MARMARA UNIVERSITY
FACULTY OF ENGINEERING

DETERMINATION OF MATERIAL PROPERTIES OF INDUSTRIAL PAPER MOLD PACKAGING MATERIALS

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Determination Of Material Properties of Industrial Paper Mold Packaging Materials

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ABSTRACT

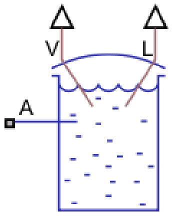
This thesis investigates the properties, production processes, modeling and applications of molded pulp packaging as a sustainable alternative to traditional packaging materials.

With the increasing awareness of environmental problems, environmentally friendly packaging has begun to emerge as an alternative in many sectors. One of the most important of these alternatives is pulp packaging obtained by recycling wastepaper. There are many advantages that lead to the preference of pulp packaging. The most prominent of these are its sustainability, lightweight structure and cost-effectiveness compared to alternatives. In addition, it can be more durable when designed appropriately.

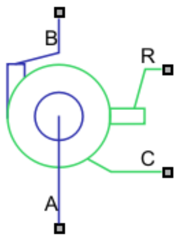
It is important to know how resistant these products are to various stresses during the design and production stages of pulp packaging. Understanding the properties of these materials is critical to calculating these stresses. The aim of this study is to experimentally determine the material properties of pulp packaging. In this study, samples from different types of pulp will be taken and their elastic moduli will be determined experimentally in a laboratory environment. In addition, compressed air and vacuum systems included in the production line were modeled and analyzed to optimize production efficiency and ensure consistent product quality. Data from this study is expected to help packaging designers and manufacturers use pulp packaging more effectively.

Keywords: molded pulp packaging; simulation; sustainability.

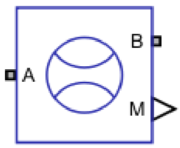
SYMBOLS



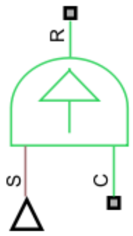
Tank: The block represents a storage tank within an isothermal liquid network, incorporating a constant pressurization mechanism and a configurable number of inlet ports. The liquid surface pressure is presumed to be equal to the applied pressurization. Additionally, the model accounts for the hydrostatic pressure gradient between the liquid surface and the inlets, as well as pressure losses occurring at the inlets due to localized resistances.



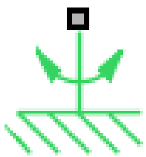
Centrifugal Pump: This block models a centrifugal pump in an isothermal liquid network, characterized by head and brake power as functions of pump capacity, with flow and pressure relationships defined by affinity laws. Ports A and B represent the liquid inlet and outlet, while ports R and C correspond to the drive shaft and casing. The pump operates with flow from port A to port B, and performance under reverse rotation is undefined.



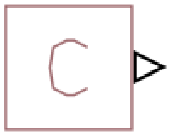
Flow Rate Sensor: This block measures mass or volumetric flow rate in an isothermal liquid network without causing a pressure drop. Ports M and V provide mass flow and volumetric flow signals, respectively, with positive flow direction from port A to port B.



Ideal Angular Velocity Source: This block represents an ideal angular velocity source that generates a velocity difference between its terminals based on the input signal. It assumes infinite power to maintain the specified velocity, regardless of the applied torque. Ports R and C are mechanical rotational conserving ports, and port S is a physical signal port for the control input. The relative angular velocity is defined as $W=W_R-W_C$, where W_R and W_C are the angular velocities at ports R and C, respectively.



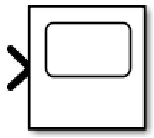
Mechanical Rotational Reference: This block represents a mechanical rotational reference, serving as a fixed frame or ground. It is used to connect mechanical rotational ports that are rigidly attached to the frame.



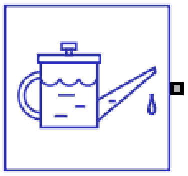
PS Constant: This block generates a constant physical signal, defined as:

y=constant

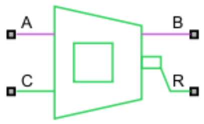
The Constant parameter can take positive or negative values, and the output is provided through a physical signal port.



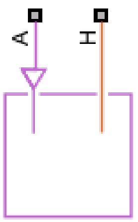
Scope: It is used to display signals generated during simulation.



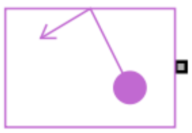
Isothermal Liquid Predefined Properties: This block supplies isothermal liquid properties to the connected isothermal liquid network and provides a selection of predefined liquids.



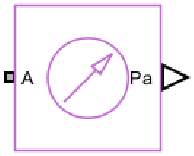
Positive-Displacement Compressor: This block models a positive-displacement compressor in a gas network, applicable to types like reciprocating piston, rotary screw, rotary vane, and scroll. It draws in gas and expels it at higher pressure. Ports A and B are for gas inlet and outlet, while Ports R and C are for shaft and casing. Positive rotation at Port R drives flow from A to B; reversed flow or rotation is undefined.



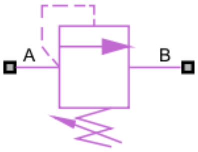
Constant Volume Chamber: This block models mass and energy storage in a gas network, with a chamber containing a constant gas volume. The pressure and temperature within the chamber evolve according to the gas' dynamic compressibility and thermal capacity. Ports A, B, C, and D are gas conserving ports corresponding to the chamber's inlets. Port H is the thermal conserving port linked to the thermal mass of the gas volume.



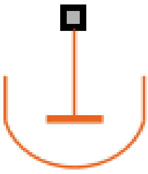
Gas Properties: This block provides gas properties to the connected network, supporting perfect, semi-perfect, or real gas models. Perfect and semiperfect gases follow the ideal gas law, with semiperfect gas properties depending on temperature. Real gas properties are temperature and pressure-dependent, specified in two-dimensional arrays. The default gas is dry air.



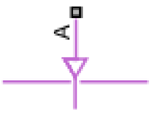
Pressure & Temperature Sensor: This block measures pressure and temperature in a gas network without any mass or energy flow through the sensor. Ports P, Pa, and Pg report the pressure difference, absolute pressure, and gauge pressure at port A, respectively. Port T reports the temperature at port A or across the sensor. Pressure and temperature differences are positive when the value at port A is greater than at port B.



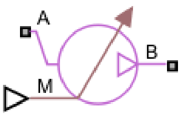
Pressure Relief Valve: This block models a pressure relief valve in a gas network. It opens when the set pressure is reached, allowing gas flow. The opening pressure can be defined as the pressure difference or gauge pressure at port A. Choking occurs at the critical pressure ratio, with no heat exchange with the environment.



Perfect Insulator: This block represents a terminus in a thermal network with no heat flow or energy storage. It acts as insulation for thermal conserving ports to prevent heat exchange with the environment and model an adiabatic process. Additionally, it can set an initial temperature value and priority at the connected port.



Reservoir: This block sets constant boundary conditions in a gas network, assuming an infinite gas volume inside the reservoir for quasi-steady flow. Gas leaves the reservoir at its pressure and temperature, while gas entering the reservoir is at the reservoir pressure, with temperature determined by the upstream gas network.



Flow Rate Source: This block represents an ideal mechanical energy source in a gas network, maintaining a constant or controlled mass or volumetric flow rate regardless of the pressure differential. It introduces no flow resistance and no heat exchange with the environment. A positive value causes gas to flow from port A to port B.

ABBREVIATIONS

AKD: Alkyl Ketene Dimer

CAD: Computer Aided Design

CD: Cross-Direction

CNF: Cellulose Nanofiber

EFB: Empty Fruit Bunch

EPS: Expanded Polystyrene

FP: Fruit Pomace

IMFA: International Molded Fiber Association

LCA: Life Cycle Assessment

MD: Machine-Direction

MFD: Molded Fiber Product

MPP: Molded Pulp Product

NP: Newspaper

OCC: Old Corrugated Container

ONP: Old Newspaper

SEM: Scanning Electron Microscope

1. INTRODUCTION

The use of single-use plastics for humans has become extremely widespread due to the low cost, lightness, high performance and ease of processing of plastics and related products. However, with this increase in single-use plastic production, plastic pollution has become one of the most urgent environmental problems that threatens aquatic animals and even human health, as most of these fossil-based plastics cannot be biodegraded. Increasing concerns about the negative effects on the environment, increasing environmental awareness and lifestyle against plastic pollution have led people to seek green/sustainable alternatives.

Molded pulp packaging, with its renewability, recyclability, sustainability, and biodegradability, stands as an innovative solution addressing the growing demand for green and sustainable alternatives. Molded pulp products, often made from recycled cellulosic fibers, are increasingly used for packaging and shipping three-dimensional objects. Although MPPs have been limited to the egg tray market for many years due to form (geometry) and aesthetic constraints, the use of molded pulp systems has recently been increasing for the packaging of electronics and special products, in line with the increasing demand due to their sustainable qualities.

Increased R&D efforts with standardized design and testing practices are essential to meet the growing demand for eco-packaging with high-quality features. The aim of this thesis is to determine the production process and final state of MPP; also analyze our tensile testing and modeling results to control process variables such as pressure, temperature, and durability. This study will also provide an overview of the environmental sustainability of MPP by examining various life cycle stages such as production, use and life cycle.

2. LITERATURE REVIEW

In this chapter, relevant information from the literature concerning molded pulp packaging is compiled. The literature review is organized under several key headings, including the classification of the material, its advantages and potential disadvantages during use, historical development, areas of application, production processes, environmental sustainability characteristics, composition, and material properties.

2.1.Molded Pulp Product Classes

Molded pulp has been classified in different ways over the years. These classifications were made according to the production process, product density and manufacturing method. Then, according to the guidelines published by the International Molded Fiber Association (IMFA) [1], classification is made as Figure 1.

Category	Mould requirement	Raw material	Product characteristics	Application
Thick wall	Open mould with a smooth inner surface and rough outer surface	A blend of kraft paper and recycled paper	Thick walled product with 5-10 mm thickness	Support packaging for non-fragile and heavy items
Transfer Mould	A forming mould and a transfer or take-off mould	Recycled newspaper	Relatively thin walled (3-5mm thickness) with relatively smooth surfaces on both sides and better dimensional accuracy	Egg trays and packaging for electronic equipment
Thermo-formed (thin wall)	Hot press mould	Partially formed products using paper and pulp.	high-quality, thin-walled products with thickness ranges from 2 to 4 mm and with good dimensional accuracy and smooth rid surfaces	Various thermoformed items.
Processed	Not Applicable	Paper and pulp products that require special treatment	Printed /coated surface	printing, coatings, or additives

Figure 1: Characteristics, Requirements, Raw Materials Used and Application of Various Types of Molded Pulp Products

The production process for thick-wall molded pulp products is shown in Figure 2.[2] It begins with an aqueous fiber suspension in a vat. A porous mold is lowered into the vat, and a vacuum pulls the fibers and any additives toward the mold's screen. The mold, now containing a moist pulp layer, is taken out of the vat. Then, the pulp product is separated and dried in an oven. These thick-walled items are primarily utilized as robust packaging for heavy or durable goods such as furniture and automotive components during transit.

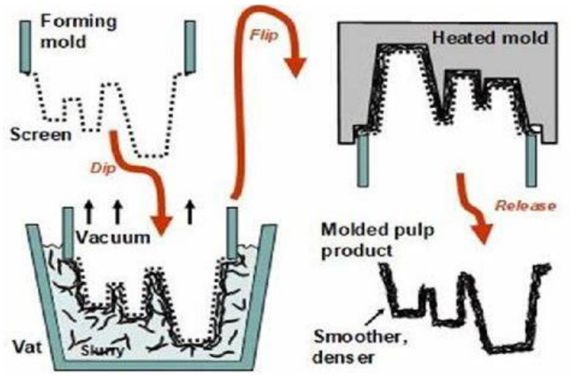


Figure 2:Schematic illustration of thick-wall process

The second category, "transfer molded" products, features thinner walls (3–5 mm) with relatively smooth surfaces on both sides and improved dimensional precision. Common applications include egg trays and electronic equipment packaging. The third type, known as "thermoformed" or "thin-wall," is a more advanced approach. These products have thicknesses of 2–4 mm, with rigid and smooth surfaces and excellent dimensional accuracy. In this process, heated molds compress, densify, and dry the product. Thermoformed pulp items are often used as eco-friendly alternatives to thermoformed plastic products. As shown in Figure 3, the process initially resembles the one for thick-wall products. However, for transfer-molded items, the damp pulp is pressed against a matching surface, resulting in smoother finishes on both sides.

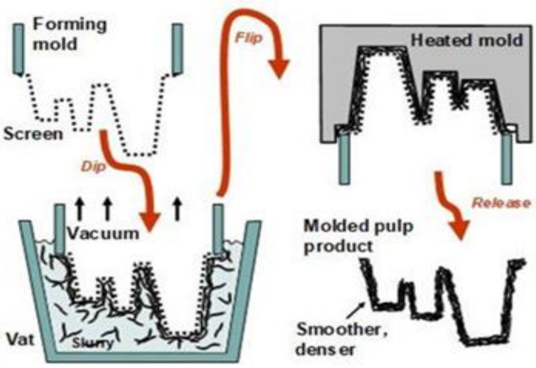


Figure 3: Schematic illustration of transfer molded process

The final category, "processed" products, involves additional steps like printing, coating, or adding specific treatments to enhance functionality.

2.2.Advantages and Disadvantages of Molded Pulp Packaging

Molded pulp products, also called molded pulp or molded fiber products, are used in many fields from electronics to food, in the packaging of manufactured products and as carriers such as food containers and serving trays. Although molded pulp packaging has had a limited market area for many years due to aesthetic limitations, demand is increasing day by day as it is an environmentally friendly and sustainable packaging material made from recycled paper, cardboard or other natural fibers.

The unique characteristic of molded pulp lies in its eco-friendly qualities; it is entirely biodegradable, compostable, and recyclable. These attributes position molded pulp as a sustainable alternative to traditional materials, aligning well with the increasing global demand for environmentally conscious packaging solutions across various industries. This shift is being embraced by the packaging sector, with support from governments and the rising expectations of consumers.

Several significant trends directly influence the molded pulp packaging market. The boom in e-commerce has heightened the need for protective and sustainable packaging options, making molded pulp an appealing choice. Its exceptional cushioning and shock-absorbing capabilities ensure the protection of delicate items during transit, solidifying its status as the preferred option. With increasing environmental awareness, the search for not only product protection features but also sustainable solutions are increasing, which increases the need for environmentally friendly packaging features of molded pulp.

One of the disadvantages of the molded pulp industry is the cost factor. The manufacturing process can be more costly than some other materials, which may be a deterrent for some manufacturers and may force them to divert to other alternatives.

In addition, material resource limitations are also a negative situation. Innovations in material sourcing focused on more efficient extraction of recycled paper materials can help reduce production costs and further increase the adoption of molded pulp packaging by increasing its affordability.

Its limited permeability to moisture, water and some chemicals may cause the packaging to not be effective if exposed to moisture, water and chemicals, and may cause the packaging to be damaged and lose its functionality [3].

2.3.History of Molded Pulp Packaging

The method of making molded products from wood pulp first began in the mid-1800s, when paper prices decreased with the increase in newspaper and book distribution, resulting in a search for new applications. The production of pulp products first began in North America in 1903 with an apparatus patented by Martin L. Keyes from Massachusetts [4] .The working principle of Keyes' invention can be explained as applying suction to a perforated mold immersed in the pulp slurry, thus adhering the slurry layer to the mold. The other side of the mold moves inward, allowing the dough to take proper shape under pressure. By proper application of pressure and suction, the pulp layer remains with the moving face of the mold; From here, the product is transferred to a conveyor belt by a third arm, also using suction. The product is dry enough to maintain its shape in this part and moves with the conveyor belt towards the oven to dry further. Canadian inventor Joseph Coyle designed molded pulp as egg packaging, but production machines were not developed until after the World War I.

The claims of most egg patents state that the invention can be applied to all kinds of breakable objects, such as fruits, light bulbs, and radio tubes. In 1920, multi-purpose packaging that could be used for all kinds of breakable items such as light bulbs and fruits was patented [5]. Since then, the use of molded pulp products has increased in many areas. An example of these patented applications includes the US patented packaging for a handset telephone by from 1940 [6].

Towards the end of the 1980s, consumers began to become curious about the environmental impact of the products they purchased. This caused the molded pulp industry to start producing innovative solutions.

In the mid-1990s, several Life Cycle Assessments (LCAs) were published (e.g., Luxenhofer, 1996) that “proved” that EPS was more environmentally friendly than molded pulp; Many of these studies were commissioned directly by the EPS industry. At that time, the weak points of molded pulp were its weight, energy consumption for drying ovens and water pollution. Particularly in the last two areas, significant progress has been made in the last decade (Goddard, 1996). Many sources have also shown that properly designed molded pulp can be more volume efficient than EPS, thus allowing smaller pack sizes (De Bever et al., 1996, Eagleton, Marcondes 1994, Lambourne, 1990). As Wever (2005) [7] shows for most Consumer Electronics, the density of packaged products is low enough that volume is the limiting factor in transportation efficiency. Therefore, the good cushioning properties of molded pulp provide a second environmentally positive property.

As interest in the material increased due to its positive environmental profile, production possibilities also improved. Advances in deinking technology result in a much lighter shade of gray, which greatly improves the quality appearance of the material (Van den Berg, 1995). Colored trays are also possible by dyeing the slurry (Hogarth, 2005). Another development is post-printing (Goddard, 1996). Due to the manufacturing process, standard molded fiber has a fine mash pattern resulting from the mold on one side and a rather rough surface on the other side. When the molded fiber shape is subsequently pressed, both sides can have a very smooth appearance.

Due to the high cost of the mold, it is important to get the design right the first time and therefore to know the appropriate design rules. The first study to examine the relationship between geometry and cushioning properties in the 1990s (Eagleton and Marcondes, 1994) did not find any relationship. Later studies showed that truncated cones have the best properties (Hoffmann, 2000, De Bever et al. 1996). Later scientific studies attempted to apply finite element modeling to understand more complex shapes (Guruv, 2003). This produced promising results, but still presents some problems be it can be applied in cushion design [8].

2.4. Molded Pulp Packaging Samples

Molded pulp packaging is becoming increasingly popular as an environmentally friendly and sustainable packaging solution. It has a wide range of uses in various industries, from electronic products to cosmetics, from food to health. As the sustainability trend in the packaging industry continues, it is anticipated that the uses of molded pulp packaging will expand further. Molded pulp packaging is widely used in the following industries:

Food and Beverage: They often offer protection and breathability for eggs, fruits, vegetables, meat and other food products and can be easily stacked.

Figure 4: Food and Beverage Packaging

Electronics: Molded pulp packaging provides shock absorption and insulation properties to protect devices during shipping or to protect sensitive electronics.

