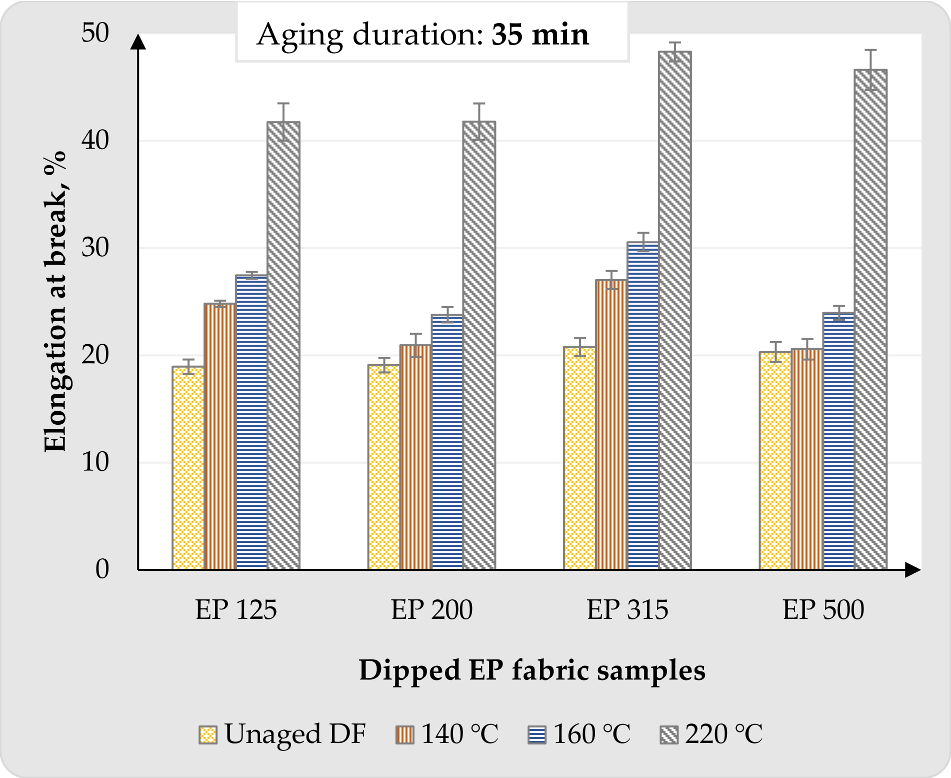

Figure 55. Influence of aging temperature on the percentage elongation of RFL dipped EP woven fabric.

In comparison to the samples aged at 140 °C for 35min, the elongation at break of EP 125, EP 200, EP 315, and EP 500 samples aged at 160 °C for 35min was increased by 10.73%, 13.62%, 13.14%, and 16.48%, respectively.

Moreover, as the aging temperature increased to 220 °C, the elongation of the samples was increased by 52.06%, 75.77%, 57.98%, and 94.57% compared to the samples aged at 160 °C. This signifies that the samples aged at a higher temperature (220 °C) for a longer duration have shown high percentage elongation at break. As it was discussed in the previous sections, thermal aging of the EP woven fabrics at 220 °C reduced the tensile strength of the fabric; however, from the above elongation analyses, the increase in aging temperature significantly increased the elongation property of the fabric under the aging conditions considered in this work. This is due to the fact that thermal energy can cause the free movement of polymer chains in the fiber, which consequently enhances the elongation property of the fabric under a tensile load. It is also important to note that trivial percentage elongation changes were observed because of the duration of thermal aging, regardless of the sample types.

In general, the analyses conducted on the mechanical property of resorcinol-formaldehyde-latex adhesive chemical dipped EP woven fabric sample with different nominal tensile strengths and intended to be utilized for the reinforcement of conveyor belt indicated that the tensile strength and elongation of the EP woven fabric is highly dependent on the thermal aging conditions.

In these analyses, the tensile and elongation property of the fabric samples were evaluated based on two factors, which are aging temperature and duration of aging. The study revealed that the tensile strength of the fabric was immensely reduced as the aging temperature reached 220 °C regardless of the aging duration. In contrast, the highest elongation of the fabric was also obtained at the aging temperature of 220 °C irrespective of the aging duration.

Therefore, the increase in percentage elongation and decrease in tensile strength of the woven fabrics at the aging temperatures above the glass transition temperature of polyester and polyamide fibers were linked with the polymer structural changes within the fiber structure. Additionally, the contribution of resorcinol-formaldehyde-latex adhesive chemical to the elongation of woven fabric samples was significantly observed.

In conclusion, the fabric used to reinforce the conveyor belt is expected to have a lower elongation at break while having high tensile strength. Therefore, the vulcanization parameters during conveyor belt production must be defined based on the fiber composition of the fabric carcass and appropriately controlled to achieve these requirements.

6.3 Analysis of EP Woven Fabric Reinforced Conveyor Belts

6.3.1 Effect of Vulcanization Parameters on the Tensile Strength of Textile Reinforced Conveyor Belts

Vulcanization is the crucial process of adhering the conveyor belt components under the application of temperature and pressure. Therefore, the influence of vulcanization parameters, primarily vulcanization temperature and duration of vulcanization on the components of the conveyor belt was analyzed meticulously to understand how the tensile property of the fabrics used for the reinforcement can be affected by this process.

Figure 56 presents the tensile strength of conveyor belts reinforced with three plies of EP woven fabric produced under the vulcanization temperature of 140, 160, and 220 °C for six and thirty-five minutes. The results signify that vulcanizing textile-reinforced conveyor belts under different vulcanization temperatures, irrespective of the duration of vulcanization, impacts the conveyor belts' tensile strength. As the vulcanization temperature increased from 140 °C to 160 °C for 6min and 35min, the tensile strength was incremented by 2.0% and 2.27%.

However, as the vulcanization temperature rose from 140 °C to 220 °C for 6min and 35min, the tensile strength was decremented by 39.80% and 88.81%, respectively. Additionally, an increase in vulcanization temperature from 160 °C to 220 °C for 6min and 35min reduced the tensile strength by 40.98% and 89.06%, respectively.

The conveyor belt's tensile strength was also varied depending on the vulcanization duration. The tensile strength of the conveyor belt samples vulcanized at 140 °C for a duration of 35min has 0.79% higher tensile strength compared to the samples vulcanized at 140 for a duration of 6min.