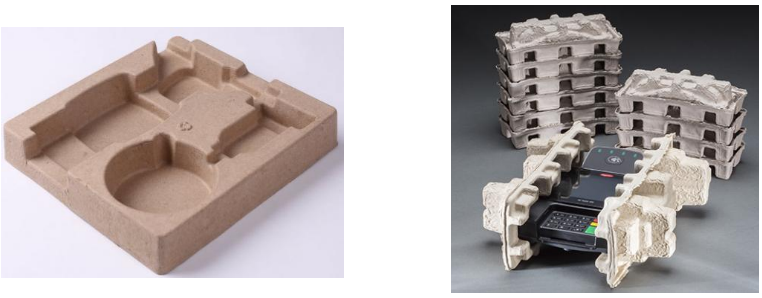


Figure 5: Electronic Packaging

Health and Medicine: Molded pulp packaging can be designed to provide protection, meeting requirements for safe and sterile packaging of medical instruments, devices and laboratory equipment.

Figure 6: Health and Medicine Packaging

Automotive: Used for packaging automotive parts during transportation and storage. They provide protection against scratches, impacts and vibrations.

Figure 7: Automotive Packaging

Agriculture: There are also models that can be used in packaging food for animals and as breeding stations for beneficial insects.

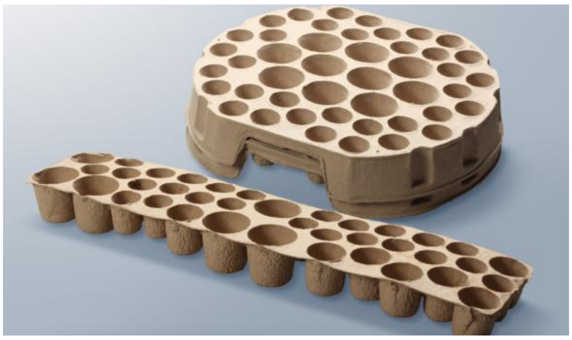


Figure 8: Agriculture Packaging

2.5.Production Process

Keyes initially developed a tool setup comprising two distinct mold halves [4]. In this process, one half of the mold was immersed in the paper pulp, after which the two halves were aligned, and the pulp was compressed. Excess water was removed through vacuum-assisted suction. Once the molded product was pre-formed between the two mold halves, it was transferred to an oven for drying. In recent years, there has been a significant increase in interest in developing efficient tools for molding products. Various types of tools have been designed to shape pulp into desired packaging solutions, addressing objectives such as replicating specific geometries, ensuring high surface finish quality, facilitating easy processing and cleaning between production cycles, providing excellent corrosion resistance, preventing adherence of pulp materials, and ensuring long service life.

In a typical molded pulp preparation process, fiber preparation begins by collecting and sorting different types of wastepaper, including kraft paper, newspapers, and corrugated paper.

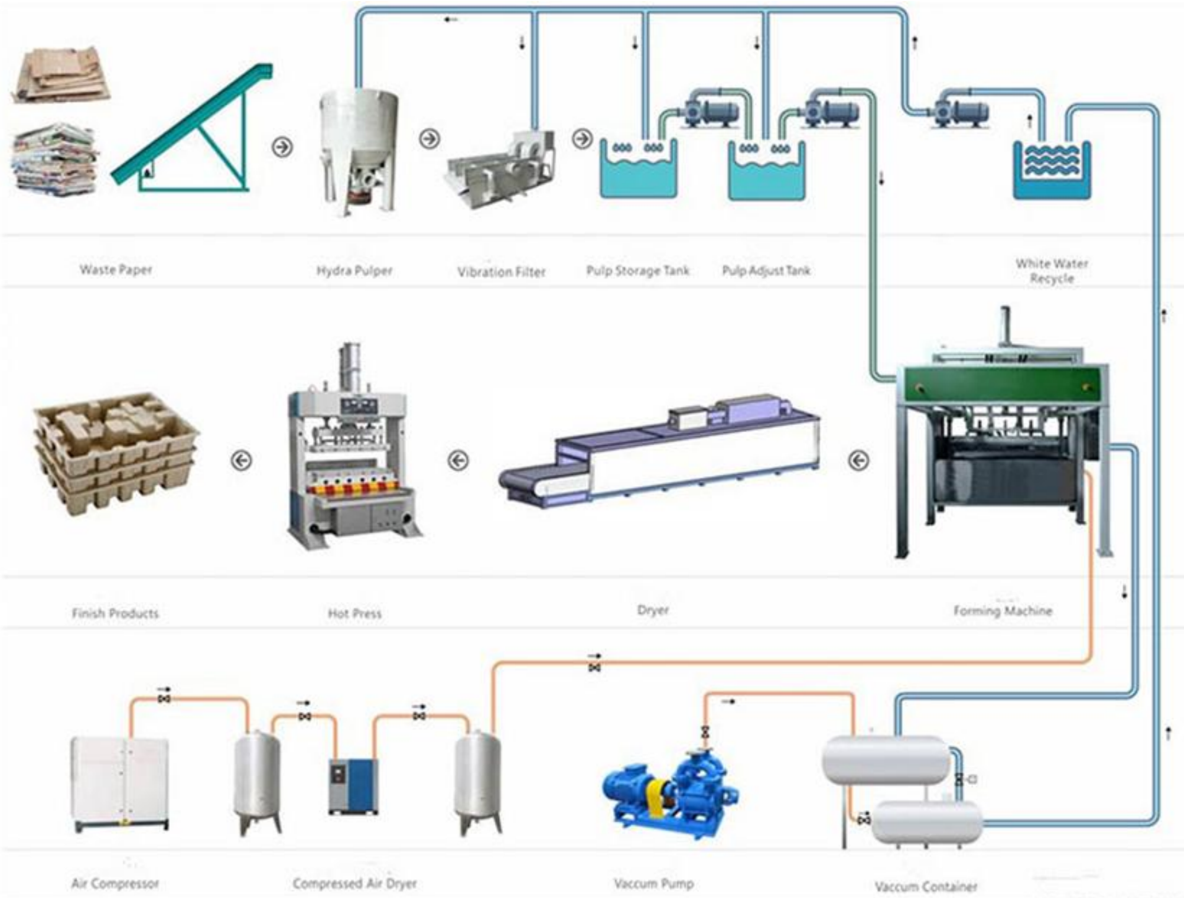


Figure 9: Flow Chart of Production Line of Molded Pulp Products

Raw Material Preparation:

Getting recycled paper or cardboard ready is the first stage in the manufacturing line for molded pulp packaging. Materials from recycling are ground. A sieve is used to extract foreign materials from documents.

Pulp Preparation:

After sorting, repulping these sorted wastepaper bales in a pulper, where loads of fiber raw materials are mixed with hot water and the fibers are detached and separated from each other under the hydrodynamic disintegration. This mixture is then kneaded in a pulp tank to achieve a specific consistency. Subsequently, the recycled fiber undergoes deinking, cleaning, and screening processes to eliminate contaminants and impurities, such as metals and plastics. If necessary, additives such as colorants are incorporated. Finally, the pulp's density is adjusted to the desired level before the molding process begins.

Formation:

During the forming process, dies, which serve as the negative mold of the desired geometry, are submerged in a tank containing pulp. Suction created by a vacuum causes the pulp to adhere to the die, accumulating to the required thickness as unbound water is expelled through compaction. This deposition of wet pulp onto the forming tool is a form of wet pressing, where the wet fibers are compressed between two plates to remove water. A platen press arrangement is particularly advantageous for the pulp-making process. In this process, water flows into the fiber network where a viscous force is experienced by the water. The interaction between fibers and water leads to uneven compaction of the wet web in the longitudinal direction, a phenomenon referred to as stratification [9].

From a tooling perspective, paper fiber agglomeration in the passageways of the forming tool can obstruct water flow. To address this issue, the tool must be thoroughly cleaned after each production cycle.

Drying:

The drying stage follows the forming process and can be categorized into two primary methods: plain (dry-press) molding and precision molding (thermoforming). While the forming process leading to the drying step remains the same for both approaches, the choice of method depends on the intended application of the final product.

In plain molding, the products are dried in an industrial oven without restraints. This method is commonly used for producing thick-walled or transfer-molded items. Plain molding systems are typically designed for high-volume production with a high degree of automation. Secondary processes, such as coating and printing, are often applied. For example, colored packaging can be achieved by incorporating dyes into the pulp, and decorative finishes can be added using spray guns [10]. Figure 10 shows the typical process chain of a plain molding process.

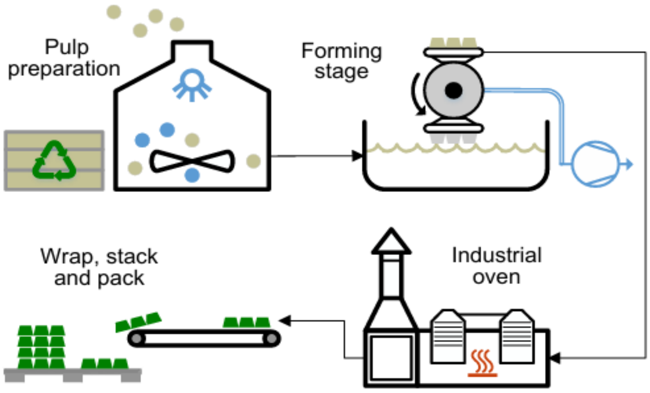


Figure 10: Typical Process Chain of a Plain Molding or Dry-Press Process

Thermoforming represents a more advanced method for creating thin-walled products with precise shapes and dimensions. Heat is applied via the surfaces of two matching mold halves, where the product is pressed. Søllner (2016) proposed a technique for producing molded items in which the formed product is transferred to the drying tool via a rotating table [11]. Here, the product is pressed from the inside while bound water is extracted through a porous mold using vacuum. This process offers several advantages, including reduced energy consumption, shorter cycle times, and lower production costs. Figure 11 depicts the typical process chain of a precision molding process.

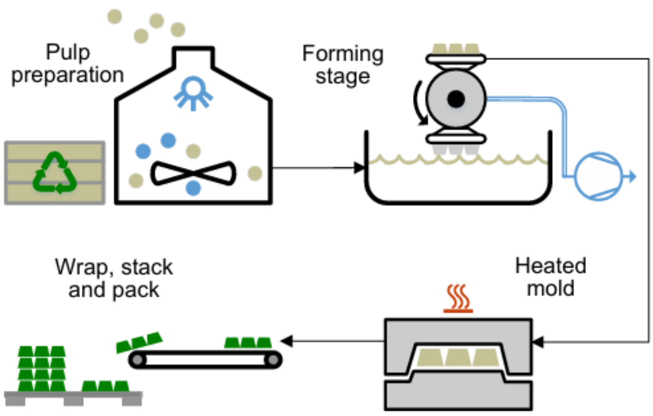


Figure 11: Typical Process Chain of a Precision Molding or Thermoforming Process

2.6.Molded Pulp Production Tooling

Tools are extremely important in the production of molded pulp products. These tools not only create the shape of the product but also enable these products to be transported on the production line. Consisting of two complementary halves, one of these tools is used to create shapes, while the other is used to transfer this product throughout the production line. The tool part used to create the shape is immersed in the dough slurry and the dough is drawn into the tool using vacuum. In this way, the shaping process takes place. The thickness of the product can be adjusted by pulling different amounts of dough depending on the characteristics of the desired product.

When the structure of these instruments is examined more closely, the first thing that catches the eye is the thin wire layer in the mesh structure inside the instruments. This layer of wire is an exact replica of the desired final product. The purpose of using this wire layer is to ensure that the dough in the dough slurry does not accumulate on the wires during vacuuming. This accumulation occurs thanks to the fibers contained in the dough. During vacuum, these fibers accumulate in the thin mesh structure wires and as a result, the product is formed thanks to the accumulated layer.

Another notable feature is the holes in the tools. Vacuums occur through these holes. Through these holes, the water of the dough slurry drawn during vacuum is discharged.

Some points to consider in the production of these tools can be summarized as follows:

- It should create exactly the shape of the product to be produced.
- It must be produced from materials resistant to corrosion.
- It must provide the desired surface quality for the products.
- It should ensure high production cycles.

There are some procedural deficiencies regarding the diameters of these holes in the tools or the positioning of the holes. A standard can be created for this process, which is usually done by trial-and-error method. In this way, designs can be made more accurately, waste of resources can be prevented and, as a result, production costs can be reduced.

Machining methods are generally used in the production of these tools. These tools, which were previously custom-designed using CAD programs, then move on to the production phase. Aluminum is generally preferred in material selection. The reasons for this can be listed as being less costly than metals such as steel, being easily processed, resistant to corrosion and abrasion, being suitable for heat treatments and having a long lifespan.

Machining is a relatively time-consuming and relatively costly form of production. In the production of these tools, new generation production methods such as 3D-printers can be used to respond faster to customers' requests. By utilizing such applications, at least in the prototype phase, the transition to mass production can be accelerated. This can also provide a significant advantage in terms of competition in the market. As mentioned above, tools must have certain features. Different materials and production methods that can provide these properties can be researched and developed [12].

Figure 12: Molded Pulp Production Tooling Samples

2.7.Materials

Molded pulp products are typically manufactured by mixing water with wood pulp derived from either virgin fiber or recycled paper products, such as old newspapers. The pulp's consistency generally ranges between 4% and 1% by weight. The specific formulation of the pulp depends primarily on the desired surface quality and stiffness of the final product. However, other considerations, such as the pulp's environmental sustainability and its suitability for food or pharmaceutical applications, may impose additional constraints. Common additives used to achieve specific functional properties include dyes, flame retardants, modified starches, and wet-strength resins [10].

Molded pulp products can be manufactured using both virgin (primary) fibers derived from wood or non-wood vegetation and recycled (secondary) fibers obtained from used paper and paperboard. Common sources of natural fibers include sugarcane bagasse, jute, flax, pineapple leaves, kenaf, bamboo, sisal, abaca, oil palm, rice husks, coir, coconut, and hemp [13]. These fibers offer attractive physical and chemical characteristics, such as impressive specific strength, rigidity, impact resilience, flexibility, and modulus, making them a compelling substitute for conventional materials. The length of the fibers plays a crucial role in determining the final characteristics of molded pulp products. Longer fibers improve strength, durability, and structural reliability, while shorter fibers aid in bulkiness (lower density), uniform texture, and surface smoothness. The diversity in fiber lengths also affects product properties—for instance, utilizing shorter fibers results in a finer structure, whereas a higher proportion of long fibers can enhance the thickness of the product. Chemical compositions of some wood and non-wood fibers are given in Figure 13 [14].

Raw material	Cellulose (%)	Klason lignin (%)	Extractives (%)	Ash (%)	Hemicelluloses (%)
Eucalyptus	46.7	27.9	4.3	1.3	19.8
Hemp hurds	43.0	24.4	2.2	1.4	29.0
Bamboo	43.2	26.7	2.2	0.8	27.1
Hardwood	44.6	26.9	3.7	1.1	23.7
Softwood	46.0	28	3.0	1.0	22.0

Figure 13: Chemical Composition of Feedstock

Cellulose is the primary element of fiber and is well-known for its strong propensity to create both intra- and intermolecular hydrogen bonds [15]. As a hydrophilic polymer, it excels in absorbing water, although this also imposes some limitations on its barrier properties [16]. Hemicelluloses play a significant role in various inherent properties of fibers, such as their ability to swell, fibrillate, bond, and resist hornification [17]. The term hornification refers to the material's capability to swell again after being dried and then reintroduced to water. Lignin, on the other hand, is a sturdy hydrophobic polymer that is largely removed during the kraft pulping process. Retaining a portion of the lignin during hot-pressing can enhance stiffness and water resistance [18]. Additionally, lignin can bolster the mechanical properties, waterproofing, thermal stability, and adhesive qualities of polysaccharide-based materials, particularly in wood. For example, when lignin content was reduced from 24.9% to 11.45%, the density increased by 6.0%, while tensile strength and bending strength jumped by 22.0% and 23.9%, respectively [19].

A significant challenge in utilizing recycled paper for molded product production lies in the potential pH discrepancies among various types of wastepaper. Using recovered fiber materials that are either acidic or alkaline without adjusting pH levels can lead to serious foaming problems. This issue arises because the calcium carbonate mineral filler found in alkaline paper begins dissolving, especially if acidic materials dominate the pH balance. When CaCO3 dissolves, it releases carbon dioxide gas, which contributes to foaming. It also leads to the release of Ca2+ ions, adding to water hardness. In scenarios where acidic material is in a minor quantity, adding a base (typically NaOH) to the water used for diluting the pulp can be a practical solution. The rosin sizing already present in the fibers will not significantly enhance hydrophobicity; thus, implementing an alkaline size, such as alkyl ketene dimer (AKD), becomes necessary. Conversely, if alkaline paper comprises a small portion of the mixture, it may be advisable to add sulfuric acid to the dilution water utilized in pulp processing. Initially, expect considerable foam generation due to the dissolution of calcium carbonate. Such high levels of dissolved calcium carbonate may complicate the hydrophobic sizing of the paper using rosin and alum. Laboratory experiments and production-scale trials will likely be essential to determine the most effective approach.

With the rising costs of wood pulp globally and the diminishing recycling rates of paper fibers due to the proliferation of digital media, there has been a steady increase in the need for alternative raw materials to produce molded pulp packaging [20]. Research indicates that using an 80/20 mix of straw pulp and kraft pulp leads to significantly enhanced tensile strength compared to expanded polystyrene (with a modulus of 0.47 MPa for the straw mixture versus 0.16 MPa for EPS). Recently, non-wood plants, including the invasive Spartina alternifolia, have been explored for their potential. Thermo-mechanical pulping of this wild grass has demonstrated promising mechanical and cushioning qualities, especially when combined with other types of chemical pulp like bamboo [21] . Additionally, another study revealed the viability of fruit pomace (FP) as a fiber source that can partially substitute recycled newspapers (NP) in the creation of molded pulp products. When a certain quantity of cellulose nanofibers (CNF) was added, the FP-based molded pulp board exhibited performance that was equal to or better than that of boards made entirely from NP [20]. A molded cup crafted from a composite of hemp and pineapple peels in a 40:60 ratio demonstrated strong structural integrity. A 0.70 mm beeswax coating on the cup was sufficient to maintain cold water for at least 30 minutes without any leakage.

Hydrophobic treatments are often beneficial for molded pulp products, particularly those used in food shipping or service. Common hydrophobic agents include sizing agents, lignin, and waxes. Traditionally, rosin products combined with aluminum sulfate (papermaker's alum) have been used for this purpose. However, complications arise when using recovered paper as the fiber source, as the calcium carbonate filler in such paper raises the pH, reducing the effectiveness of rosin and alum. In such cases, alkyl ketene dimer (AKD) is a practical alternative. AKD can be added to the pulp slurry before forming and drying, providing effective hydrophobicity [22].

Lignin, which is one of the three primary components of wood, can be characterized as a natural phenolic resin. Thanks to its low cost, typically hydrophobic properties, and potential for enhancing bonding when adequately heated, lignin has been considered as an additive for thermoformed or heat-cured molded pulp items [23] observed positive outcomes when introducing enzymatic hydrolysis lignin into the fiber blend when creating molded pulp products.

Cationic emulsions derived from maleic anhydride modified fatty acids like oleic acid, along with abietic acid, can serve as a viable hydrophobic sizing agent given their affordability, environmental friendliness, and abundance. Importantly, the interaction and self-assembly of the hydrophobic tails in fatty acids that contribute to the sizing effect should be noted. The addition of aluminum sulfate to these fatty acids will assist in adhering to the fiber surfaces and enhance the hydrophobic capability of the paper [24].

Flocculating agents are essential for the effective operation of pulp molding processes. There are two primary types of flocculants frequently employed. Aluminum sulfate-based flocculants are a budget-friendly option when dealing with new fibers, including those from mechanical or chemical pulping. Aluminum sulfate not only helps stabilize rosin sizing but also aids in forming a compact, porous layer that traps small particles during vacuum operations.

Within a pH range of 4.5 to 6, aluminum ions produce oligomers and $Al(OH)_3$ precipitates that significantly improve the flocculation of cellulosic suspensions in slightly acidic environments [25]. Polymeric flocculants consist of high-molecular-weight acrylamide copolymers with a cationic charge that varies from 3% to 10%. Their effectiveness in interacting with cellulosic materials is especially pronounced due to their ability to attach to negatively charged fiber surfaces, thereby creating connections between macromolecules. They function best at pH levels that range from neutral to alkaline (7–8.5). Flocculants facilitate water removal during production and help reduce the buildup of deposits on manufacturing equipment surfaces.

Figure 14 summarizes various research efforts aimed at developing waterproof biodegradable materials, categorized by their base materials and the additives employed.

Base material	Additives
Recycled paper pulp	Diatomite and bentonite.
Softwood pulp	Low molecular weight and highly cationic coagulant followed by a high molecular weight anionic flocculent. Grease and water-proofing.
Unbleached Kraft pulp Old newspapers	Palm oil extracted from empty fruit bunches (EFB) and AKD (alkyl ketene dimer). The addition of EFB provided a higher water contact angle, which gave improved water resistance properties.

Figure 14: Examples of Waterproofing of Molded Pulp Products

Innovative and non-conventional materials have also been investigated at the laboratory scale for molded pulp production, including coconut husk and natural latex. Additionally, partial integration of more environmentally friendly materials has been explored.

Table 1 provides a summary of the most notable research efforts related to the use of diverse material types in molded pulp production, highlighting advancements in sustainable material integration.

Table 1: Materials Used for Pulp Preparation and Affected Properties

Noguchi et al.[26]	Combining shredded pulp with plastic microspheres and starch powder. Improved shock absorbing properties and reduced cycle time.
Sung et al.[27]	Adding polyelectrolyte and changing pulp temperature. Improved water drainage rate during formation.
Gavazzo et al.[28]	Varying pulp consistency and quantities of Old Newspaper (ONP) and flocculating agent. Establishment of reference values for the raw materials quality indices.
Cho et al.[29]	Using unsorted Old Newspaper (ONP). Reduce raw material cost.
Park et al.[30]	Mixing Old Newspaper (ONP) and Old Corrugated Container (OCC). Establish an optimum mixing ratio of ONP and OCC.
Li et al.[31]	Mixing Blast Furnace Slag (BFS) with waste pulp. Reduce the environmental impact of BFS.
Wang et al.[32]	Modifying pulp fiber with chitosan. Improve dyeing properties.
Sridach et al.[33]	Using sugarcane bagasse and binders. The experiments proved that MPP can be made with these materials.
Park et al.[30]	Mixing Old Corrugated Container (OCC) with Empty Fruit Bunch (EFB). Controlling the water absorption rate.

2.8. Mechanical Properties of Molded Pulp Products

Promoting the use of environmentally friendly packaging, such as molded pulp products (MPP), necessitates a thorough understanding of their fundamental mechanical properties. For packaging applications, key properties of interest include tensile strength, compressive strength, cushioning performance, and the variability of these properties under changing environmental conditions.

However, providing a precise definition of the mechanical properties of MPP is challenging, as the mechanical behavior of each sample is influenced by factors such as its dimensions, specific geometry, and wall thickness. Furthermore, the lack of strict control over dimensional tolerances during the production of cushioning products results in significant variability in material strength and overall performance characteristics.

2.8.1. Differences Relative to Expanded Polystyrene (EPS)

The main properties of molded pulp products are their mechanical strength and cushioning ability. These properties make molded pulp comparable to expanded polystyrene. The main function of molded pulp packaging is to cushion products and protect them from breakage. To achieve this, the packaging must hold the product securely and provide some degree of reversible deformation. This cushioning effect is designed to minimize potential damage by absorbing shocks and vibrations during transportation.

Studies such as those conducted by Pacific Pulp have shown that molded pulp performs better than expanded polystyrene as a protective cushion. The apparent density of molded pulp varies greatly, reflecting the various processing conditions used [34]. In the cited study, densities typically range from 0.28 to 0.69 g/cm^3, with 0.6 g/cm^3 being determined as optimum. Howe (2010) [35] noted that the densities of typical molded pulp products are higher than that of expanded polystyrene, which is unfavorable from the perspective of the mass than needs to be transported. Paine (1991) [36] documented wider density ranges between 0.2 and 1.0 g/cm^3 among different molded pulp products.

2.8.2. Stress Strain Relationship

The micro-scale mechanical behavior of molded pulp was studied by Ji et al. [37] with the use of a scanning electron microscope (SEM). The experimental results showed that the material was not only elastic-plastic, but it also had viscous, or emplastic, characteristics. However, the strain distribution appeared irregular due to the presence of voids, impurities, and the random orientation of fibers. The authors later published another research work in which they carried out short-span compressive experiments in order to fit the stress-strain curve. Results proved that with an increasing strain rate, the material responded with increasing ultimate strength but maintaining the same elastic modulus. The stress also decreased after unloading the sample, thus exhibiting a stress relaxation behavior. This result confirmed that a non-linear emplastic stress-strain model can best describe the behavior of MPP.

The following graphs show the stress and strain curves for molded pulp in comparison with oriented paper board material. Data were collected from different papers [38,39] . Molded pulp has been compared with oriented paper board material because it has a similar density but it differs in the way it is manufactured, in particular and like paper, it shows orthotropic behavior.

Figure 14 illustrates tensile stress as a function of extension for molded pulp and oriented paperboard, measured in both the machine direction (MD) (the direction of production flow) and the cross direction (CD) (perpendicular to the production flow.) The associated table summarizes various testing methodologies and parameters, including tensile test rates and specimen types.

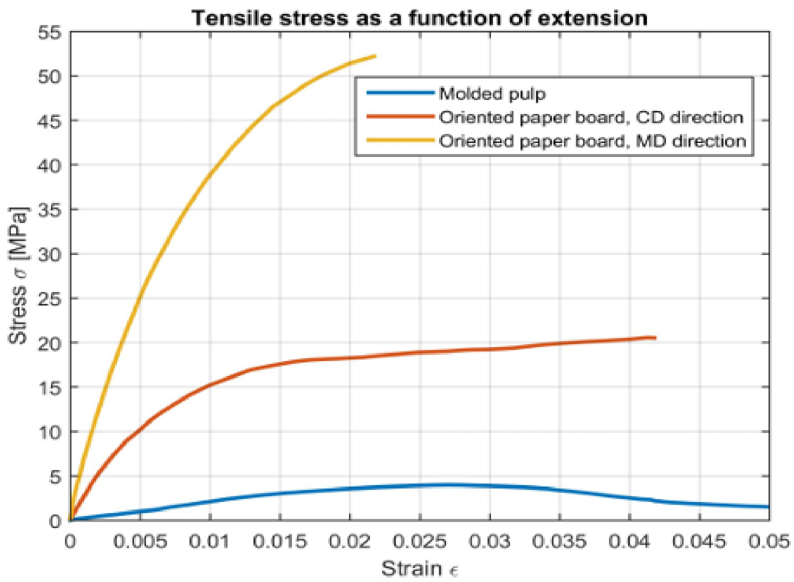
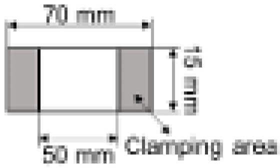


Figure 15: Tensile Stress as a Function of Extension, Comparison Between Molded Pulp and Paper Board (CD: Cross-Direction; MD: Machine-Direction)

Table 2: Figure 14 Parameters Setting.

Color	Researcher	Rate (s^{-1})	Specimen	Density (kg/m^3)
Blue	Gurav et al., 2003 [38]	0,00167		350
Orange Yellow	Ji et al., 2010 [39]		Oriented paper board formed in a dynamic sheet former using unbleached chemical pulp.	590

Due to the presence of voids, impurities, and the random alignment of fibers, molded pulp exhibited lower tensile strength compared to oriented paperboard samples.

Figure 15 illustrates the relationship between compressive stress and compressive strain for molded pulp. A direct comparison with paperboard material could not be presented within the same graph, as the compressive strain of paperboard is two orders of magnitude smaller than that of molded pulp. This significant difference highlights the distinct mechanical behavior of the two materials under compression.

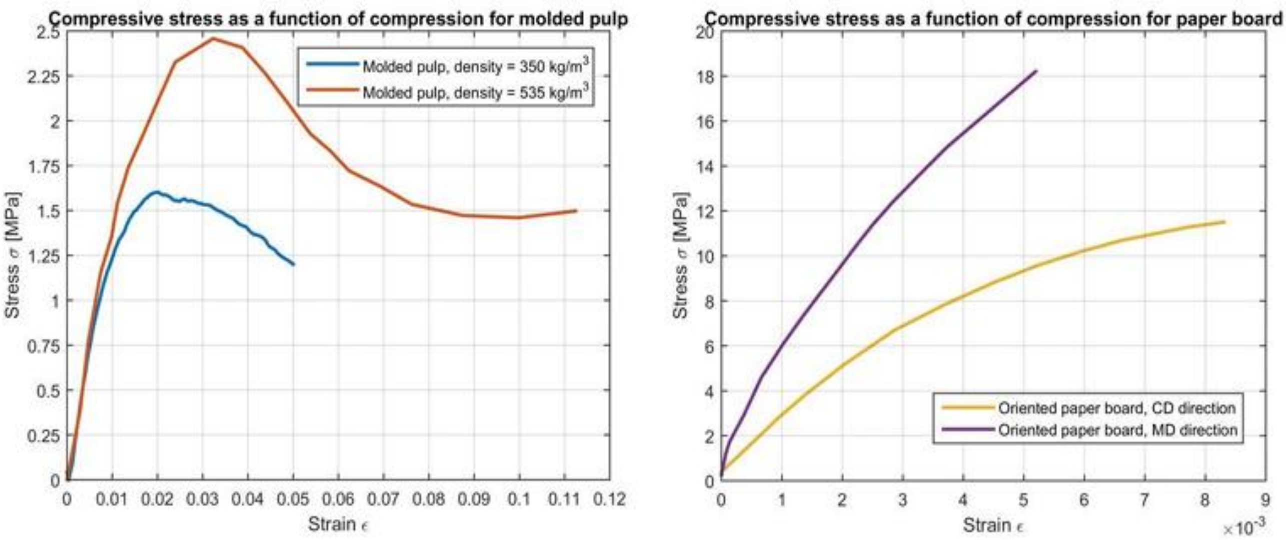
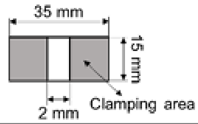
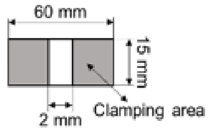


Figure 16: Compression Stress as a Function of Compression for Molded Pulp (Left) and Paper Board (Right) (CD: Cross-Direction; MD: Machine-Direction)

The corresponding table provides the parameter settings used during the experiments, offering details such as the testing conditions and the equipment configurations for each material.

Table 3: Figure 15 Parameter Settings

Color	Researcher	Test	Rate (s^{-1})	Specimen	Density (kg/m^3)
Blue	Gurav et al., 2003 [38]	Short span compressive test TAPPI standard T826	0,00833		350
Orange	Ji et al., 2010 [39]				535,2
Yellow Purple	Carlsson et al., 1980 [40]	Compressive test		Oriented paper board formed in a Formette Dynamique former using unbleached chemical pulp	590

2.8.3. Cushioning Properties

Cushion curves are commonly employed to evaluate the dynamic shock absorption capacity of cushioning materials. Molded pulp products are often compared to plastic alternatives, such as polystyrene, in this context. Significant research efforts have been directed at achieving comparable performance to polystyrene, with the goal of providing a more sustainable option.

The most widely used method for assessing shock attenuation is outlined in ASTM D1596, Standard Test Method for Shock Absorbing Characteristics of Package Cushioning Materials [41]. This standard involves plotting transmitted deceleration against static loading (the product's weight per unit area) for a specific material type, thickness, and drop height. Cushion curves are then used to identify the optimal material combination needed to protect a product with a defined fragility level.

The shock absorption ability of molded pulp depends on several geometric factors as well as the incorporation of additives. For example, adding plastic microspheres and starch powder to the pulp mix can enhance its shock-absorbing properties. However, such modifications may complicate the recycling process, potentially undermining the material's environmental benefits.

2.8.4. Degradation

The ability of molded pulp products to maintain consistent stacking strength over time and under varying environmental conditions is a critical factor for packaging applications.

Photodegradation: Ou et al. [42] studied the mechanical property changes in molded pulp containers exposed to prolonged UV irradiation. The tests revealed a 50% reduction in the degree of polymerization, a 10–16% weight loss, and a 10–30% decrease in tensile strength.

Humidity effects: Moisture cycling accelerated compressional creep behavior, resembling that of paper material, which negatively impacted stacking strength. Additionally, temperature variations, such as transferring molded trays from cold to ambient conditions, caused condensation and induced significant initial creep deformation.

Compressive failures: These failures, often due to buckling, result from internal defects such as impurities and voids. The random orientation of paper pulp fibers makes it challenging to predict and locate the type and site of failure.

2.9. Environmental Sustainability

When evaluating the environmental sustainability of molded fiber products (MFPs), understanding their life cycle is crucial, as it serves as a foundational component for sustainability assessments. A commonly used method for evaluating the environmental impact of a product throughout its life cycle is Life Cycle Assessment (LCA). LCA is a comprehensive tool that examines a product's environmental effects from production to disposal. However, limited data exists on the potential environmental impacts of MFPs.

This chapter explores the key environmental considerations associated with each stage of the life cycle of molded pulp products and highlights the potential environmental impacts that may arise.

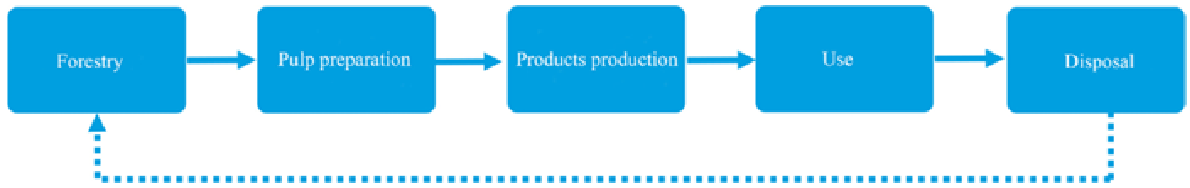


Figure 17: Life-Cycle Stages of a Typical Molded Pulp Product

Molded pulp products (MPPs) are primarily produced using wood fiber, a bio-based and potentially renewable resource when forests are sustainably managed. Life Cycle Assessments (LCAs) generally indicate that forestry has a minor contribution to the environmental impact of paper products. MPPs can be manufactured from either virgin or recycled fibers through the same production process. Most molded product facilities source commercial fibers and recycle fibers from external mills. These recycled fibers require repulping, a process that uses significantly less energy and fewer chemicals compared to virgin fiber production. One of the key advantages of using recycled fiber is the reduction in the number of trees needed alleviating pressure on forests. Additionally, producing a ton of recycled fiber pulp consumes 27% less energy than virgin fiber pulp [43]. However, fiber quality diminishes with each recycling cycle. The recyclability of fibers, typically ranging between five to seven cycles [43], depends on factors such as the wood species, pulping method, and the fiber's application. Furthermore, the quality of the wastepaper used as a source material significantly influences the final fiber quality, which, in turn, impacts the performance of the molded pulp products [44].

In the pulp production stage, all analyzed LCAs indicate that pulp and paper production are the most environmentally impactful phases in the life cycle. A study by Das and Houtman [45] compared the environmental effects of mechanical and Kraft pulping processes, revealing that mechanical pulping contributes more significantly to global warming. In contrast, Kraft chemical pulping has a higher impact on acidification, a process involving major chemical changes in ocean environments. The molding of the pulp into a product includes a drying process, which can require a high amount of energy. This is independent of what type of pulp is used. The environmental impact of this process varies depending on factors such as the heat source (e.g., steam or heated air), the drying method (dry press, wet press, or impulse drying), and the duration of the heating process.

Molded pulp products (MPP) have several disposal options. One common method is recycling them into other paper products, which requires collection and processing through steps like pulping, screening, refining, washing, drying, and finishing. Environmentally, recycling is often more favorable than incineration for energy recovery, but its benefits depend on the specific technologies employed. Biodegradation or composting is another viable option, provided the additives used (such as inks and adhesives) allow for it. The success of biodegradation largely depends on environmental conditions at the disposal site, such as oxygen availability and humidity levels. Landfilling is also an option, but it has significant drawbacks. Paper products can degrade anaerobically in landfills, producing methane, a potent greenhouse gas. As a result, landfilling contributes substantially to the global warming potential of paper products .

A detailed research study on the life cycle analysis of molded pulp materials enables a deep analysis of the environmental impacts. The analysis is a detailed examination of the environmental impacts that are produced in the entire life cycle of the product, which includes raw material supply, manufacturing, use, and disposal. First, there is a need to identify the source, type, and delivery method of the raw materials used. For example, it is relevant to analyze the sources of natural or recycled fibers as raw materials, as well as to quantify the energy and water used by these fibers in the course of their processing. It is also necessary to analyze the amounts of waste generated during the manufacturing stage, as well as the energy consumed, chemicals used, and carbon dioxide emissions.

The system being studied has its boundaries defined. For example, it needs to be determined whether the study should cover just the production stage or the entire life cycle from raw material extraction, through production and use, to disposal. One of the critical ways of carrying out Life Cycle Assessment (LCA) study is the identification of the functional unit. This forms a reference quantity used as a measurement unit in the study, through which all the processes under consideration can be evaluated to enable comparison. For example, a kilogram of a product could be evaluated, or a package of molded pulp material. During each process involved, an inventory is compiled by collecting data on energy use, water use, chemical additives, waste produced, and emissions released. This inventory is then converted into environmental impact categories (like carbon footprint, water footprint, energy use, and acidification potential) by the software used in the study.

There are several different software tools for performing an LCA analysis. OpenLCA can be used free of charge and is suitable for beginners, as well as for people who want to work with basic data. In the case of simple analyses, one can use the open-source database provided by OpenLCA. For more complex analyses, other software options, such as SimaPro, GaBi, and Umberto, are recommended. These tools allow working with large databases and also provide an opportunity to evaluate several categories of impact. For example, SimaPro attracts attention because, in this tool, such comprehensive analytical methods are widely used in big industrial projects. GaBi has the most extensive user community and a powerful analysis capability in energy-intensive processes.