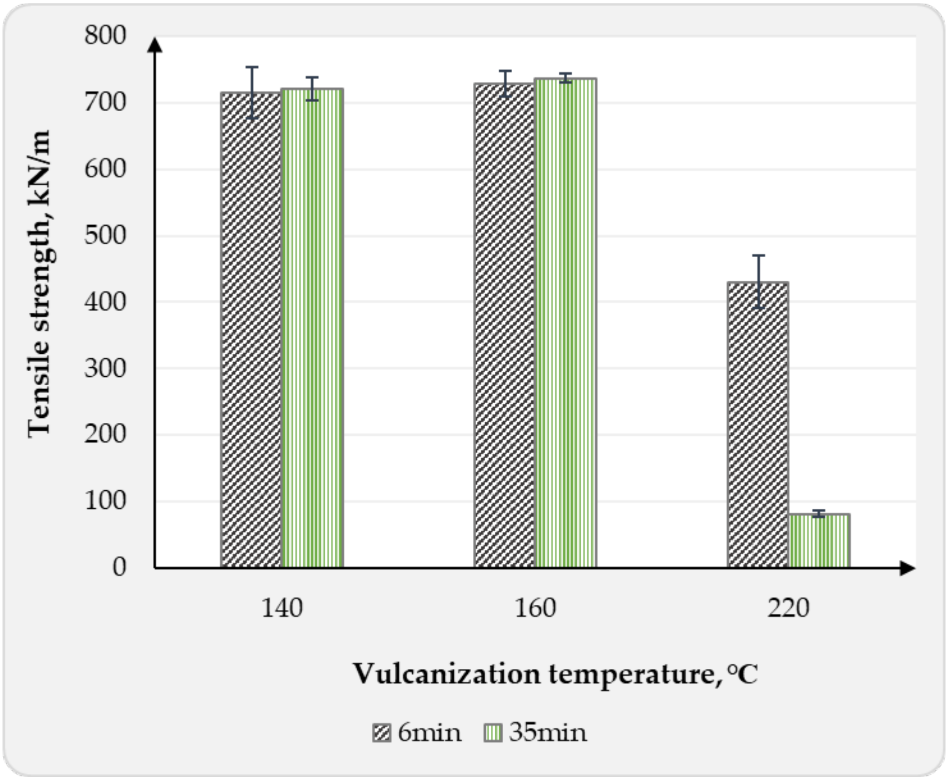

Figure 56. Effect of vulcanization temperature on the tensile strength of conveyor belts.

The sample vulcanized at 160 °C for 35 min has shown an insignificant statistical difference of 1.06% higher tensile strength compared to the sample vulcanized at 6min. However, the sample vulcanized at 220 °C for the duration of 6min has shown 81.27% higher tensile strength compared to the sample vulcanized for the duration of 35 min.

6.3.2 Effect of Vulcanization Parameters on the Percentage Elongation of Textile Reinforced Conveyor Belts

The elongation property of a textile-reinforced conveyor belt is a key property in determining the performance and suitability of the conveyor belt for a given application. The stretchability of the belt under a tensile load of a material being conveyed is expressed as an elongation property. Therefore, the elongation property determines the belt's ability to handle the load imposed on the belt during operation and the dimensional stability of the belt. Thus, the influence of vulcanization process temperature and vulcanization duration was investigated to determine the optimum temperature and time under the given pressure for three layers of textile-reinforced heavy-duty conveyor belts.

In Figure 57, the analyses of the conveyor belt elongation under different vulcanization parameters are shown. The results analysis indicates that as the vulcanization temperature roses from 140 °C to 160 °C for 6 min and 35 min, the percentage elongation of the conveyor belt was increased by 8.0% and 26.04%, respectively. The increase of vulcanization temperature from 140 °C to 220 °C for 6min increased the elongation by 20.02%. However, as the vulcanization duration changed to 35min, the elongation percentage dropped by 84.95%.

The increase in vulcanization temperature from 160 °C to 220 °C with a vulcanization duration of 6min increased the percentage elongation of the conveyor belt by 11.14%. But, as the vulcanization duration increased to 35min, the percentage elongation was reduced by 88.05%. Besides the vulcanization temperature, the duration for how long the reinforcement undergoes the vulcanization process under a specific temperature also highly influenced the percentage elongation of the conveyor belts. For example, the percentage elongation of a conveyor belt vulcanized at 140 °C for a longer duration(35min) was reduced by 10.88% compared with the sample vulcanized for the duration of 6min under the same vulcanization temperature (140 °C).

Additionally, the increase of vulcanization duration from 6min to 35min while the temperature remained at 160 °C incremented the percentage elongation of the conveyor belt by 4.0%. However, the conveyor belts vulcanized at elevated temperature (220 °C) for a longer vulcanization time(35min) have shown 88.82% lower elongation percentage than the samples vulcanized at 220 °C for 6 minutes.

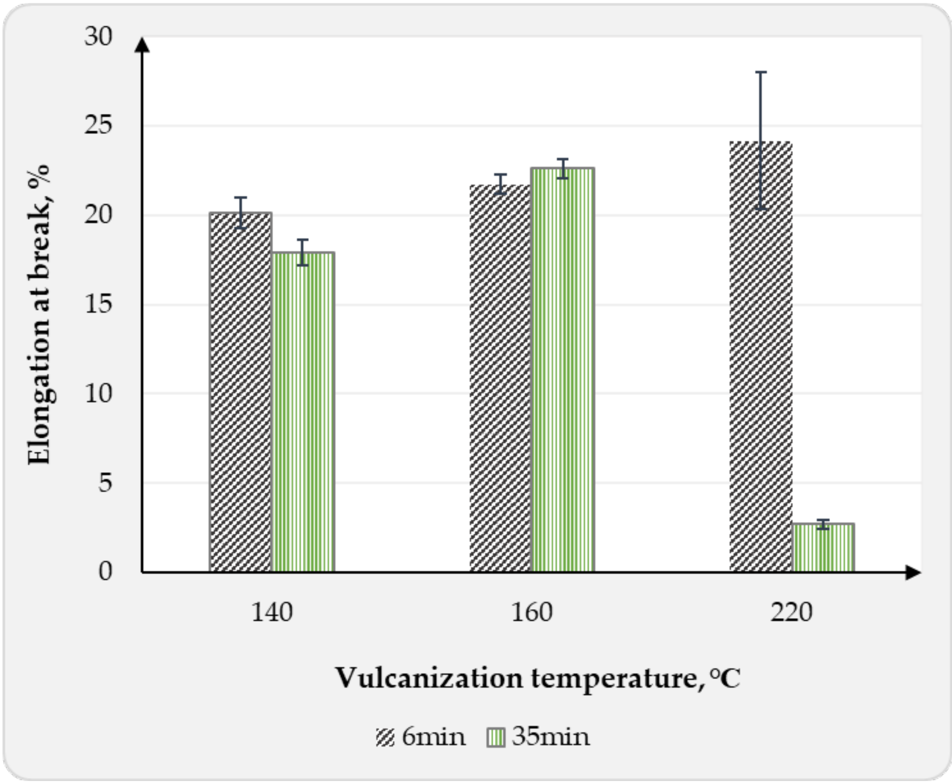

Figure 57. Effect of Vulcanization temperature on the elongation property of conveyor belts.