Determining whether molded pulp products (MPP) are truly a more environmentally sustainable option compared to alternatives depends on their specific application. To minimize their environmental impact, it is essential to consider the key factors influencing each stage of their life cycle, including raw material sourcing, production processes, energy consumption, and disposal methods. By addressing these factors, the sustainability of MPP can be optimized for their intended use.

2.10. MATLAB Simulink

Simulink is a MATLAB-based graphic programming environment for modeling, simulation, and analysis of multi-domain dynamical systems. Its primary interface is a graphical block diagramming tool and a set of customizable block libraries. It offers tight integration with the rest of the MATLAB environment and can be run or scripted from MATLAB. Simulink is widely used for multi-domain simulation and model-based design in the fields of automatic control and digital signal processing.

Simscape is a tool that is used in conjunction with Simulink and is designed for the modeling of physical or physics-based systems. It also provides pre-built components and libraries to perform simulations of electric, mechanical, thermal, and hydraulic fields. This tool thus allows for the correct modeling of physical systems which should exhibit the behavior of the real world and facilitates the simulation of complex physical interactions in engineering projects. Simulink and Simscape, through the model-based design approach, have supported system control design, optimization, and dynamic behavior analysis in a very efficient way.

3. EXPERIMENT

The mechanical properties of molded pulp packaging constitute a crucial factor directly impacting the level of protection provided to products. Understanding and characterizing the mechanical behavior of materials possessing elastic properties stands as a fundamental necessity within the realms of industrial design, engineering, and materials science. In this context, the determination of mechanical properties for flexible materials like molded pulp packaging assumes significant importance, facilitating the evaluation of product durability, the packaging's resistance to tensile, compressive, and impact forces, its response to environmental influences during usage, and overall performance assessment. This chapter focuses on the analysis of stress-strain relationships and force-displacement behaviors of molded pulp packaging through the application of tensile testing. The outcomes of these experiments furnish valuable insights into the durability and strength of packaging, thereby enabling enhancements in product design and manufacturing processes. Consequently, a comprehensive evaluation encompassing a detailed exposition of the applied tensile tests on molded pulp packaging, coupled with an in-depth examination of the experimental design, execution, and result interpretation, will be presented.

3.1.Materials and Equipment

The experiments were carried out on SHIMADZU brand AGS-X 50kN tensile testing device. We observed the tensile test results on the computer using TRAPEZIUM software.

Figure 18: SHIMADZU AGS-X-50kN Tensile Testing Device

At the time of the experiment, the ambient temperature was recorded as 23°C and the humidity was 55% and kept constant. Tensile tests are based on ISO 1924-2 and the tensile rate was set to 10 mm/min.

The experiment used samples of packaging used to hold liquids or small objects in medical or industrial uses. It contains 78% corrugated cardboard scrap, 18% third pulp paper scrap and 4% alkyl ketyl dimer (AKD). The experiment was carried out by taking samples from two different packages: hot pressed and rough. Testing was carried out on 5 tensile specimens, 3 from hot-pressed packaging and 2 from rough packaging.

Figure 19: Hot Pressed and Rough Sample

The dimensions of the tensile test specimens, measured with a caliper, are shown in Table 1.

Table 4:Specimen Size

Specimen Type	Gage Length (mm)	Width (mm)	Thickness (mm)
Hot-Pressed Specimen 1 (K1)	50.85	10.00	0.97
Hot-Pressed Specimen 2 (K2)	51.00	10.00	0.97
Hot-Pressed Specimen 3 (K3)	53.63	10.00	0.97
Rough Specimen 1 (N1)	57.10	10.00	1.30
Rough Specimen 2 (N2)	58.08	10.00	1.30

3.2.Test Procedure

Test samples were placed in the jaws of the tensile testing device and stretched at a constant stretching speed of 10 mm/min.

Stress and force data were recorded in real time and testing continued until the sample broke.

During stretching, the force and displacement data automatically recorded by the experimental device were used to draw stress-strain and force-displacement graphs.

The same procedure was repeated for all five samples.

3.3.Discussion of Tensile Test Results

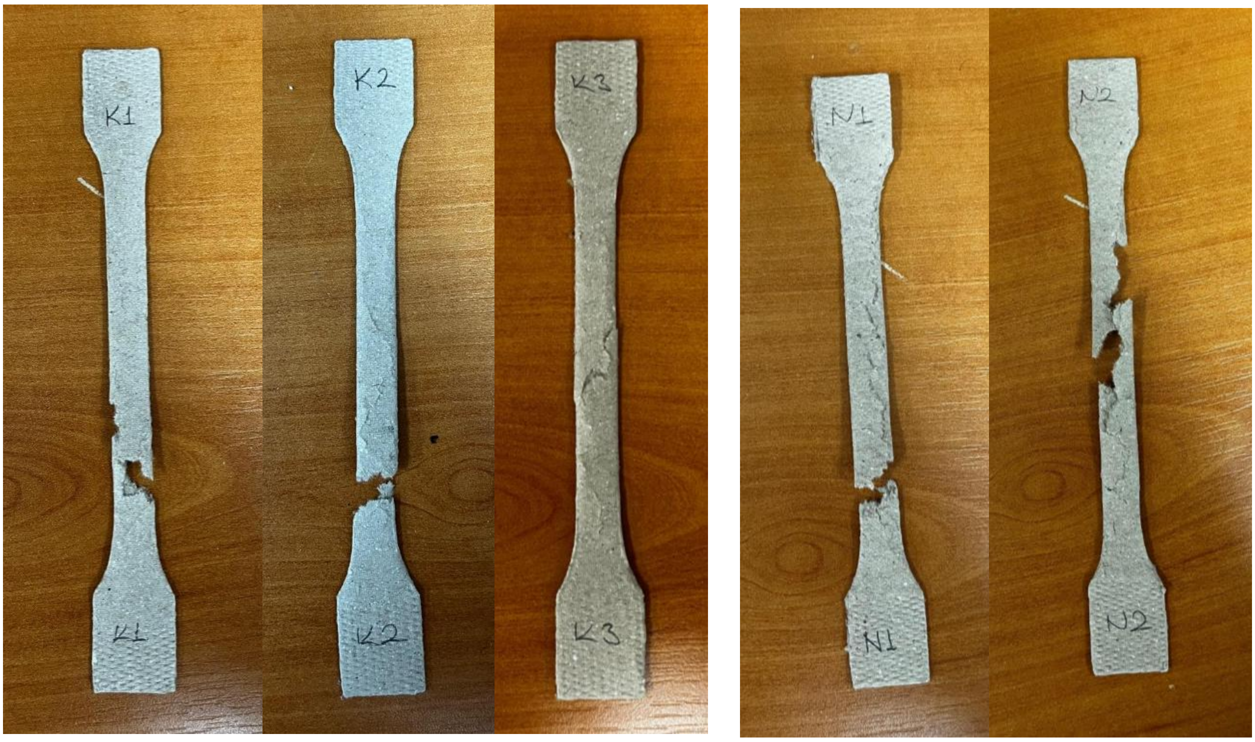


Figure 20: Fracture Surfaces of Hot-Pressed (K1,K2 and K3) and Rough (N1 and N2) Molded Pulp Tensile Test Specimens

The raw data obtained from tensile tests for each sample included the following parameters:

- Time (s): Duration of the test.
- Force (N): Applied load on the specimen.
- Displacement (mm): Total movement of the testing machine's crosshead.

- Extension (Ext.1) (mm): Measured elongation of the specimen via extensometer.

These parameters were organized systematically in Excel to facilitate the construction of stress-strain curves for each sample.

For each sample, stress-strain curves were generated through the following calculations:

$$\sigma = \frac{F}{A} \tag{1}$$

Where:

σ = Stress (Mpa)

F = Applied Force (N)

A = Original Cross-sectional Area (mm²)

$$\varepsilon = \frac{\Delta L}{L_0} \tag{2}$$

Where:

ε = Strain

ΔL = Extension (mm)

L_0= Original Length (mm)

These calculations were performed for each data point, enabling the plotting of stress versus strain for all five samples.

Young's Modulus (E), or the Elastic Modulus, was calculated by identifying the linear (elastic) region of each stress-strain curve. A linear trendline was fitted to this region, and the slope of the trendline was extracted as Young's Modulus:

For each stress-strain curve, the following parameters were identified:

- Maximum Stress (σ_{max}): The highest stress value reached before the onset of necking or fracture.
- Strain at Maximum Stress (ε_{max}): The corresponding strain value at σ_{max}.

Yield Strength (σ_y) was determined using the 0.2% Offset Method, which involves the following steps:

Offset Line Construction: An offset strain of 0.002 (0.2%) was applied to the linear (elastic) region of the stress-strain curve. A line parallel to the initial linear trendline was drawn, starting at $\varepsilon = 0.002$.

Intersection Point Identification: The intersection of the offset line with the actual stress-strain curve was identified. The stress value at this intersection point represents the Yield Strength.

Visualization: The Yield Strength point was marked on each stress-strain curve for clarity.

This method provides a standardized approach to determine the yield point, especially in materials where the yield point is not distinctly observable.

Shear Modulus (G), also known as modulus of rigidity, measures a material's resistance to shear deformation. It quantifies how much a material deforms under shear stress without changing its volume. The relationship between Shear modulus , Young's modulus and Poisson's ratio is expressed by the following formula:

$$G = \frac{E}{2*(1+v)} \tag{3}$$

Where:

G : Shear modulus

E : Young's modulus

ν : Poisson's ratio

Calculations were made by taking into account that Poisson’s ratio of the molded pulp is 0.044.

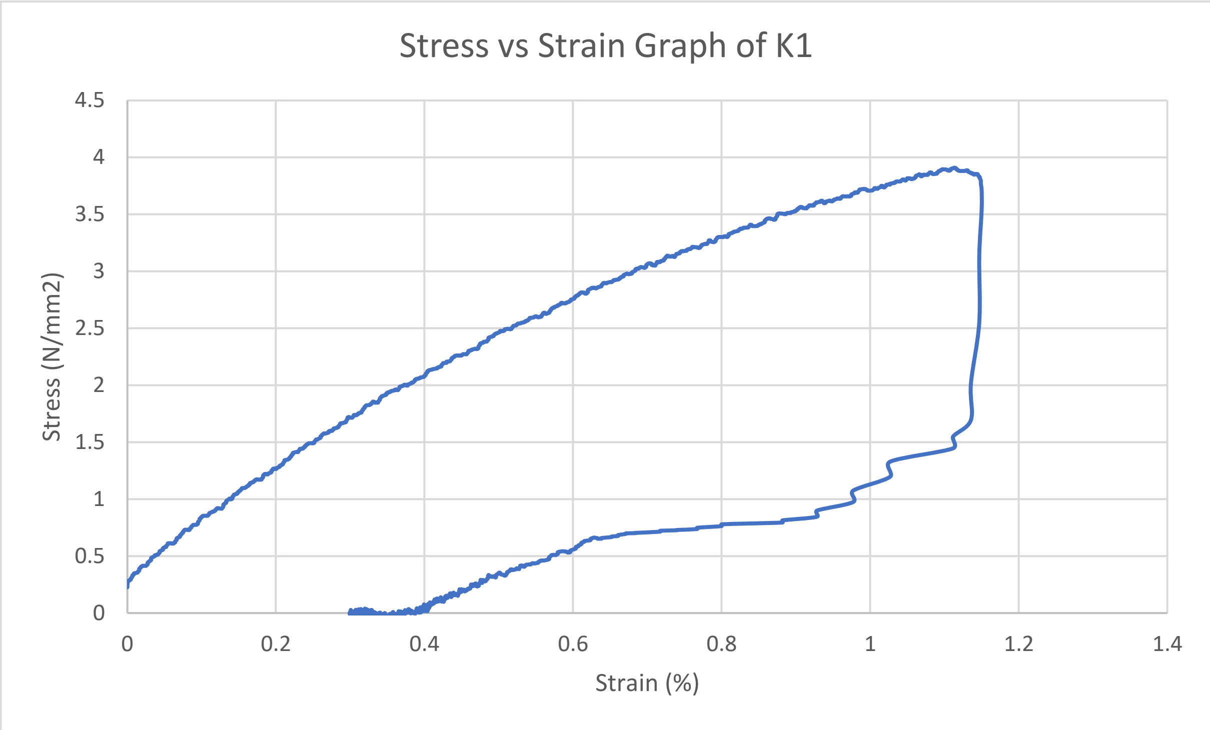


Figure 21: Stress-Strain Graph for Sample K1

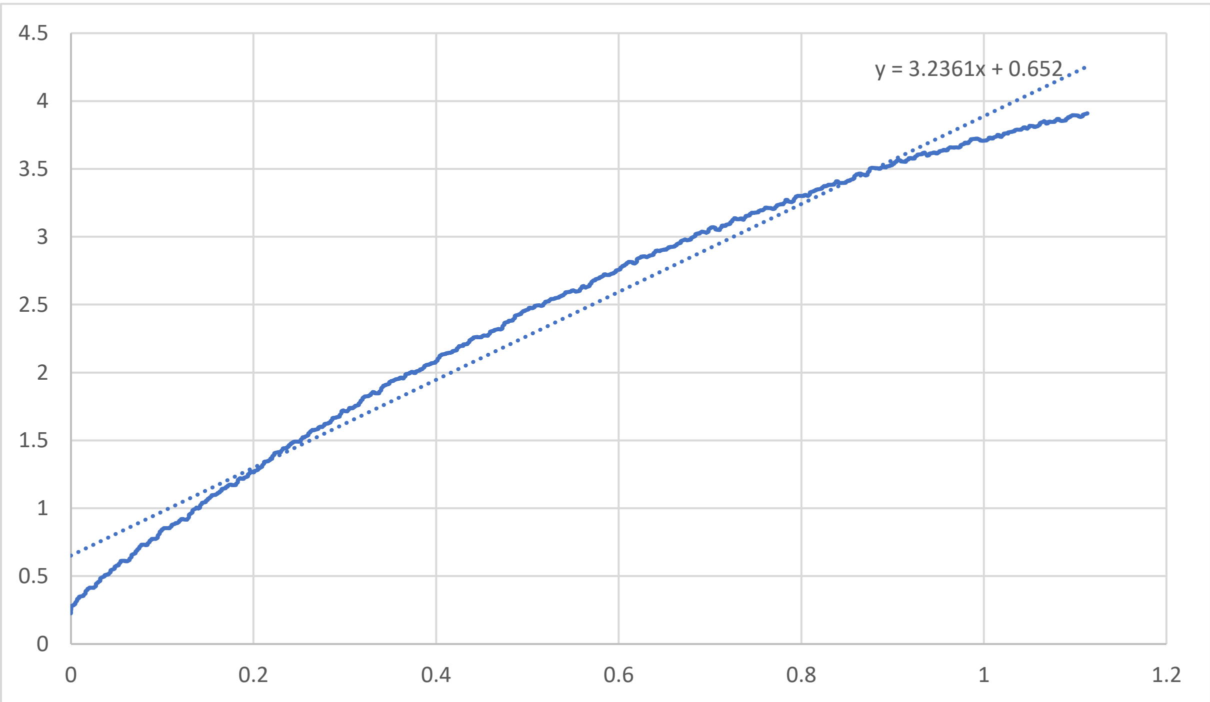


Figure 22 Linear Trendline for Sample K1

The highest tensile capacity of the material (σ_{max}) in Figure 18 is 3.910 MPa. After this point, the material undergoes serious plastic deformations. The amount of elongation when the material reaches maximum stress (ε_{max}) is 1.113%.

The Young's Modulus of the sample K1 was determined as 3.236 from the slope obtained by adding a linear trendline to the data points in the elastic region in Figure 19.

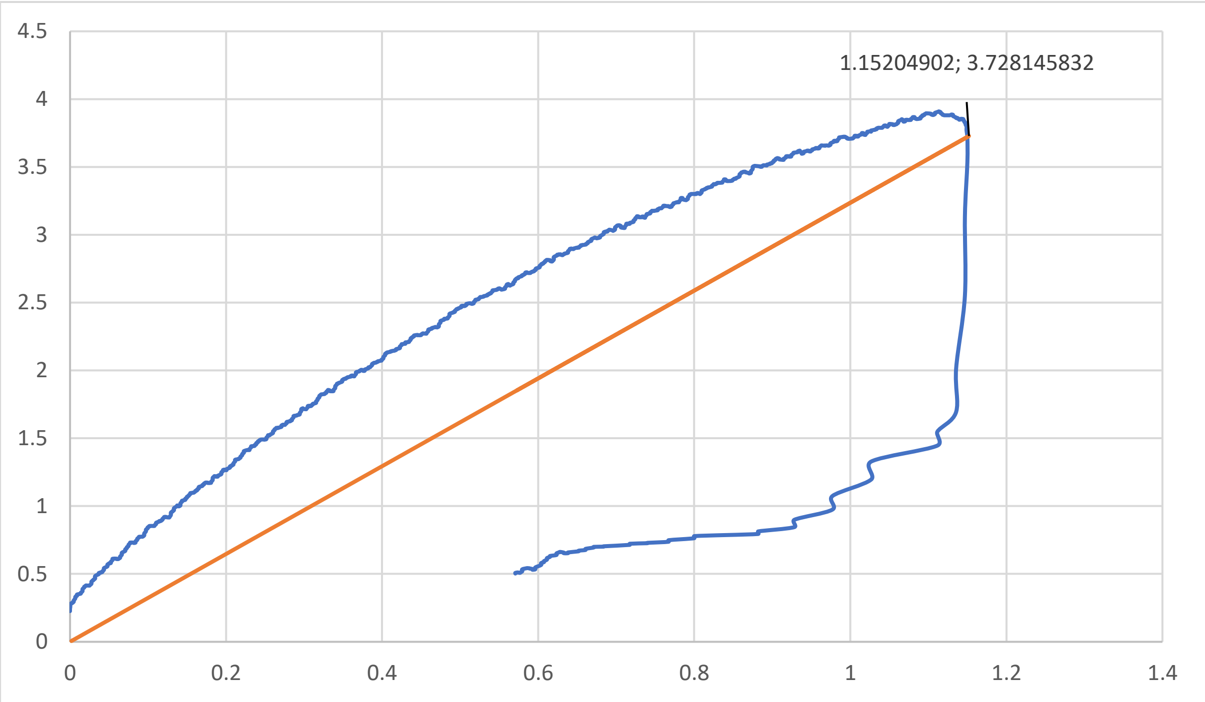


Figure 23: 0.2% Parallel Offset Line for Sample K1

The orange linear line in Figure 20 is parallel to the slope in the elastic region and is shifted to 0.2% elongation. This line gives the yield strength (σ_y) at the point where it intersects the stress-strain curve. This value for Specimen K1 is 3.728MPa. Percentage elongation of the sample K1 relative to its original length at the point of fracture during a tensile test is 1.152%.

The stress-strain graphs obtained for the other two samples of hot-pressed molded pulp material and the values obtained from these graphs are shown below.

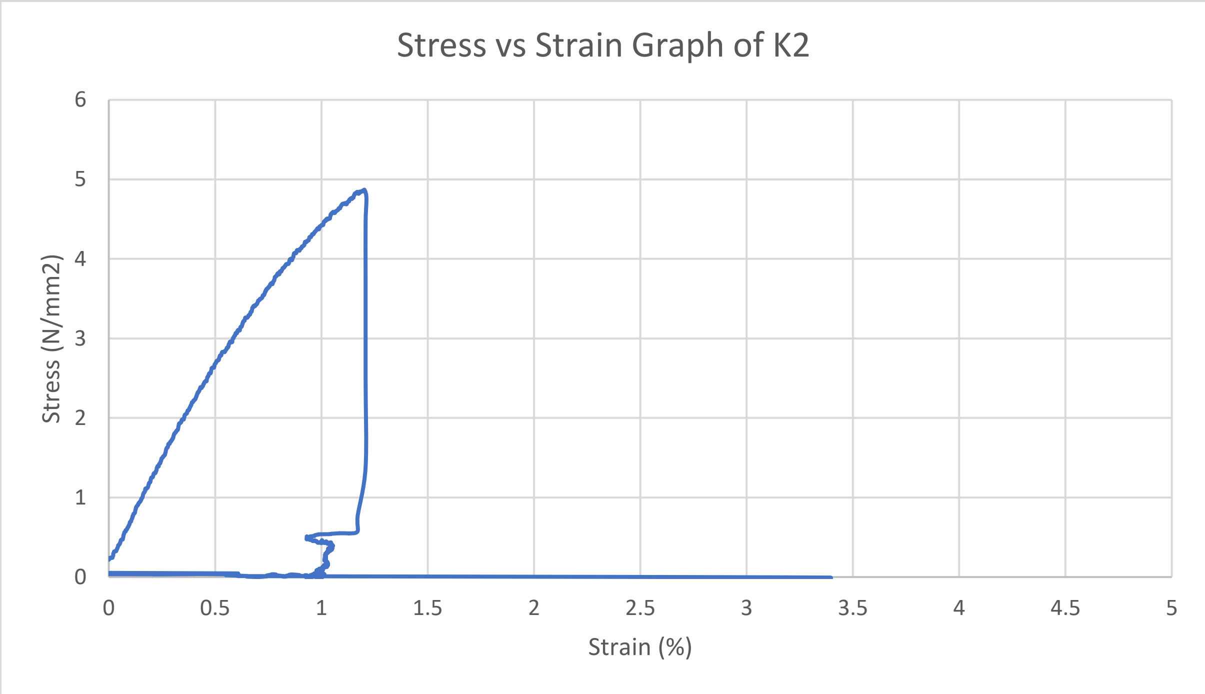


Figure 24: Stress-Strain Graph for Sample K2

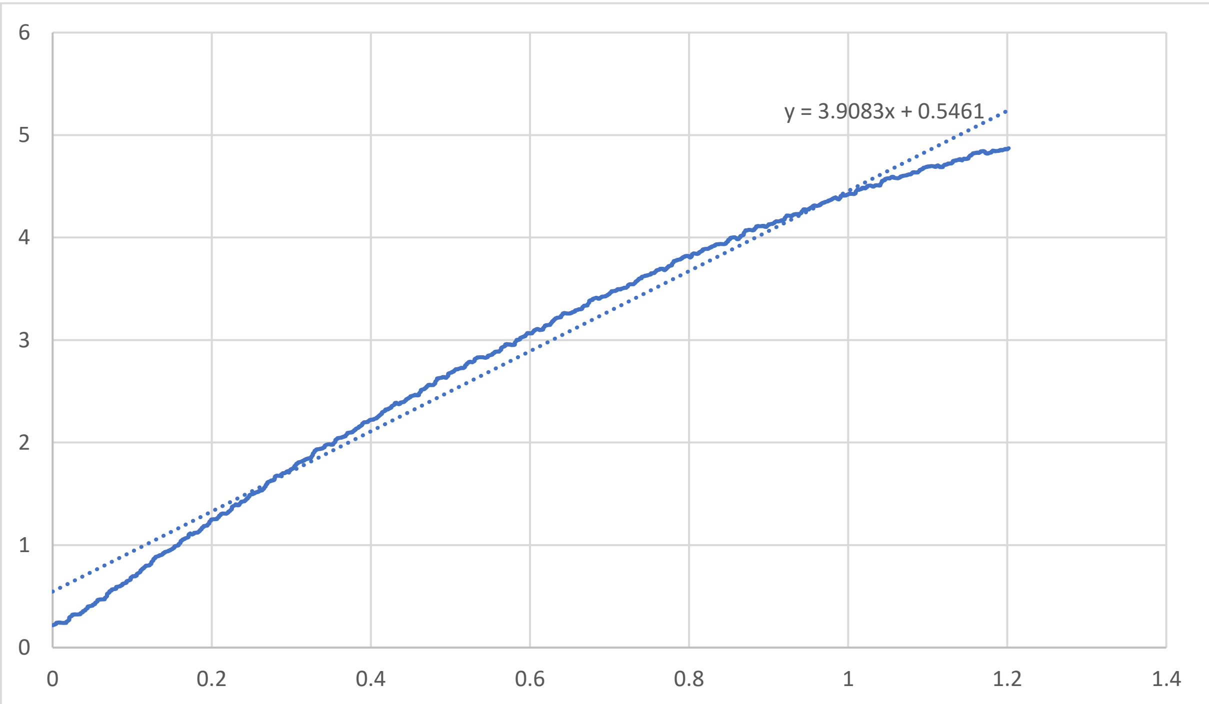


Figure 25: Linear Trendline for Sample K2

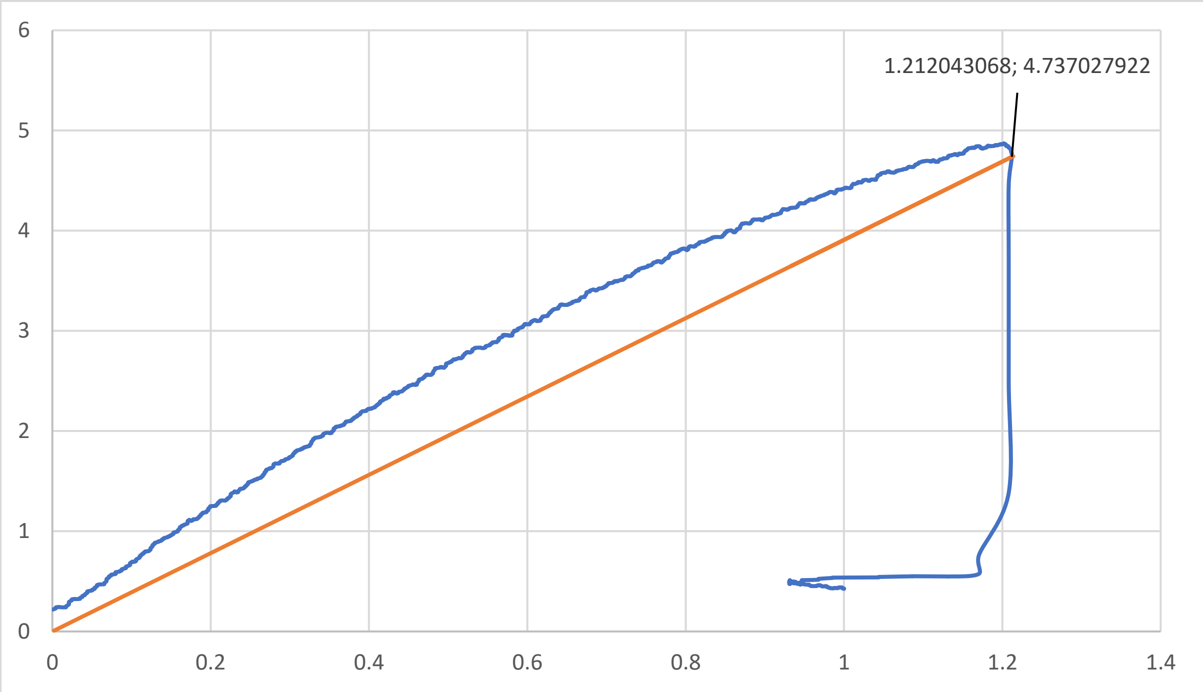


Figure 26: 0.2% Parallel Offset Line for Sample K2

The maximum stress of the sample K2 from Figure 21 is 4.872 Mpa and the amount of elongation when the material reaches maximum stress is 1.202%. The Young's modulus for this sample K2 was calculated from Figure 22 as 3.908 MPa. The Yield Strength was determined in Figure 23 to be 4.737 MPa, which is the point at which the material begins to undergo permanent deformation and the strain at failure value of 1.2120% shows how much deformation this material has experienced at the point of rupture.

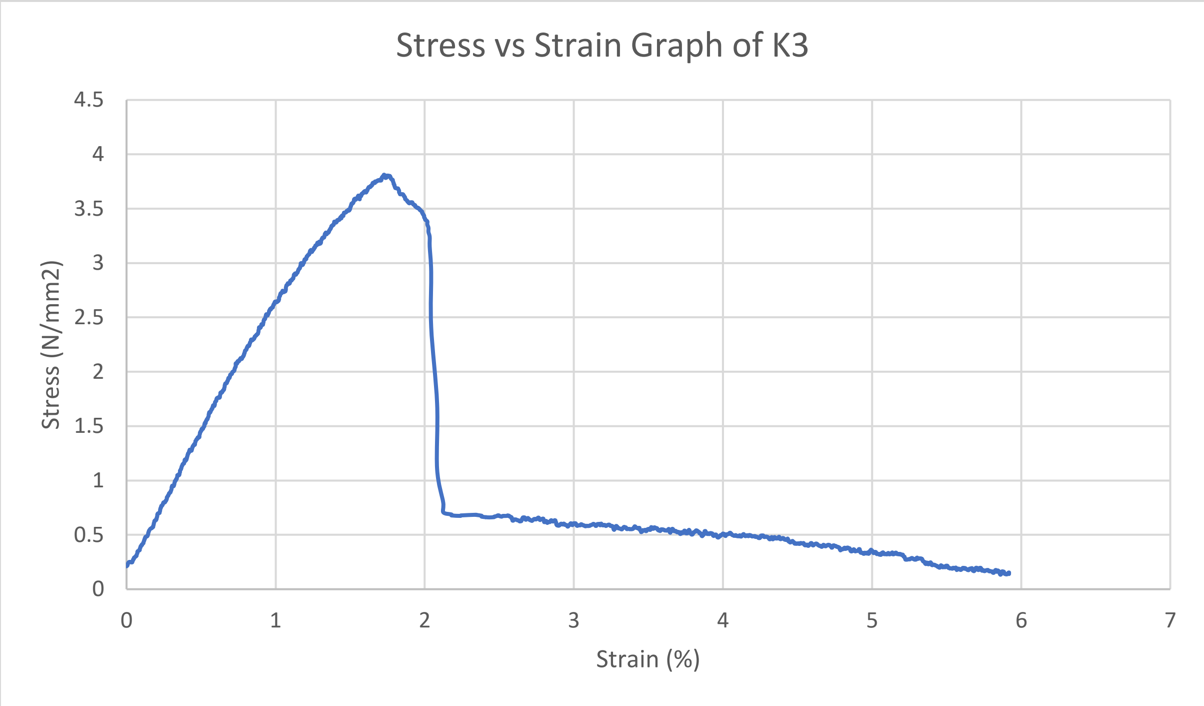


Figure 27: Stress-Strain Graph for Sample K3

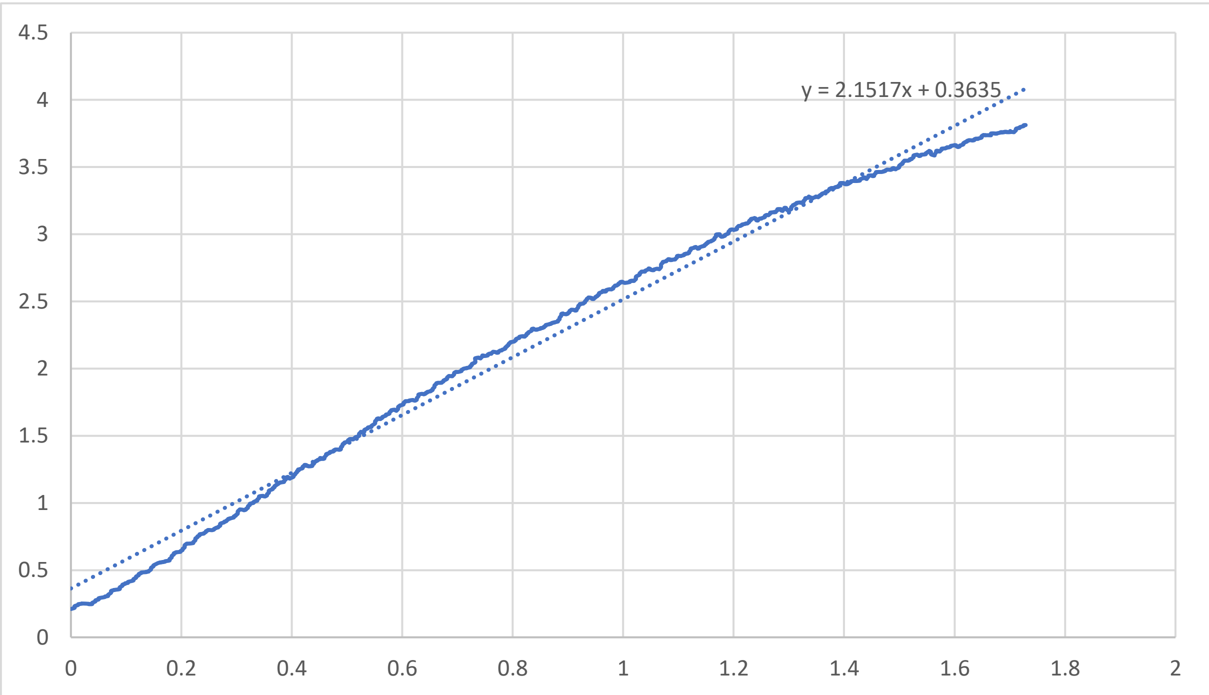


Figure 28: Linear Trendline for Sample K3

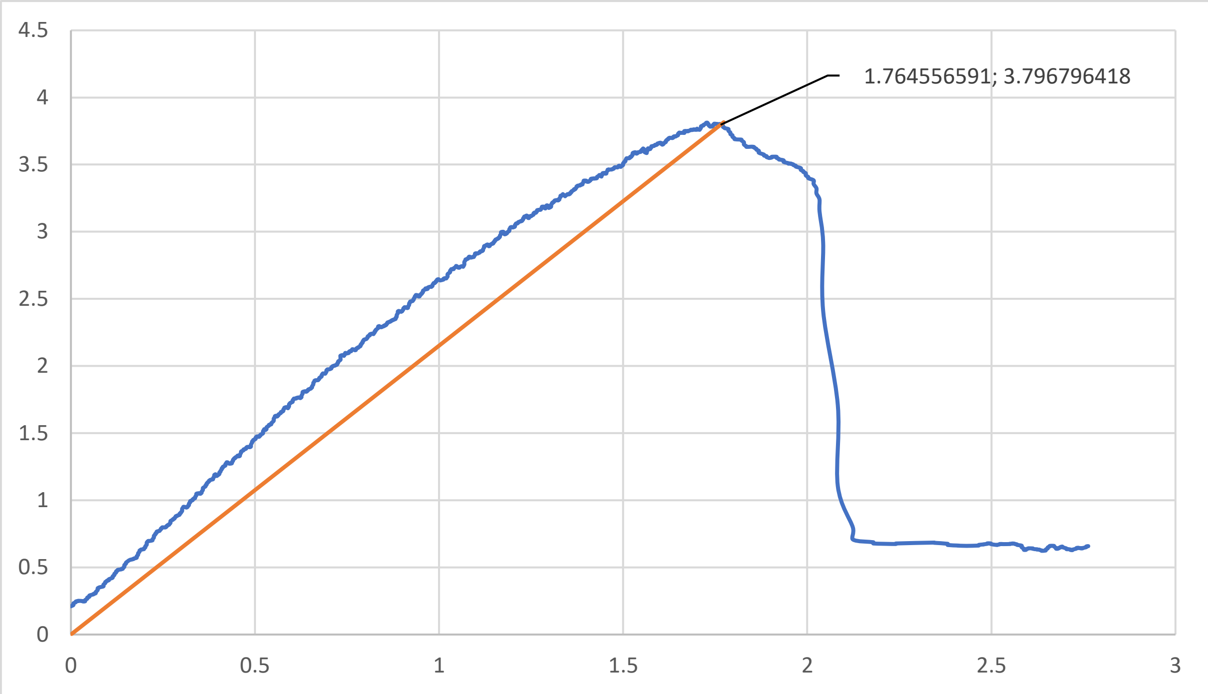


Figure 29: 0.2% Parallel Offset Line for Sample K3

K3 is the 3rd and last sample in the hot-pressed molded pulp material category. The Young Modulus value for this sample is 2.152 MPa, Maximum Tensile Strength is 3.8122MPa and Strain at Max Stress value is 1.72877%. Yield Strength was determined as 3.7968MPa and Strain at Failure value was observed as 1.7646%.

The stress-strain graphs obtained for two samples of rough molded dough material and the values obtained from these graphs are shown below.