Therefore, the above percentage comparison between the vulcanization parameters and elongation property of the conveyor belt provides insight into the cruciality of vulcanization parameters in a textile-rubber vulcanizing process. It is also vital to know what it means to have a conveyor belt with a higher or lower elongation.

The conveyor belt with lower elongation can resist stretching during the operation, maintains the shape of the belt, and will not be bent under heavy load. This reduces the risk of the conveyor belt slippage or coming off the conveyor system during the operation.

In contrast, the conveyor belt with a higher elongation percentage increases the risk of belt slippage or coming off the conveyor system during the operation, and as a result, the conveyor belt can be damaged and causes downtime. Therefore, the percentage elongation of the conveyor belt needs to be carefully considered.

6.3.3 Effect of Vulcanization Parameters on the Tensile Properties of Woven Fabric Carcass Removed from the Conveyor Belts

Post-vulcanization, the conveyor belt components were separated from each other manually (Figure 58) before cooling to analyze the effect of vulcanization process parameters on the tensile property of EP woven fabrics that were used to reinforce the belt. Separating the conveyor belt component was only possible immediately after vulcanization; if the reinforcement is cooled, it is impossible to separate the samples without causing damage to the fabric. Of course, the effect of thermal aging parameters on the mechanical properties of EP woven fabrics was presented in section 6.2.

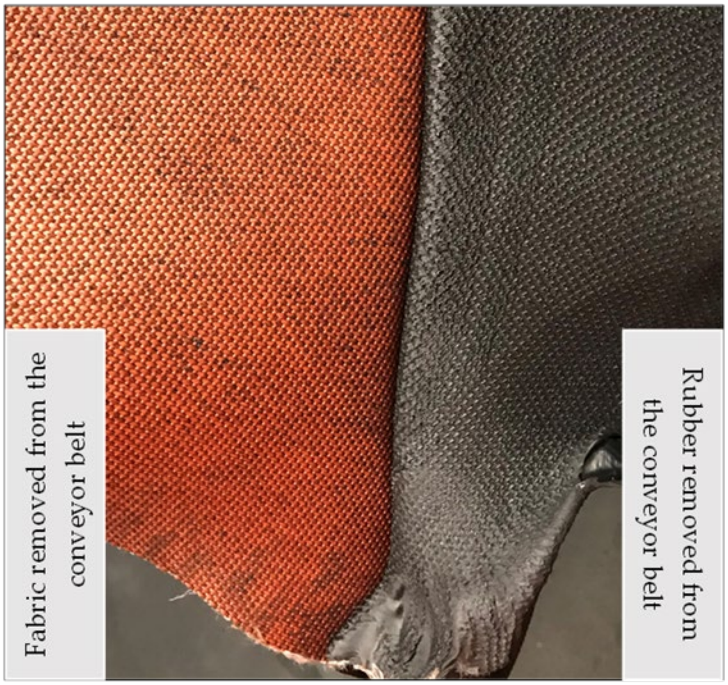

Figure 58. Woven fabric sample manually removed from sample vulcanized at 140 °C for 6min.

However, the woven fabrics were aged in the oven under free pressure (no applied pressure was imposed on the fabric), but the conveyor belt vulcanization was carried out under pressure according to the vulcanization processes adopted in the industry. Therefore, in order to understand the effect of pressure imposed on the reinforcement during conveyor belt vulcanization, a mechanical property analysis was conducted on a carcass ply of the conveyor belt. Figures 59 & 60 show the tensile strength comparison of EP 200 woven fabric aged in an industrial oven and the carcass ply removed from the conveyor belt for six and thirty-five minutes, respectively. Regardless of the aging or vulcanization parameters, the fabrics subjected to thermal aging in an industrial oven are less influenced by thermal aging compared to the fabric ply removed from the conveyor belt. Moreover, the fabric ply removed from the sample vulcanized under the temperature of 220 °C for 6 min has shown 58.11% lower tensile strength than the fabric aged in an industrial oven. As mentioned above, such a difference primarily arose from the pressure (200 Bar) applied on the reinforcement during the vulcanization of the conveyor belt.

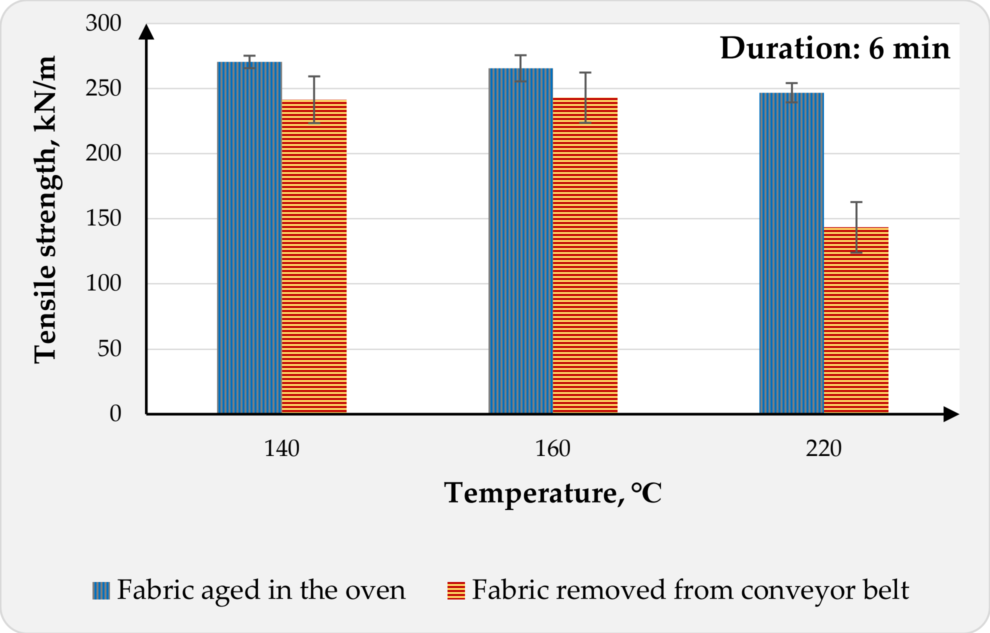

Figure 59. Tensile strength of EP 200 woven fabrics aged in the oven and removed from the conveyor belt reinforcement.

Furthermore, as shown in Figure 60, the tensile strength of fabric ply removed from the conveyor belt vulcanized under 220 °C for a longer duration (35 min) was massively reduced (86.27%) compared to the fabric aged in an industrial oven under a similar aging temperature and duration.

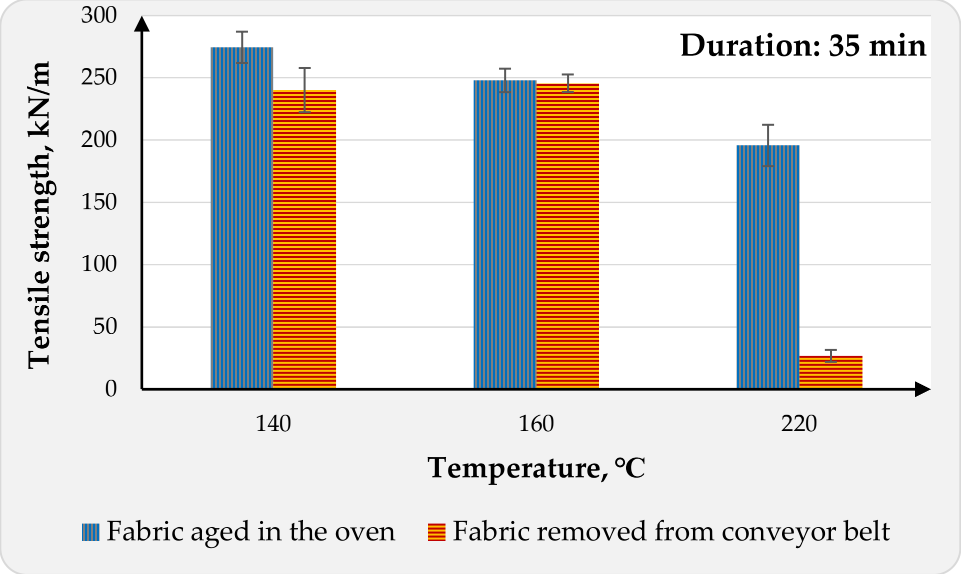

Figure 60. Tensile strength of EP 200 woven fabrics aged in the oven and removed from the conveyor belt reinforcement.

In addition to the tensile strengths, the percentage elongation at break of the EP woven fabric ply removed from the conveyor belt was also analyzed and graphically presented in Figures 61&62. Figure 61 shows the percentage elongation of fabric removed from the conveyor belts produced at six minutes of vulcanization duration and EP fabric aged in an industrial oven. The result signifies that even though the temperature and duration of the aging and vulcanization were similar, the fabric ply removed from the conveyor belt showed lower elongation at break. A significant difference of 36.56% lower percentage elongation at break of woven fabric removed from the conveyor belt vulcanized at 220 °C for 6 min was obtained compared to the sample aged in the industrial oven.

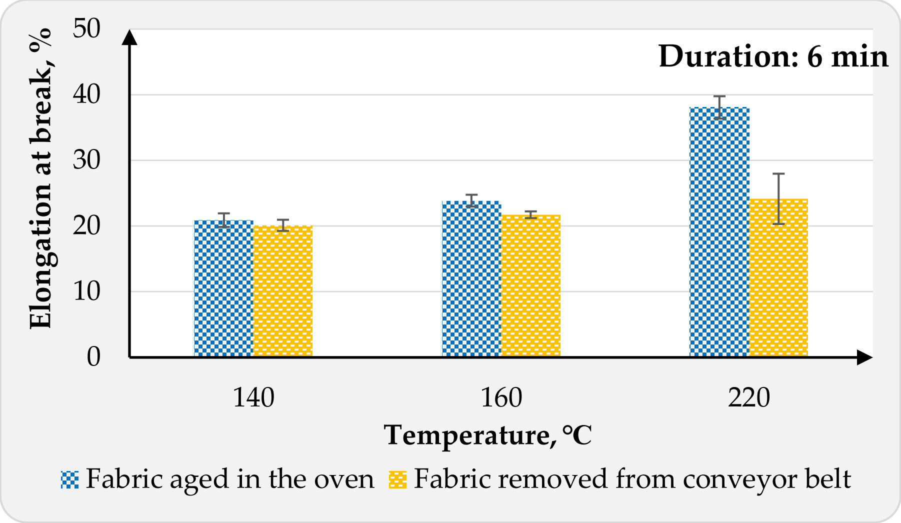

Figure 61. The percentage elongation of EP 200 woven fabrics aged in the oven and removed from the conveyor belt reinforcement.

As shown in Figure 62, the percentage elongation at break of the fabric ply removed from the conveyor belt vulcanized under the parameters of 220 °C for 35 min was significantly lower by 93.56% compared to the fabric aged in the oven.

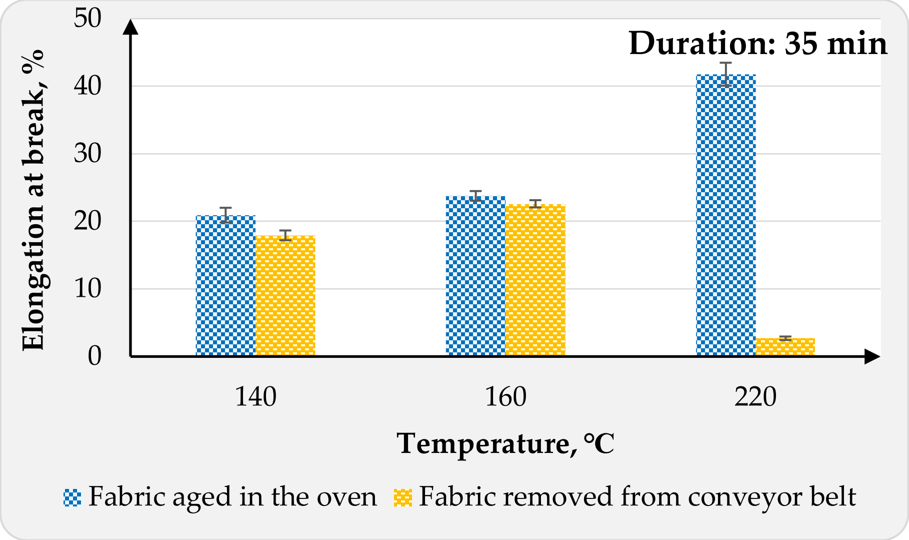

Figure 62. The percentage elongation of EP 200 woven fabrics aged in the oven and removed from the conveyor belt reinforcement.

Overall, it can be concluded that the pressure applied on the conveyor belt's reinforcement during the vulcanization process has an immense effect on the tensile properties of the fabric carcass of the conveyor belt.

The fabric's tensile property can also be destroyed at higher vulcanization temperatures (220℃) for a longer duration (35 min). Therefore, vulcanization is a crucial process in conveyor belt production, but if the process parameters cannot be controlled or appropriately determined, it can have a negative consequence on the properties of the fabric carcass as well as on the conveyor belt’s properties.