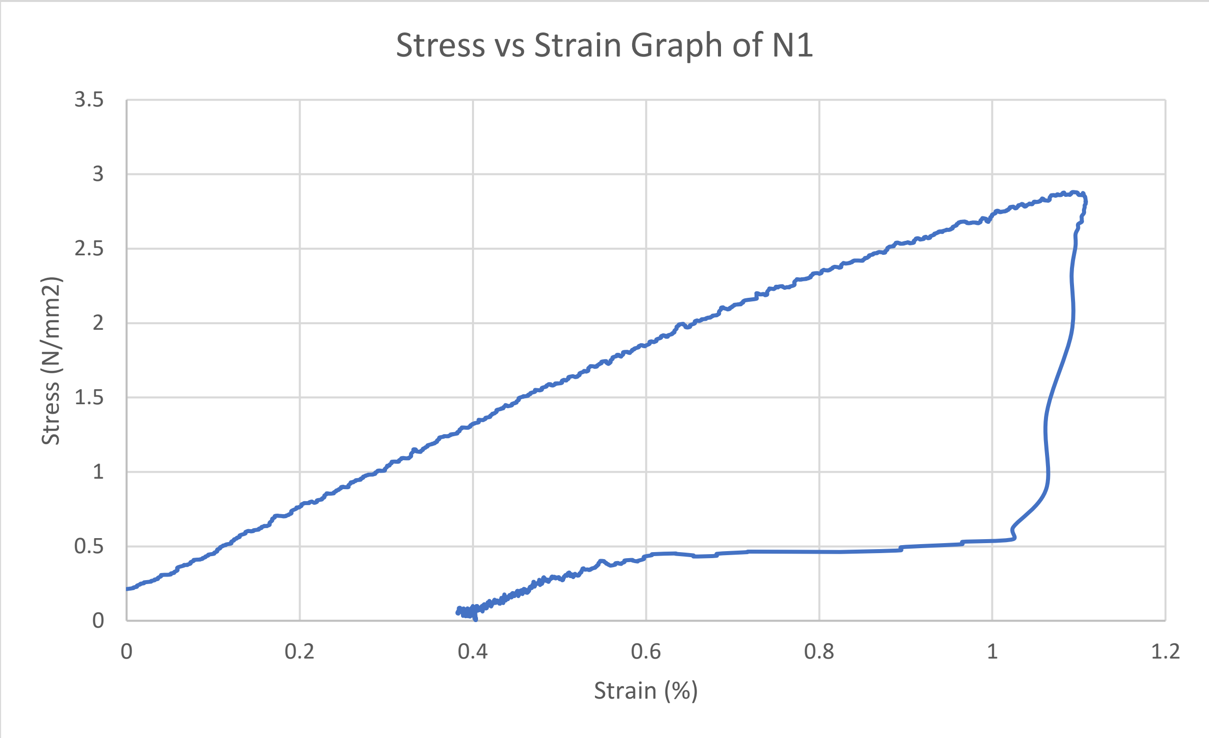


Figure 30: Stress-Strain Graph for Sample N1

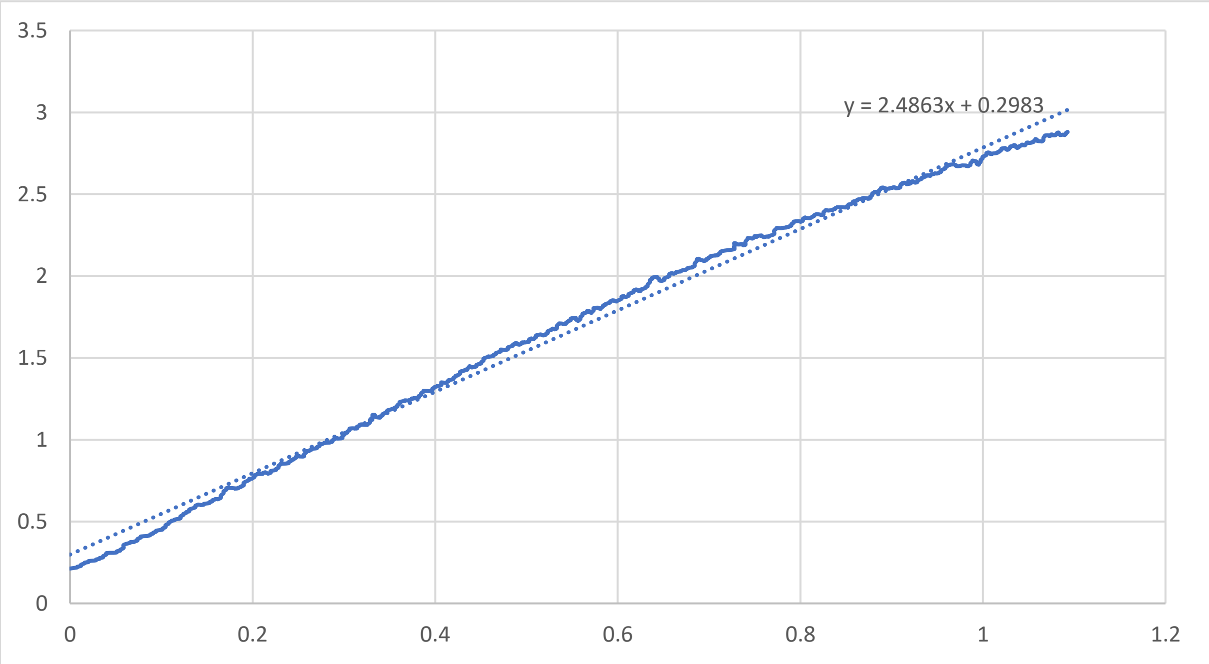


Figure 31: Linear Trendline for Sample N1

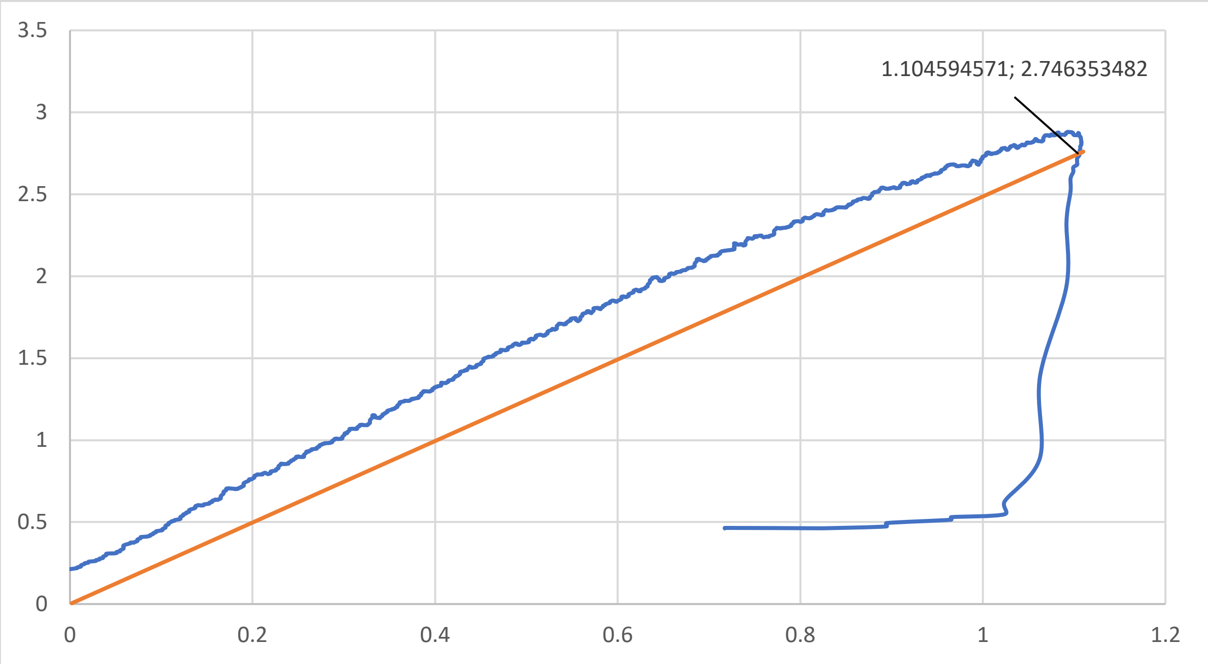


Figure 32: 0.2% Parallel Offset Line for Sample N1

The fourth sample belongs to the rough molded pulp material class. The Young modulus value for this sample was calculated as 2.486 MPa. The maximum stress is found to be 2.881 MPa, and the strain at max stress value is 1.093%. The yield strength was calculated as 2.746 MPa, and the strain at failure value was determined as 1.105%.

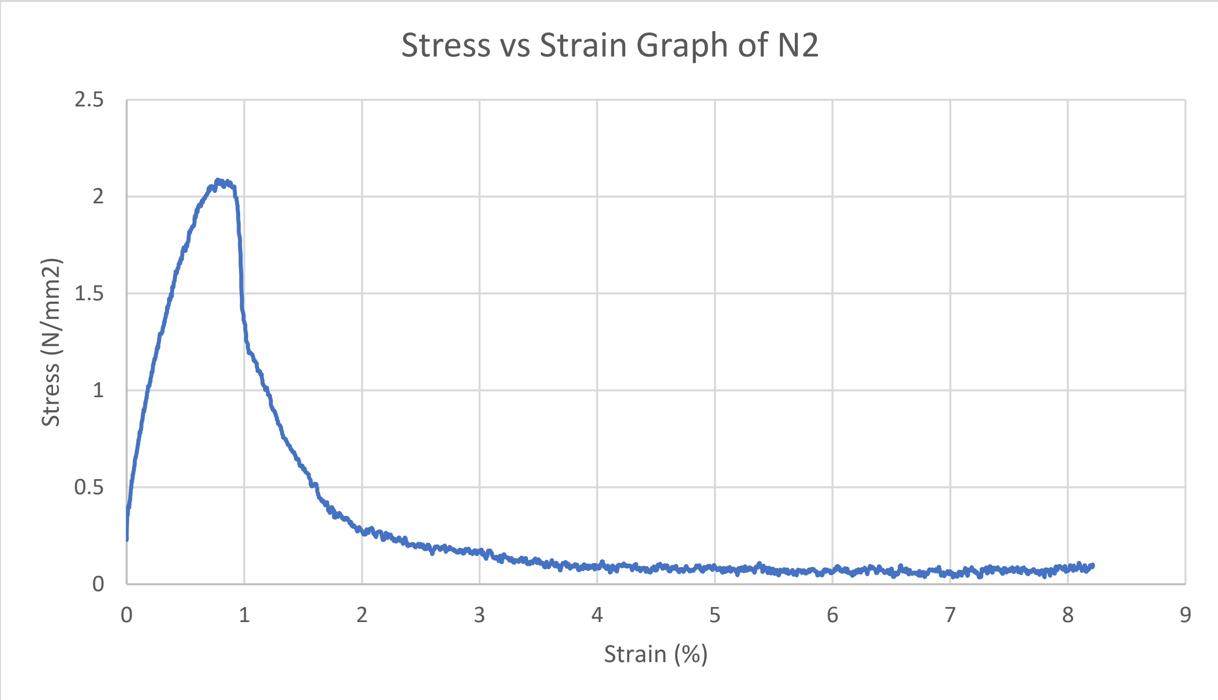


Figure 33: Stress-Strain Graph for Sample N2

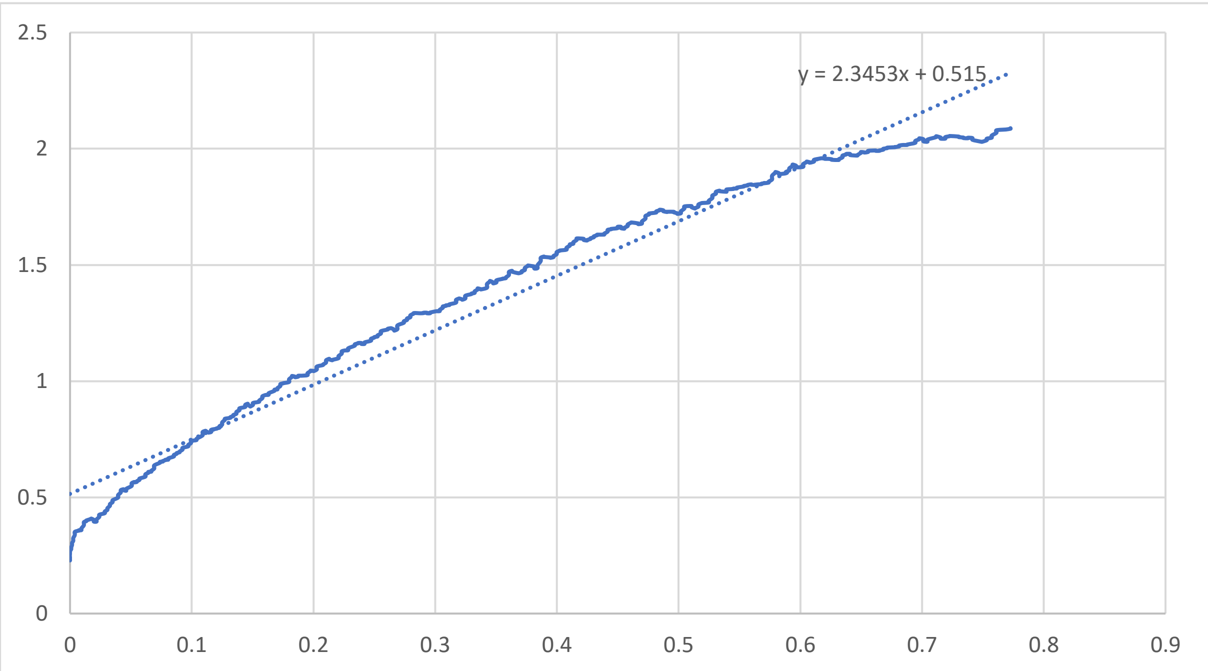


Figure 34: Linear Trendline for Sample N2

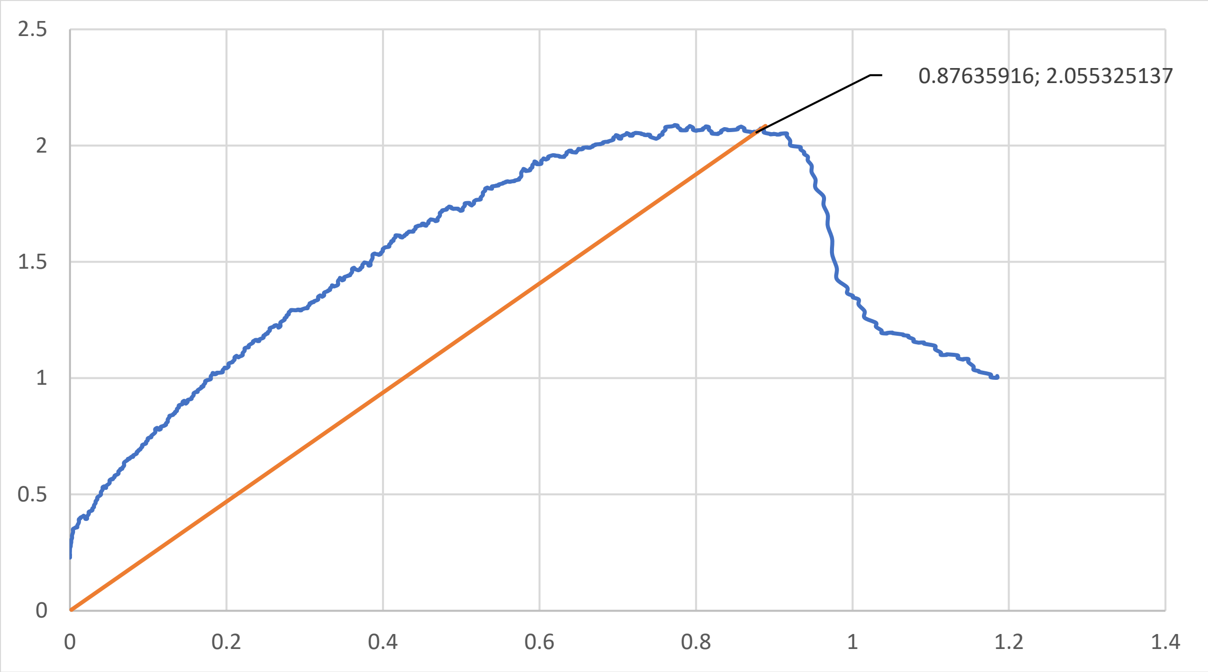


Figure 35: 0.2% Parallel Offset Line for Sample N2

The fifth and last sample is a test sample of the rough molded pulp material type. The young modulus value for this sample was determined as 2.345 MPa and the maximum stress was measured as 2.088 MPa. The strain at maximum stress was 0.773%. Finally, the yield strength was found to be 2.055 MPa and the strain at failure value was determined as 0.876%.

Five samples were tested, with key parameters such as elastic modulus, maximum stress, strain at maximum stress, strain at failure, and yield strength determined for each. These results have been summarized in the following table to provide a clear comparison between the two material types and to serve as a foundation for the subsequent discussion of their mechanical behavior and potential applications.

Table 5: Material Properties of Molded Pulp Products

Specimen Type	**Young Modulus (Mpa)**	**Max Stress (Mpa)**	**Strain at Max Stress**	**Yield Strength (Mpa)**	**Shear Modulus (Mpa)**
K1	3.236	3.910	1.113	3.728	1.550
K2	3.908	4.872	1.202	4.737	1.872
K3	2.152	3.812	1.765	3.797	1.031
N1	2.486	2.881	1.093	2.746	1.191
N2	2.345	2.088	0.773	2.055	1.123

A comparison of the tensile test results for hot-pressed and roughly molded pulp samples reveals notable mechanical differences linked to their respective manufacturing methods. The hot-pressed molded pulp displays significantly enhanced mechanical properties, which is due to the densification and better fiber bonding that occur during the pressing process. This technique minimizes internal voids and promotes a tighter interlocking of cellulose fibers, thereby boosting both stiffness and strength. The average elastic modulus (E=3.099MPa) for hot-pressed samples is considerably greater than that of the rough samples (E=2.416MPa), demonstrating an increased resistance to elastic deformation when subjected to loads. Correspondingly, the maximum stress (σ_{max}=4.198) and yield strength (4.087MPa) of the hot-pressed samples exceed the values for rough molded pulp (σ_{max}=2.485MPa, 2.401MPa). These results underscore the superior structural integrity of hot-pressed molded pulp, rendering it more appropriate for applications that demand a higher load-bearing capacity.

In terms of ductility, hot-pressed samples also exhibit better performance. The strain at failure, with an average of 1.3762%, surpasses the 0.9905% noted for rough molded pulp, indicating that hot-pressed samples can withstand greater deformation prior to failure. This enhanced ductility, combined with increased strength, is crucial for applications that require flexibility and durability under fluctuating loads. In contrast, rough molded pulp, which demonstrates weaker mechanical performance, highlights the drawbacks of less sophisticated production methods. The lack of a hot-pressing phase results in a more porous and uneven microstructure, undermining fiber bonding and diminishing the overall strength and elasticity of the material.

Even though all samples stem from the same basic material, the results from tensile testing show significant variability among both the hot-pressed and roughly molded pulp groups. These discrepancies can be linked to several factors that are intrinsic to the material and the methods used in its production.

Initially, molded pulp is an irregular material made up of cellulose fibers, fillers, and leftover moisture. Differences in the length, alignment, and distribution of the fibers can lead to variations in mechanical characteristics. Even small changes in the pulp's composition or how the fibers bond can greatly affect properties like strength, stiffness, and ductility. For example, fibers that are aligned more effectively with the direction of the load or demonstrate stronger bonding contribute to higher tensile strength and elastic modulus, whereas areas with weaker or poorly bonded fibers can act as points of stress concentration, hindering overall performance.

Furthermore, the production process itself can introduce added inconsistencies. During hot-pressing, uneven pressure or varying temperatures across the surface can lead to localized differences in density and fiber compactness. Generally, regions with higher density show better mechanical properties, benefiting from increased fiber interlocking, while less dense areas may serve as vulnerable points. Likewise, in the case of rough molded pulp, the absence of a pressing phase makes it prone to defects like voids, misaligned fibers, or non-uniform thickness, any of which can detract from its effectiveness.