6.3.4 Effect of Vulcanization Parameters on the Adhesion Strength Between Plies of the Textile Reinforced Conveyor Belts

The adhesion between the components of the conveyor belt, such as carcass, skim, bottom, and top covers, determines the conveyor belt's durability and strength. The strong adhesion helps to avoid delamination of the conveyor belt’s components and ensures even distribution of the load across the belt. This prolongs the lifespan of the belt and prevents the belt from critical failure, which may cause downtime. Therefore, conveyors are expected to have good adhesion to maintain the integrity between the components and ensure the reliability of the conveyor belt throughout its service life. In this work, the impact of vulcanization parameters on the adhesion strength between components of the conveyor belt was investigated. Even though the overall adhesion between the components is what matters for the reliability of the belt, in this study, the adhesion between each component was thoroughly analyzed to identify where the weakest adhesion is in the belt’s components. The physical views of the component separation post-adhesion strength test for the conveyor belts vulcanized at 160 ℃ for 6 min are shown in Figure 63.

The adhesion strength of the conveyor belt is dependable on the vulcanization temperature and duration of the vulcanization. Vulcanizing textile reinforced conveyor belts with styrene-butadiene rubber covers at a lower temperature (≤140 ℃) for 6 minutes or lower causes poor adhesion between the belt plies.

As shown in Figure 63(a & d), it is visible that the adhesion between the covers and the carcass is not strong enough due to insufficient vulcanization.

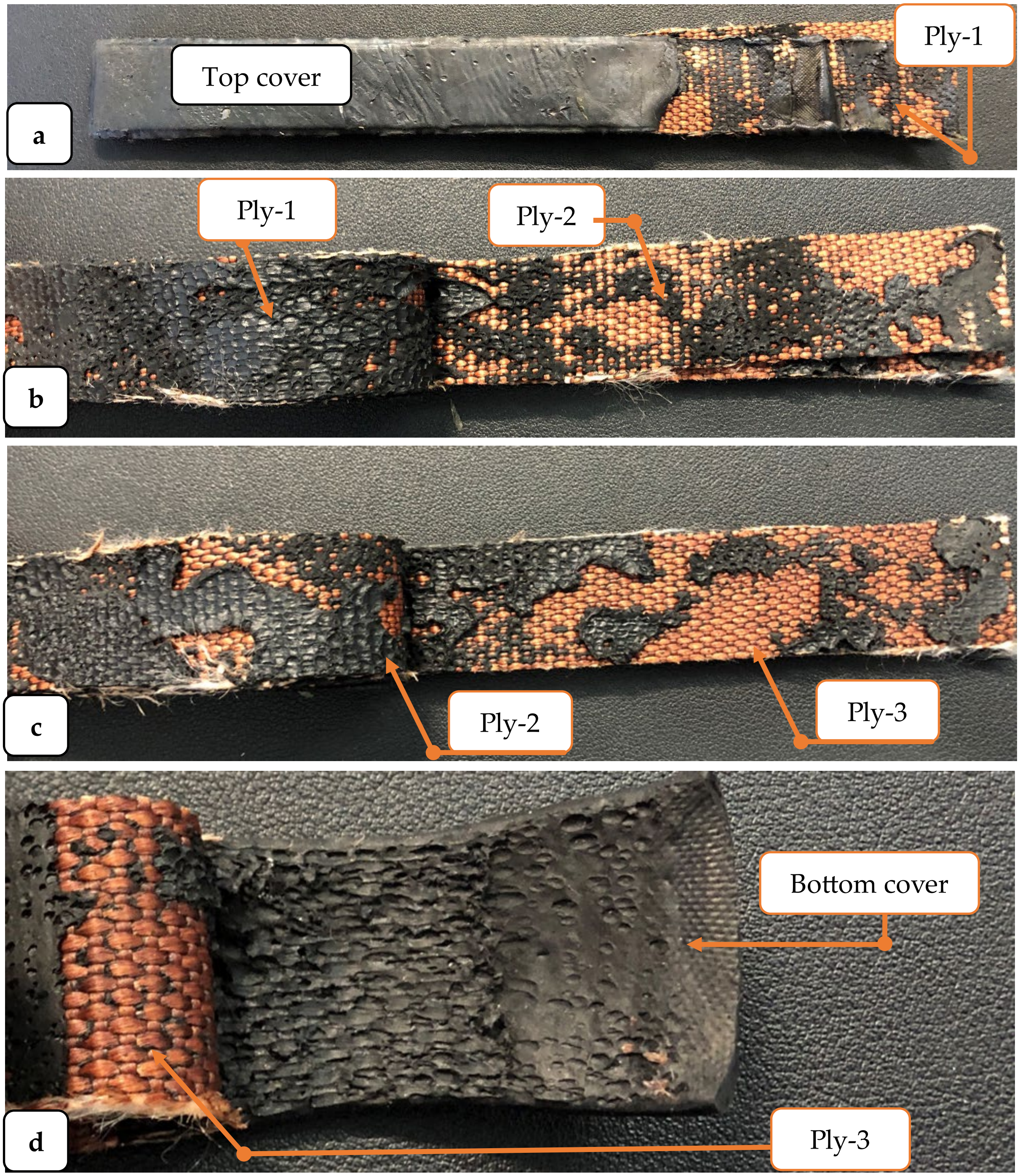

Figure 63. Plies of textile reinforced conveyor belt vulcanized at 160 °c for 6min post-adhesion strength test. (a) Top cover (TC) to ply-1(P1), (b) Ply-1(P1) to ply-2(P2), (c) Ply-2(P2) to Ply-3(P3), & (d) Ply-3(P3) to bottom cover (BC).

The adhesion between the top and bottom covers of the conveyor belt is relatively lower compared to the adhesion between the fabric plies, which is on average by 10.64%, 37.78%, and 13.75% as the vulcanization temperature changed from 140, 160 to 220 °C, respectively. This signifies that the intermolecular force between the fabric and rubber at lower vulcanization temperatures is weaker. Also, due to the difference between the physical and chemical properties of the yarn, the adhesion between the fabric and rubber is lower regardless of the vulcanization time and temperature.

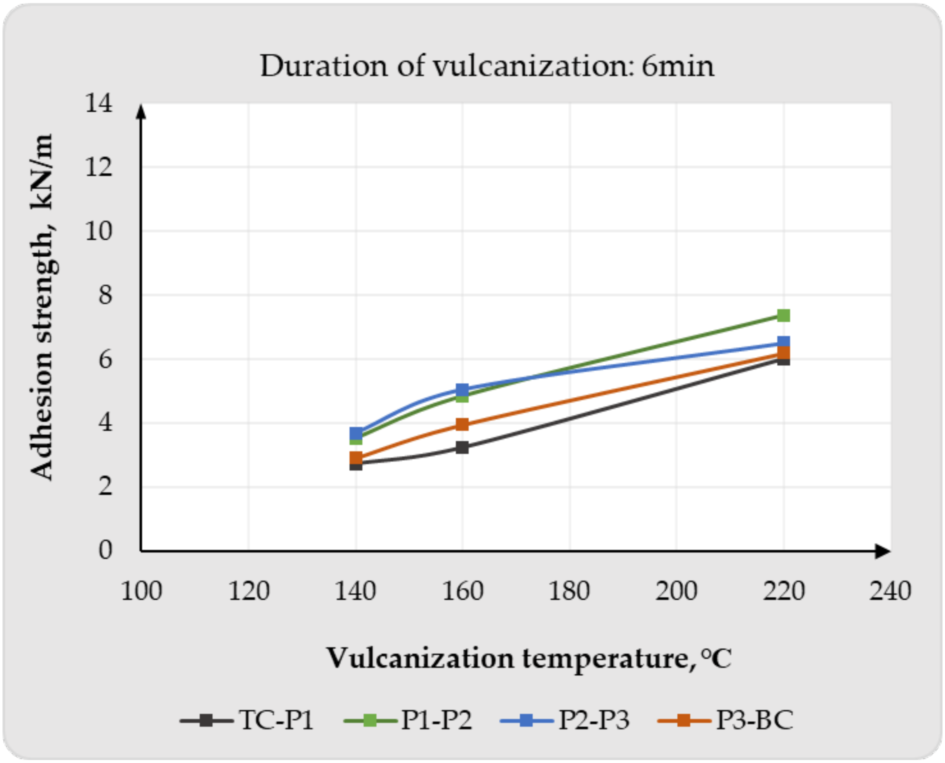

Figure 64. Effect of vulcanization temperature on the adhesion strength of conveyor belt plies.

The graph shown in Figure 64 indicates that the adhesion between all components increased with the increase of vulcanization temperature for the samples vulcanized for 6 minutes. This indicates that the lower vulcanization temperature (≤140 °C) for the short vulcanization time(≤6min) results in inadequate crosslinking of the SBR rubber molecules. This, consequently, reduces the adhesion between the rubber and fabric carcass.

The standard vulcanization temperature for the styrene-butadiene rubber is between 150 °C and 165 °C. Figure 65 presents the conveyor belt samples vulcanized at 160 °C for 35 minutes post-adhesion strength experimental test.

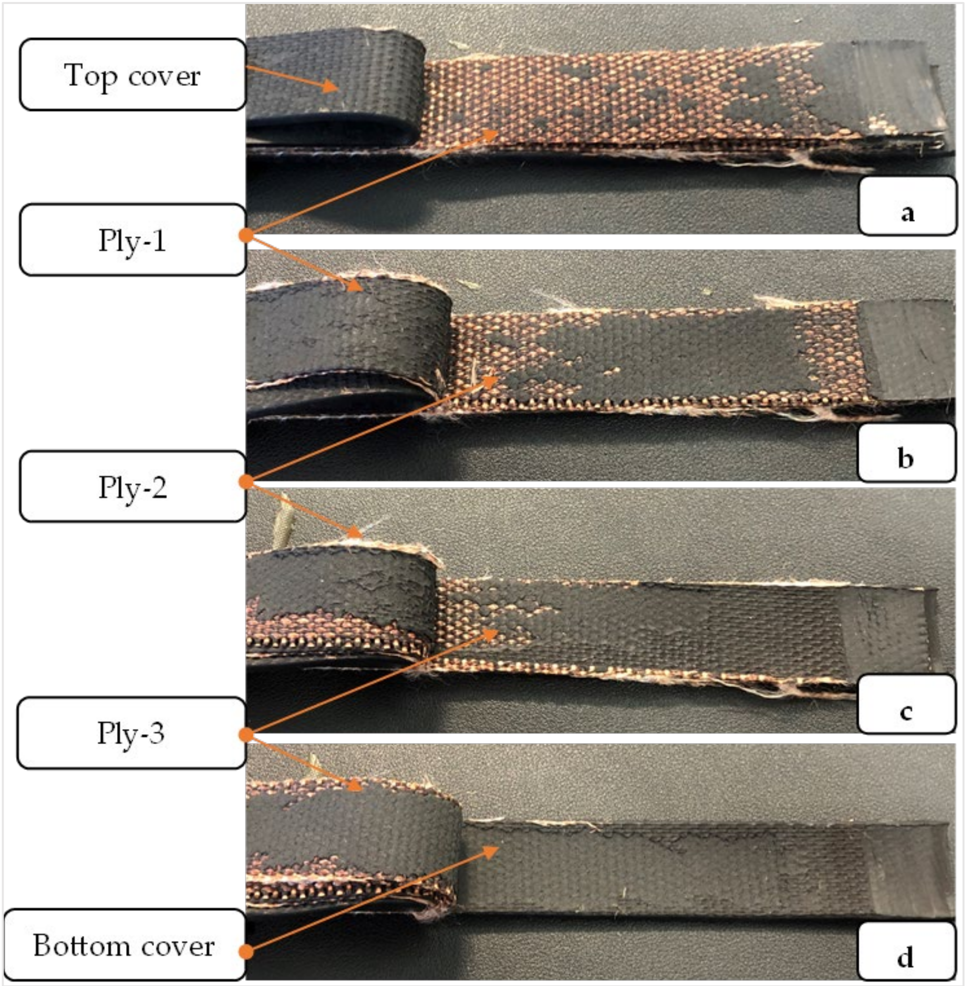

Figure 65. Plies of textile reinforced conveyor belt vulcanized at 160 °c for 35min post-adhesion strength test. (a) Top cover (TC) to ply-1(P1), (b) Ply-1(P1) to ply-2(P2), (c) Ply-2(P2) to Ply-3(P3), & (d) Ply-3(P3) to bottom cover (BC).

The impact of vulcanization duration on the adhesion strength of the conveyor belt was observed from these samples and the previously presented samples under Figure 63(a-d). The adhesion strength result of the conveyor belts vulcanized for a longer duration(35min) indicates that the adhesion between all conveyor belt components can be improved by incrementing the vulcanization temperature to certain points for the specific vulcanizing temperature.