Lastly, external conditions during or post-manufacturing might also influence these variations. Differences in drying conditions, such as humidity levels or drying speed, can affect the moisture content of the material and, in turn, its mechanical performance. Leftover moisture can diminish the stiffness and strength of the material, whereas excessive drying can lead to brittleness or micro-cracking.

To sum up, while molded pulp is known for being a sustainable and adaptable material, its mechanical properties are naturally subject to fluctuations caused by the inherent heterogeneity of the material, the conditions under which it is manufactured, environmental factors, and the techniques used in sample preparation. Gaining insight into and minimizing these factors is crucial for achieving consistent performance and for optimizing the material for various uses.

3.4.Enhancing the Mechanical Performance of Molded Pulp Materials

There are various approaches to bolster the tensile strength of molded pulp materials, utilizing lessons learned from tensile assessments. These suggestions center around refining material ingredients, enhancing manufacturing techniques, and maintaining uniformity in production.

Incorporating longer and superior quality cellulose fibers can greatly enhance tensile strength. Longer fibers provide better interlocking and load transfer, enhancing the material's structural integrity. Additionally, incorporating chemically or mechanically refined fibers can lead to stronger bonds between fibers.

Modifying pressing conditions like temperature, pressure, and the duration of pressing can greatly influence fiber adhesion and overall material density. It is vital to apply pressure and heat evenly to avoid weak spots that can arise from inconsistent densification. Additionally, enhancing the pulp refining method to achieve uniform fiber distribution and eliminating contaminants can diminish variability and boost mechanical properties. Pre-treating fibers with enzymes or chemicals could also enhance surface adhesion.

Irregular drying techniques might lead to inconsistencies in mechanical properties, risking the overall structure. Introducing real-time monitoring systems to measure thickness, density, and fiber arrangement throughout the production cycle can assist in detecting and addressing defects before they propagate in the manufacturing process.

Surface treatments or coatings, like water-based adhesives or biopolymer layers, increase strength due to the improved fiber connection and resistance against environmental factors. In addition, the coatings protect the material from moisture, which impairs the mechanical properties of the material.

In summary, improving the tensile strength of molded pulp materials requires a multi-faceted approach, addressing material selection, process refinement, and structural design. By implementing these strategies, molded pulp products can be optimized for diverse applications, bridging the gap between sustainability and mechanical performance.

4. SIMULINK

4.1. Energy Efficiency and Simulation of Compressed Air Systems

Compressed air systems, vacuum systems and water transmission circuits are important fluid systems frequently used in industrial applications. These systems are widely used in facilities where molded pulp packaging products are produced. In fact, the proper and trouble-free operation of these systems is very important in order to avoid problems with production. Proper design and analysis of these systems is of great importance in order to reduce costs and increase efficiency. Programs such as MATLAB, Dymola, Amesim are some of the programs commonly used to perform such analyses and simulations. In this section, previous research on compressed air, vacuum and water transmission systems is reviewed and the theoretical foundations that will contribute to the thesis are summarized.

4.1.1. Compressed Air Systems

Compressed air systems are widely used for different purposes in many industrial processes. It can be used for many different purposes such as energy transmission, actuator control and cleaning processes. In molded pulp packaging production facilities, it is used to separate the pulp from the mold after it has taken shape and to allow it to continue with the next processes. The basis of these systems is based on the principle of compressing air and storing it in air tanks and directing this air through valves and using it. Despite their widespread use, compressed air systems are known for their high energy consumption and low efficiency. Therefore, it is critical that they are optimized for energy saving. This section examines the latest developments in modeling, optimization and energy efficiency improvements of compressed air systems.

4.1.2. Energy Efficiency of Compressed Air Systems

Compressed air systems represent a large portion of industry energy use, with the indication that they can account for 10-30% of industrial electricity use in individual countries. Compressed air, the study reports, is among the most inefficient types of energy because only 10 to 30 percent of the air generated reaches the point of use, while the remaining air is lost through leaks and heat dissipation, as well as through inefficient designs.

The authors highlight the significance of effective system design, particularly the choice of variable speed drive (VSD) compressors instead of fixed speed drive (FSD) compressors to enhance energy efficiency. VSD compressors modify their motor speed according to demand, leading to lower energy usage compared to FSD compressors, which run at a constant speed no matter the variations in demand.

The energy efficiency of VSD and FSD compressors for a variety of air flow outputs is contrasted in Figure 36 As can be seen, when a compressor is operating at a part-load for extended periods of time, VSD compressors can be financially appealing. A FSD uses less energy than a VSD while producing the same amount of air flow, making it more efficient when operating at full load. On the other hand, because a VSD uses a lot less energy when under partial load, it is more appropriate and energy efficient than an FSD.

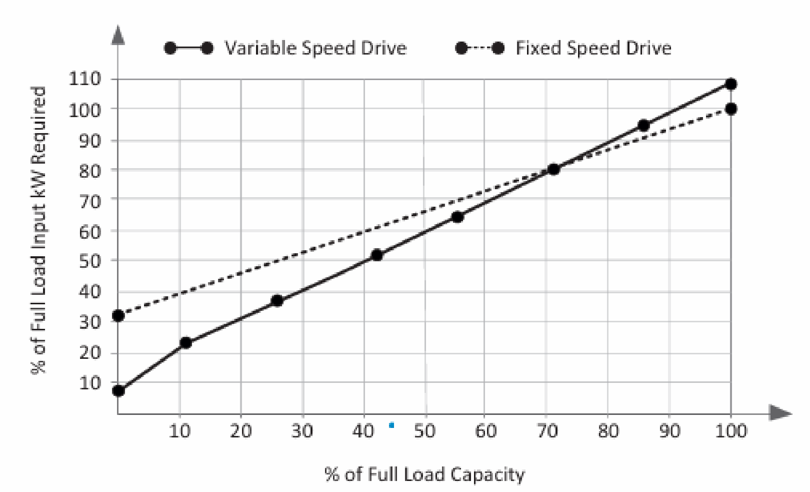


Figure 36: Energy Efficiency Comparison of VSD and FSD Compressors

The study also highlights significant challenges in compressed air systems, including oversized compressors, inadequate control systems, and inefficient operational strategies. The authors suggest that simulation modeling can be an effective tool for examining various system configurations and pinpointing potential energy-saving opportunities [46].

4.1.3. Modeling and Simulation of Compressed Air Systems

Simscape is a modeling environment provided by Simulink, a tool developed within the MATLAB ecosystem, designed for modeling, simulation, and analysis of physical systems. The fact that physical systems (tanks, pumps, sensors, etc.) are included in the application library as ready-made blocks provide great convenience to users in terms of modeling.

The primary elements of a compressed air system, such as compressed air generation, preparation, and distribution, are depicted in Figure 37. The compressor converts the electrical energy it uses into the internal energy of the pressured air before delivering it to the customers. [47].

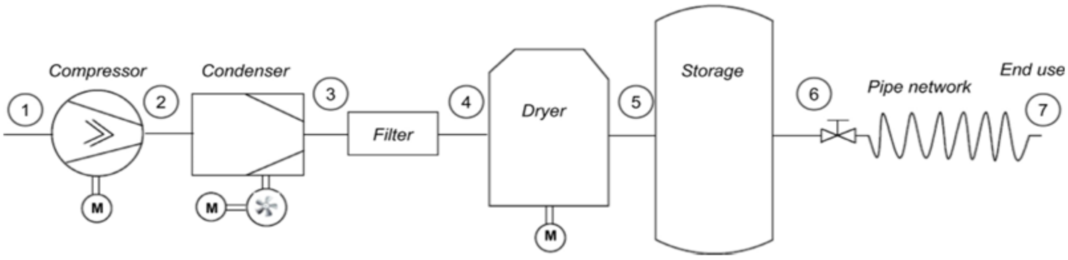


Figure 37: Components Commonly Found in Compressed Air Systems

Figure 38 shows the dynamics that occur when a gas flow enters a pressurized tank using a compressor. The mass flow rate controlled by the compressor monitors the temperature, pressure, mass, and heat flow rate of the gas entering the tank via sensors. The diagram describes the overall structure of the model and the interactions between the components.

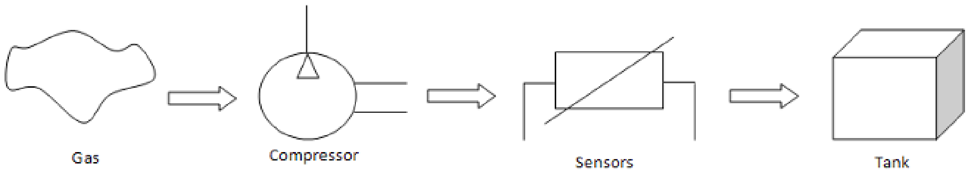


Figure 38: The Model Dynamics

Figure 39 shows the code structure of the pressure tank model created in the Simscape environment. The model includes main components such as a compressor, sensors and a gas tank, and is designed to examine the dynamic variables of the gas such as temperature, pressure and mass flow over time.

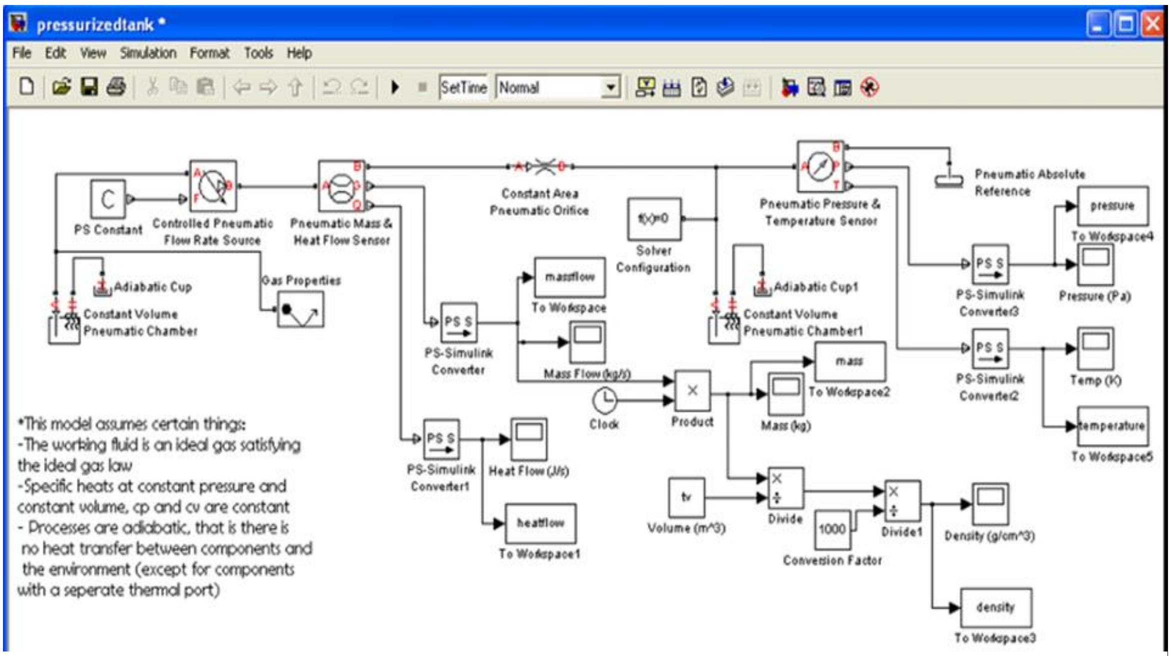


Figure 39: The Simscape Code of the Pressurized Tank Model

Figure 40 shows the graphical user interface developed for the pressure tank model. The interface allows users to specify the initial conditions of the tank and gas (volume, pressure, temperature), control the gas flow rate, and set the simulation time. In addition, the results of the simulation are visualized with six different graphs.

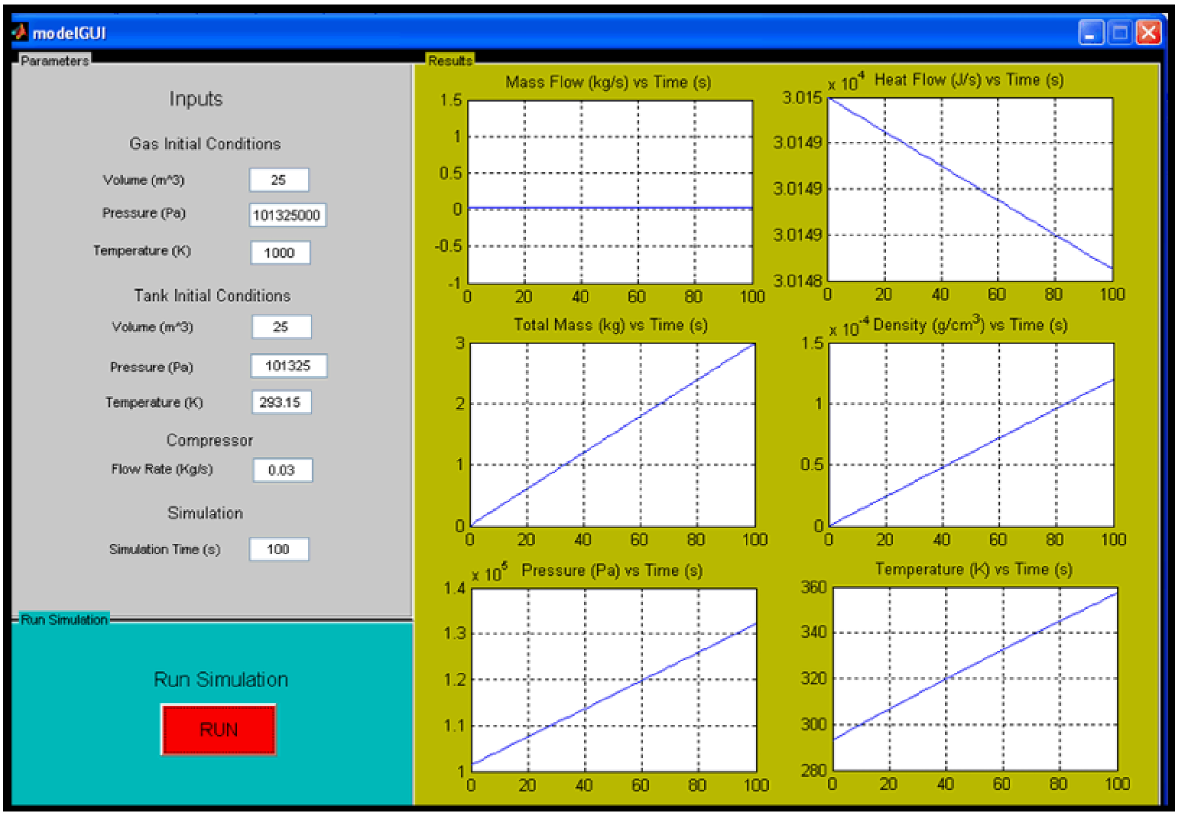


Figure 40: The GUI for the model

The pressurized tank model in this study features essential components such as a compressor, sensors, and a gas tank, all linked via Simscape's Pneumatic Block Library. This model allows for the simulation of the tank's behavior based on specific initial conditions, including volume, pressure, and temperature. Users can adjust parameters like gas flow rate and simulation time through an intuitive graphical user interface. The simulation outputs include plots that display mass flow rate, heat flow rate, total mass, density, tank pressure, and temperature over time. These results provide valuable insights into the dynamic performance of compressed air systems, highlighting aspects such as the stabilization of mass flow rate and changes in adiabatic temperature [48].

4.2.Modeling Of the Subsystems Used in The Production Facility with Simscape

This study was carried out in the MATLAB Simscape environment in order to examine the dynamic behavior of compressed air systems and to model the interactions between the components in the system section. The model was designed to reveal the relationship between various parameters and the pressure generated. Figure 41 shows the modeling of the compressed air system in the MATLAB-Simscape environment and the interconnection of the components. This model represents a compressed air system consisting of a positive displacement compressor, piping, constant volume tanks, pressure relief valve, and other related components. In real life, this model can be used to understand the performance of industrial compressed air systems.

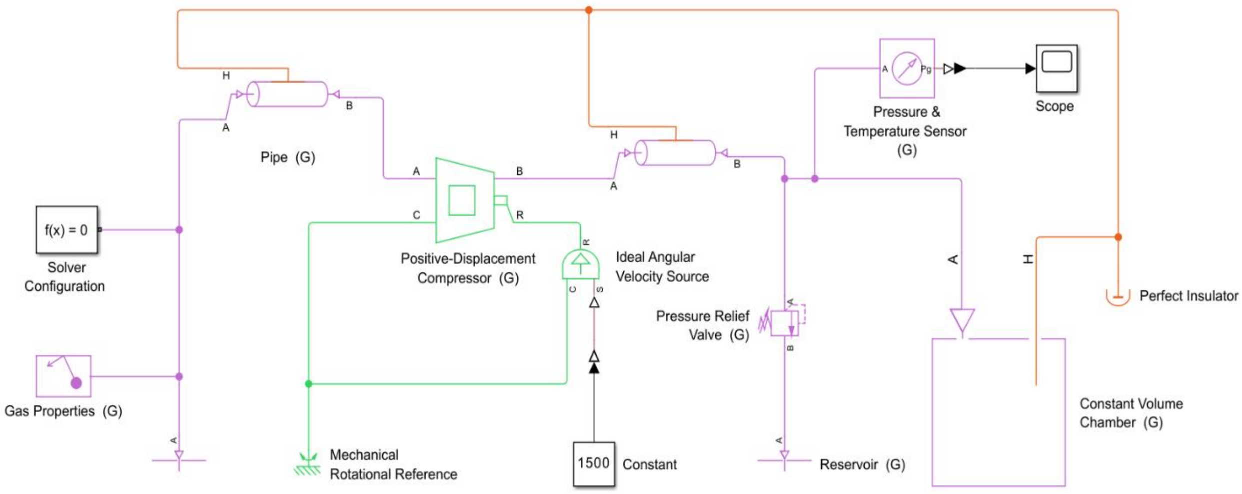


Figure 41: Modeling of Compressed Air System in Simscape Environment

A positive displacement compressor creates airflow by rotating at a certain speed and increases the airflow to a constant pressure level. The pipes are the channels through which the flow travel and affect parameters such as pressure loss and flow rate. The pressure relief valve releases excess pressure from the system when a certain pressure level is exceeded. The fixed volume tank is used to monitor pressure and temperature changes. Sensors measure pressure and temperature values and collect data as a result of the simulation.

The simulation was carried out under different operating scenarios. The parameter values for each scenario are shown in Table 6. The first scenario is to show the effect of compressor speed, the third scenario is to show the effect of pipe length, and the fourth scenario is to show the effect of tank volume on the pressure change in the tank. Gas was selected as the ideal gas. The flow in the pipes is assumed to be laminar. Heat transfers in the system are neglected. The simulation time was set as 20 s.

Figures below show the parameters and initial conditions of the components in the modeling.