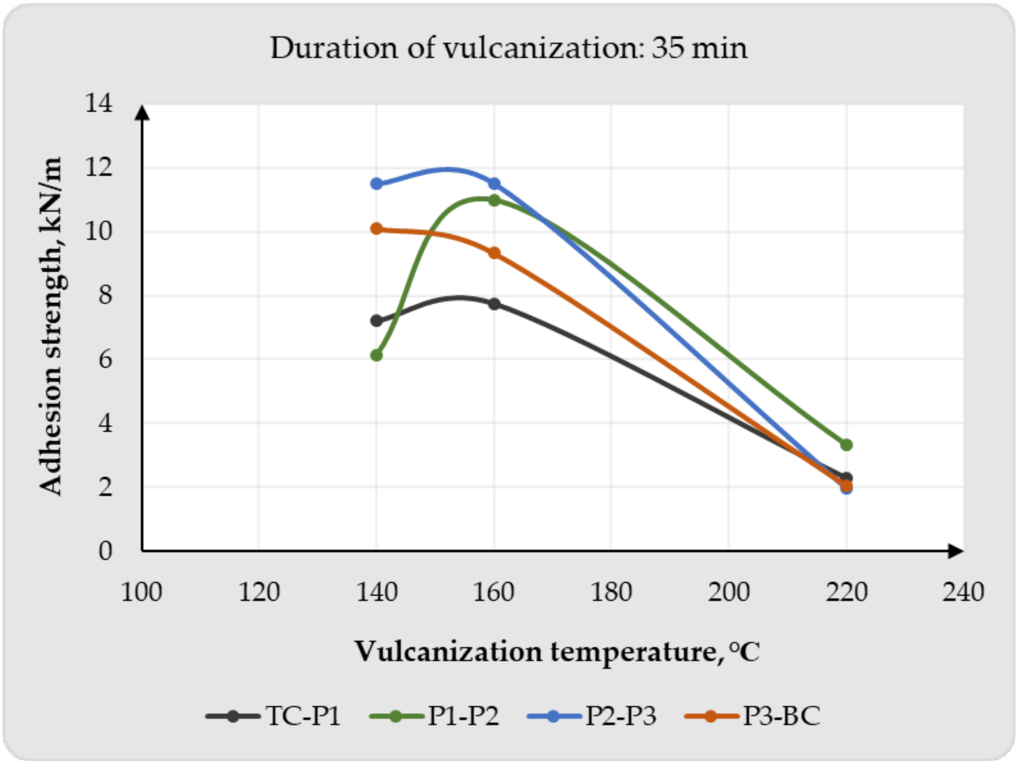

Figure 66. Effect of vulcanization temperature on the adhesion strength of conveyor belt plies.

The adhesion between the top and bottom covers of the conveyor belt to the carcass and between fabric carcasses was increased as the vulcanization temperature of the conveyor belt increased from 140 to 160 °C for the vulcanization duration of thirty-five minutes. However, as the vulcanization duration increased to 220 °C, the adhesion strength between the plies of the conveyor belt diminished, as shown in Figure 66. The decrement in the adhesion strength of the plies of the conveyor belt arose from the over-curing of the skim rubbers and cover rubbers, which destroyed the bond between the polymer chains of the rubber molecules.

6.3.5 Effect of Vulcanization Parameters on the Overall Adhesion Strength of the Textile Reinforced Conveyor Belts

The adhesion strength of the conveyor belt is determined by the overall adhesion of the conveyor belt components. In Figure 67, the influence of vulcanization temperature and duration on the properties of the conveyor belt was summed up and presented to clarify how the vulcanization parameters affected the adhesion strength of the conveyor belt. An increase in the vulcanization temperature from 140 to 160 °C for six and thirty-five minutes increased the adhesion strength of the conveyor belts by 9.63% and 13.40%, respectively.

Additionally, as the vulcanization temperature increased from 160 to 220 °C for six minutes, the adhesion strength of the conveyor belt was increased by 85%. This indicates that the adhesion strength of the conveyor belt could be improved by increasing the vulcanization temperature for a lower duration. Nevertheless, rapid vulcanization of rubber would result in the poor hardness of the top and bottom covers of the belt because of inadequate crosslinking between the rubber molecules. Therefore, this option of vulcanizing a textile-reinforced conveyor belt cannot be considered as an optimum condition. Additionally, the adhesion strength of conveyor belts vulcanized at 220 °C for a longer duration (35 min) was reduced by 75.66% compared to the belts vulcanized at 160 °C for a similar vulcanization time.

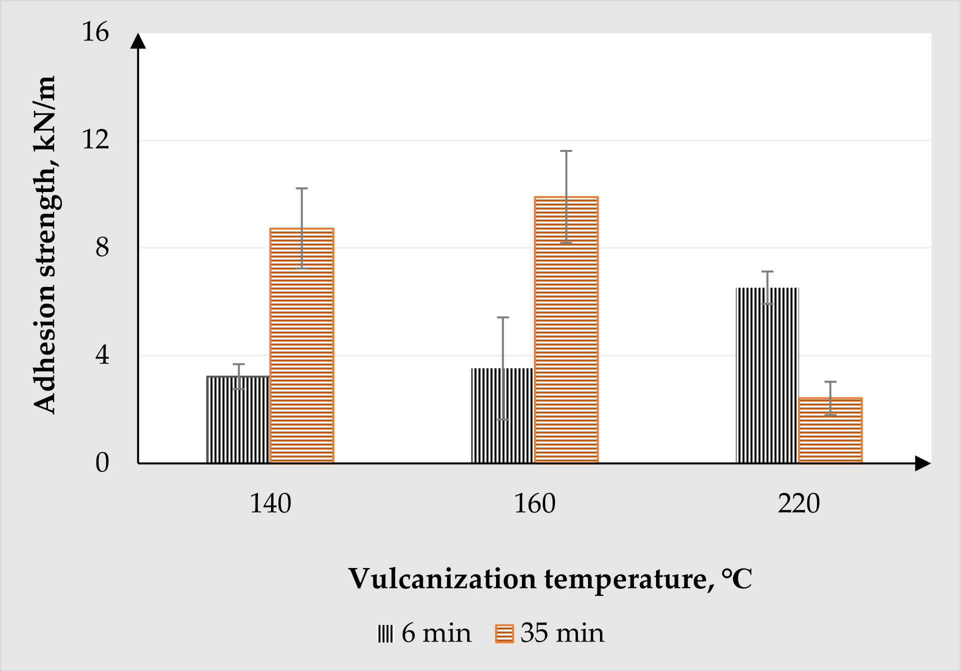

Figure 67. The overall effect of vulcanization temperature and duration on the adhesion strength of conveyor belts.

The adhesion strength between the textile and rubber materials depends entirely on several factors, including the conveyor belt's vulcanization conditions involving temperature, pressure, time, and tension [94, 134]. Overall, from the current study, it can be concluded that the adhesion strength of the conveyor belt constituent element primarily depends on the vulcanization temperature, duration, and properties of the constituent materials. Therefore, to ensure the conveyor belt components to stay intact during operation when the belt is subjected to repetitive flexing under applied load, it is necessary to develop a vulcanization condition that provides optimum adhesion strength. The adhesion strength of the belt also has an influence during connecting of the belts using the splicing technique [135]. Therefore, it is worth avoiding extremely high adhesion strength as it may create problems during the splicing process of the conveyor belt. In conclusion, based on the parameters considered for vulcanizing a three-layer of woven fabric carcass conveyor belt, an optimum adhesion strength was obtained for the conveyor belts that underwent the vulcanization process at the temperature of 160 °C for 35 min.

7. CONCLUSIONS AND RECOMMENDATIONS

7.1 Conclusions

The thesis work was aimed to contribute a novel insight into the field of textile-rubber reinforcement technologies with a primary focus on the conveyor belt carcass. Therefore, the objective of the thesis was to investigate the influence of vulcanization process parameters on the physio-mechanical properties of textile materials used in the reinforcement of mechanical rubber goods and establish an optimum vulcanization temperature and time for a specific type of conveyor belt.

To accomplish the objective of the thesis, an extensive experiment was developed to analyze the influence of thermal aging on the high tenacity polyester yarn and EP woven fabric, and the impact of vulcanization parameters on the textile-reinforced conveyor belts' physio-mechanical properties in collaboration with Sempertrans Ltd. conveyor belt producing company. The thermal aging parameters for the yarn and fabric were designated based on the fiber's melting temperature and glass transition temperature. Additionally, the vulcanization parameters of the conveyor belt were defined by considering the results obtained from the woven fabric and yarn investigations, the vulcanization parameters adopted at Sempertrans Ltd. company, the maximum temperature of the vulcanizing machine, ultimate thermal property of the rubber being used in the reinforcement, and the safety of workers during the vulcanization process. The physical and mechanical properties of the high-tenacity polyethylene terephthalate yarn, polyester-polyamide (EP) woven fabric, and textile-reinforced conveyor belt were thoroughly investigated at different processing levels under defined thermal aging and vulcanization conditions.

The following conclusions of the thesis are drawn based on the research conducted on the high tenacity polyester yarns, EP woven fabrics, and textile-reinforced conveyor belts.

- The finding signified that the physical and mechanical properties of textile yarns and fabrics were determined by the condition under which these materials operate. Besides this, the mechanical properties of the conveyor belt reinforced with the textile carcass were also affected by the properties of the woven fabric and the processing parameters.
- Thermal aging of high tenacity polyethylene terephthalate yarns and EP woven fabrics above the glass transition temperature of polyester fiber (≈180 ℃) and below the melting point (≈262 ℃) led to the modification of the fiber's internal structure and caused the deterioration of the polyester yarn and EP fabrics tensile strength.
- Thermal aging of high tenacity polyethylene terephthalate yarns and EP woven fabrics and conveyor belt vulcanization at a temperature of ≥ 220 ℃ lead to a significant increase in percentage elongation of yarn and fabric, which the percentage of increase depends on the duration of the thermal aging. Therefore, thermal aging of PET yarns and EP woven fabrics or vulcanizing EP fabric-reinforced conveyor belts at or above 220 °C will lead to the deterioration of tensile strength and incrementation of percentage elongation under a minor applied load.
- High conveyor belt elongation leads to power fluctuation on the drive-sharing rollers, causes burning out of the driving motor, and reduces the service life of the belt. Therefore, vulcanizing textile-reinforced conveyor belts ≥ 220 °C can lead to such a problem.
- Vulcanization of the conveyor belt at a temperature ≤ 160 °C for the minimum duration of vulcanization (≤ 6min) results in the dimensional instability (under-curing of top and bottom cover rubbers) of the belt. On the other hand, vulcanizing the conveyor belt at ≥ 220 °C for ≥ 35 min causes over-curing of the rubber and reduces the adhesion strength between the components of the conveyor belts.

- Therefore, rapid vulcanization of three layers of EP woven fabric reinforced conveyor belts could result in inadequate crosslinking between the rubber molecules. Also, prolonged vulcanization could cause the over-curing of the rubber molecules.

Overall, this thesis work underlined the impact of the vulcanization process on the physical and mechanical properties of EP woven fabric utilized as a conveyor belt carcass. Furthermore, the work conducted proved the validity of the hypothesis that thermal aging can cause physio-mechanical deterioration of the textile-reinforced conveyor belt were vulcanizing the EP woven fabric-reinforced conveyor belt at a high temperature (≥ 220 °C) for a longer duration (≥ 35 min) yields a lower tensile strength of the belt and increases the elongation of the belt. This causes malfunctioning of the belt and reduces the lifespan of the conveyor belt. Hence, the glass transition and the melting temperature of fibers in the fabric composition need to be considered to design the vulcanization parameters of textile-reinforced conveyor belts.

Therefore, determining vulcanization parameters that yield optimum tensile strength and elongation of the conveyor belt was compulsory for the effective functioning of the belt. The work concluded that the vulcanization temperature and duration of vulcanization have an immense influence on the tensile strength and elongation property of the textile-reinforced conveyor belts. Therefore, based on the thermal aging and vulcanization parameters considered in this work and experimental investigations conducted on the yarns, fabrics, and conveyor belts, the vulcanization parameter of 160 °C for 35 minutes was found to be an optimum parameter to vulcanize three layers of the textile-reinforced conveyor belt. The results obtained from this work have resulted in the introduction of an optimal production process for Sempertrans Bełchatów Ltd.'s conveyor belt producing company.

7.2 Recommendation for Future Work

This thesis unfolded various unknowns in the field of textile-reinforced conveyor belts, and one of the main questions during the production of the textile-reinforced conveyor belt was to know what is happening on the textiles during the vulcanization of the rubber with the textile. An effort has been made to answer this question in the current work. However, the work of this thesis was only limited to the effect of temperature and duration of vulcanization on the physio-mechanical investigation of the polyester yarns, EP woven fabrics with plain weave, and three layers of EP woven fabric reinforced conveyor belts.

Therefore, in the future, it is suggested to also conduct research on woven fabrics with various weave structures, mainly on fabric with twill and broken twill weave types, fabric woven from polyamide warp and polyamide weft yarns, and the conveyor belt with higher than three layers of fabric carcass.

There is significant potential for improving the mechanical properties of the conveyor belt by manipulating the processing parameters of the conveyor belt and the structure of textiles used for the carcass of the belt. It is recommended to conduct analysis on various processing parameters using the finite element analysis software before conducting experimental tests.

Finally, during the designing of the vulcanization process, it is recommended to take into account the thermal properties of the fibers in the fabric composition to achieve high-quality conveyor belt properties.

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