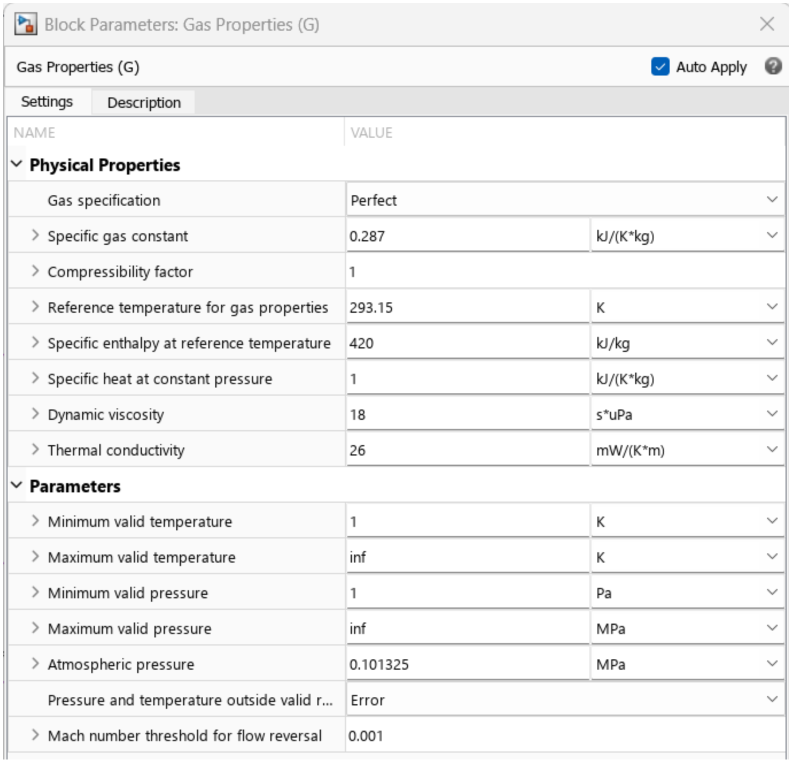


Figure 42: Properties of The Gas Used in The CA System Modeling

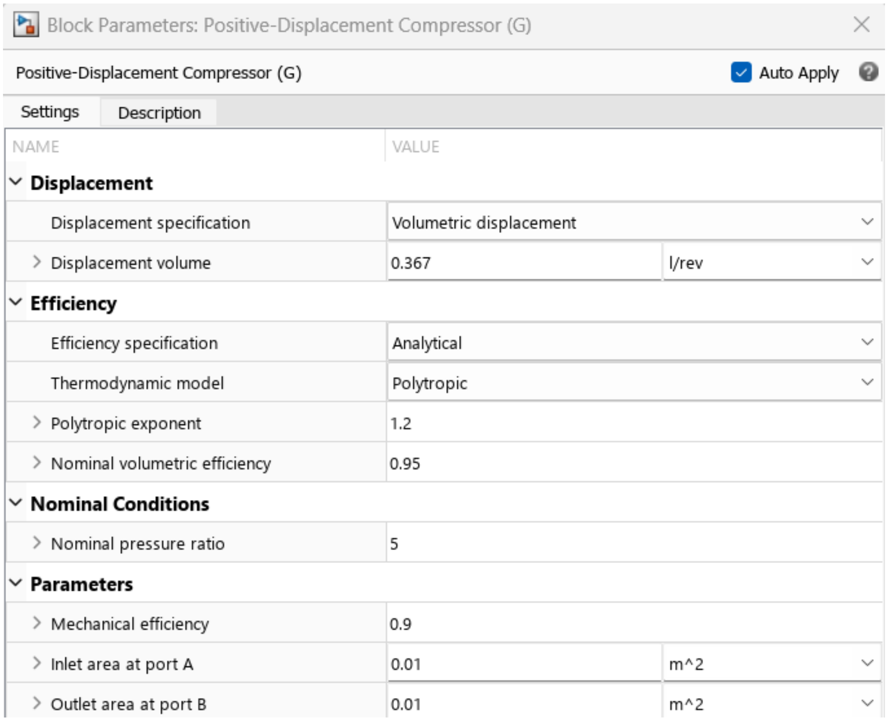


Figure 43: Properties of the Compressor Used in the CA System Modeling

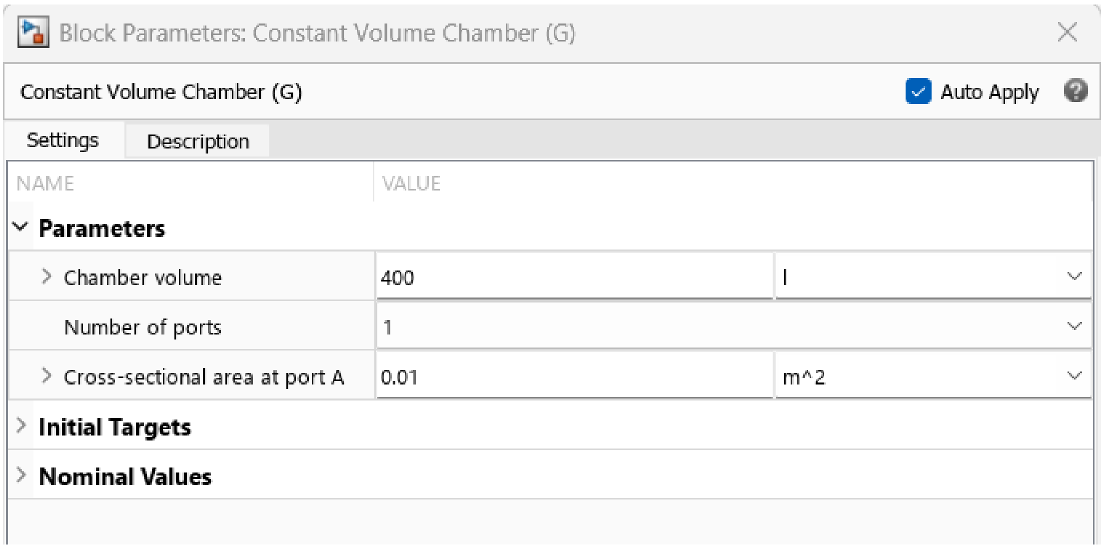


Figure 44: Properties of the Constant Volume Chamber Used in the CA System Modeling

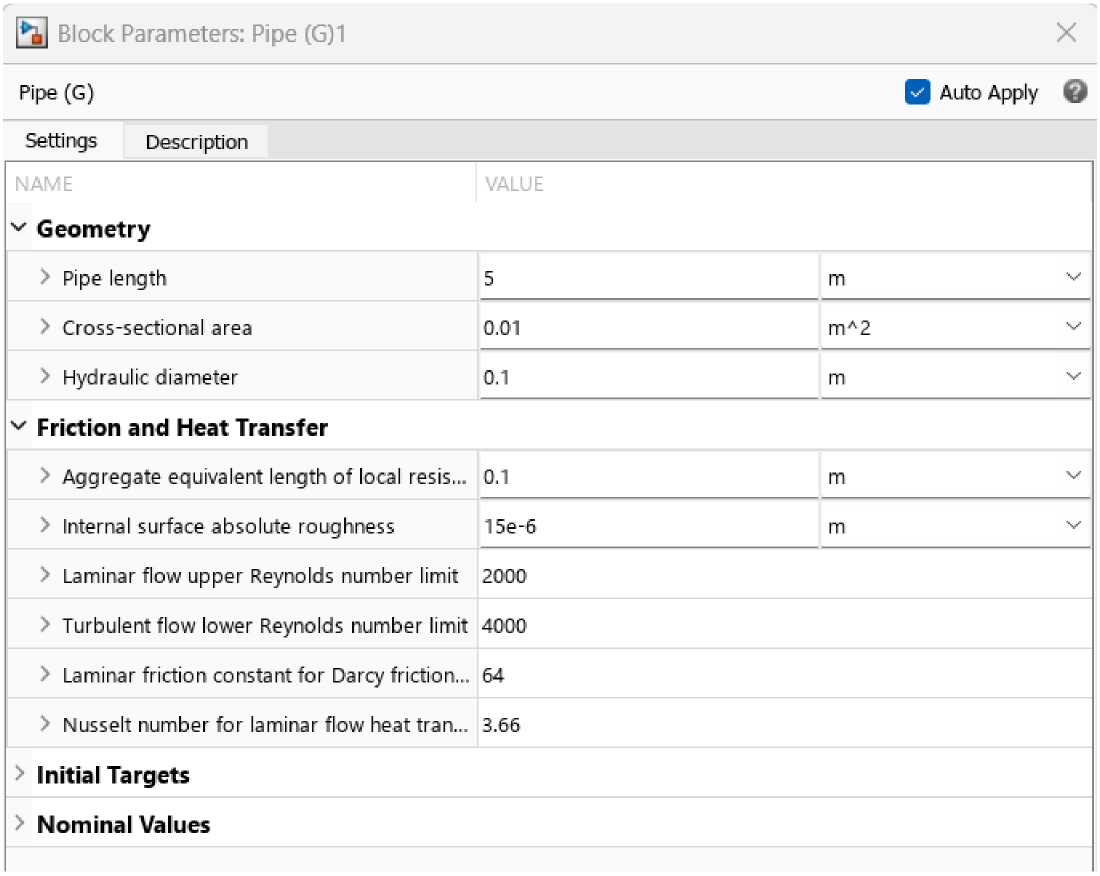


Figure 45: Properties of the Pipes Used in the CA System Modeling

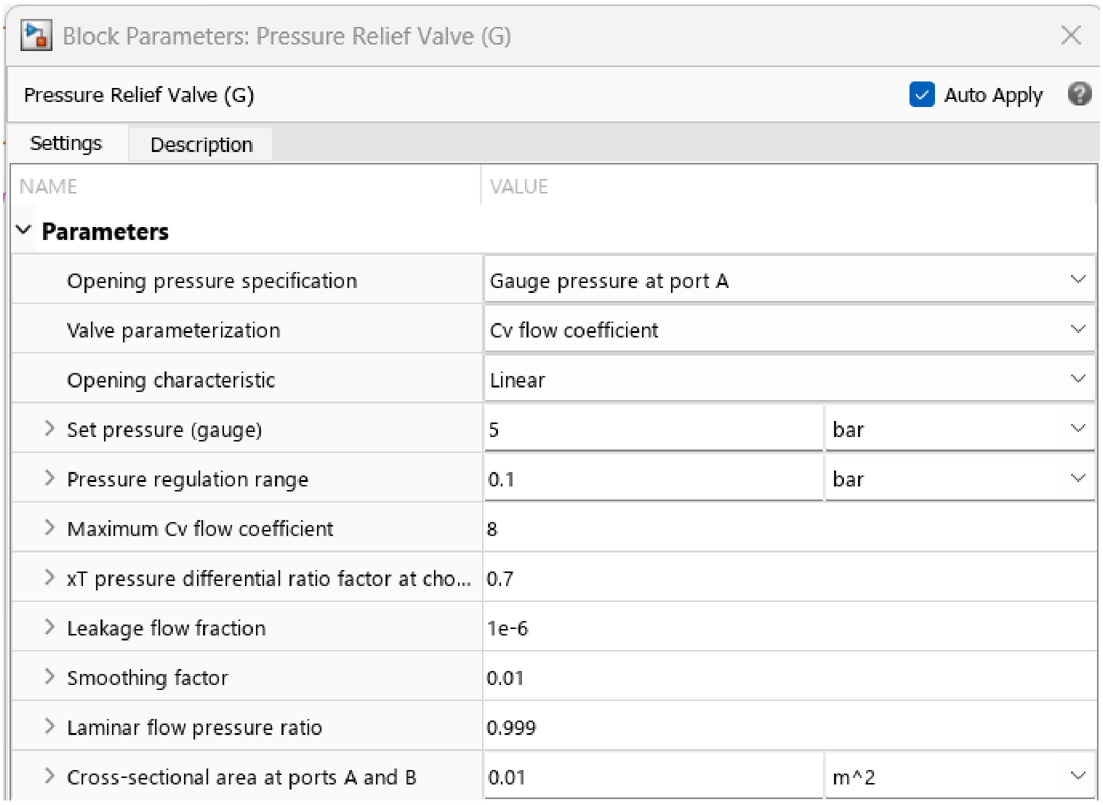


Figure 46: Properties of the Relief Valve Used in the CA System Modeling

Table 6: Table of Parameters with Different Scenarios for CA System

	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Compressor Speed (rpm)	1500	2000	1500	1500
Pipe Length (m)	5	5	7	5
Tank Volume (L)	400	400	400	250
Initial Tank Pressure (bar)	0	0	0	0
Pressure Relief Valve (Gauge Pressure) (bar)	5	5	5	5

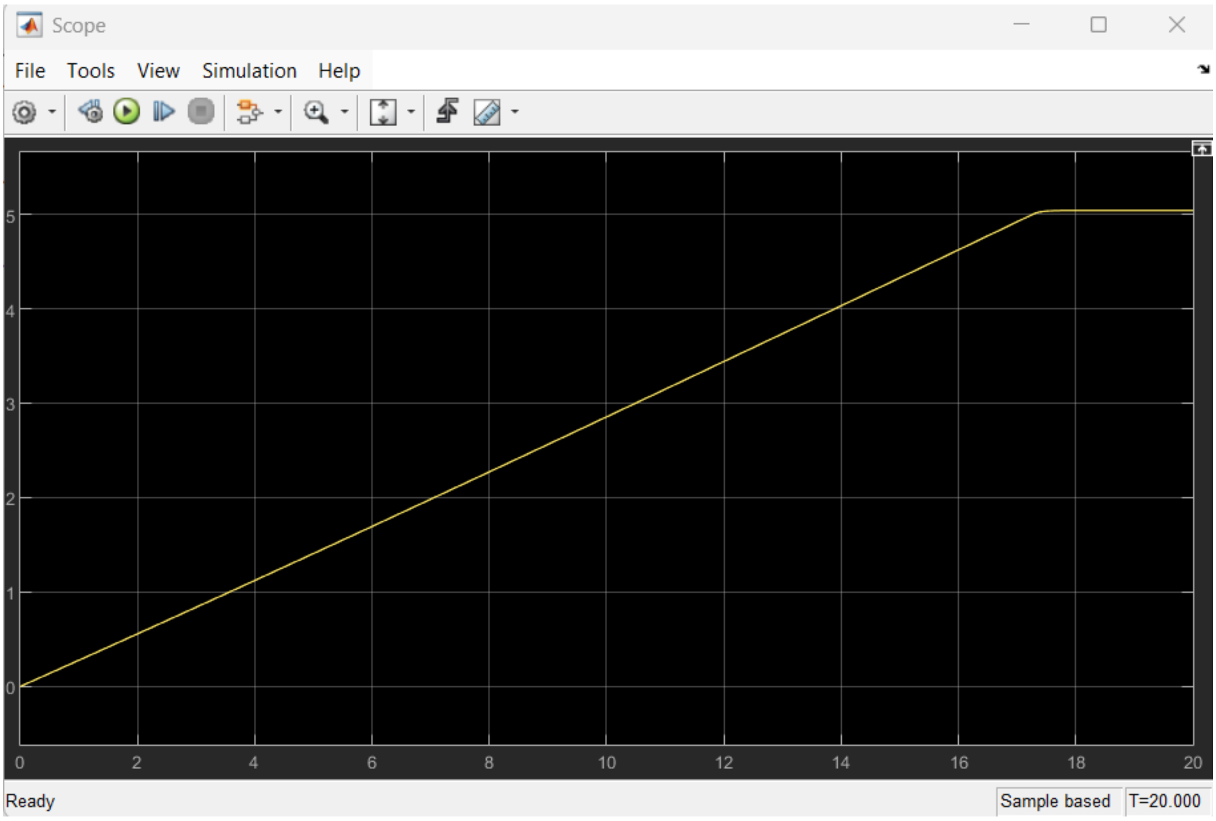


Figure 47: Pressure(bar) vs Time(s) Plot for Scenario 1 of CA System

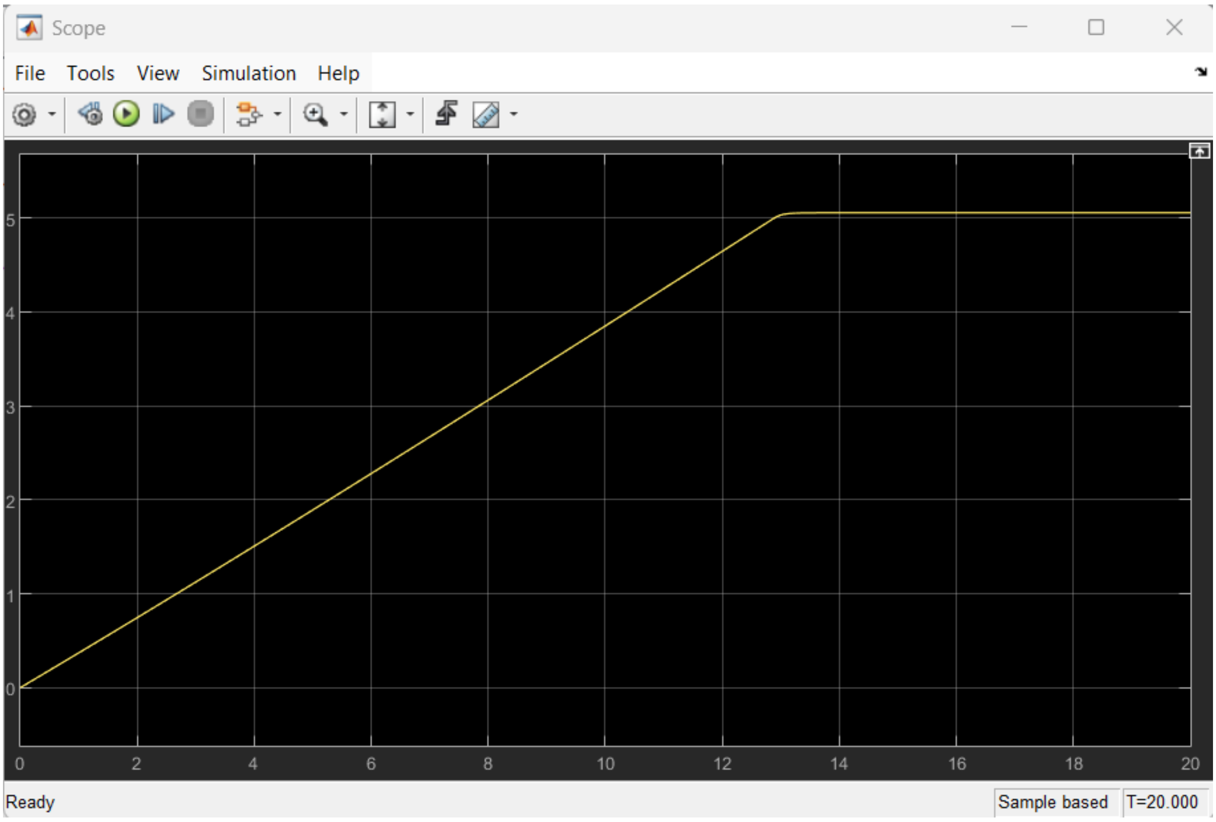


Figure 48: Pressure(bar) vs Time(s) Plot for Scenario 2 of CA System

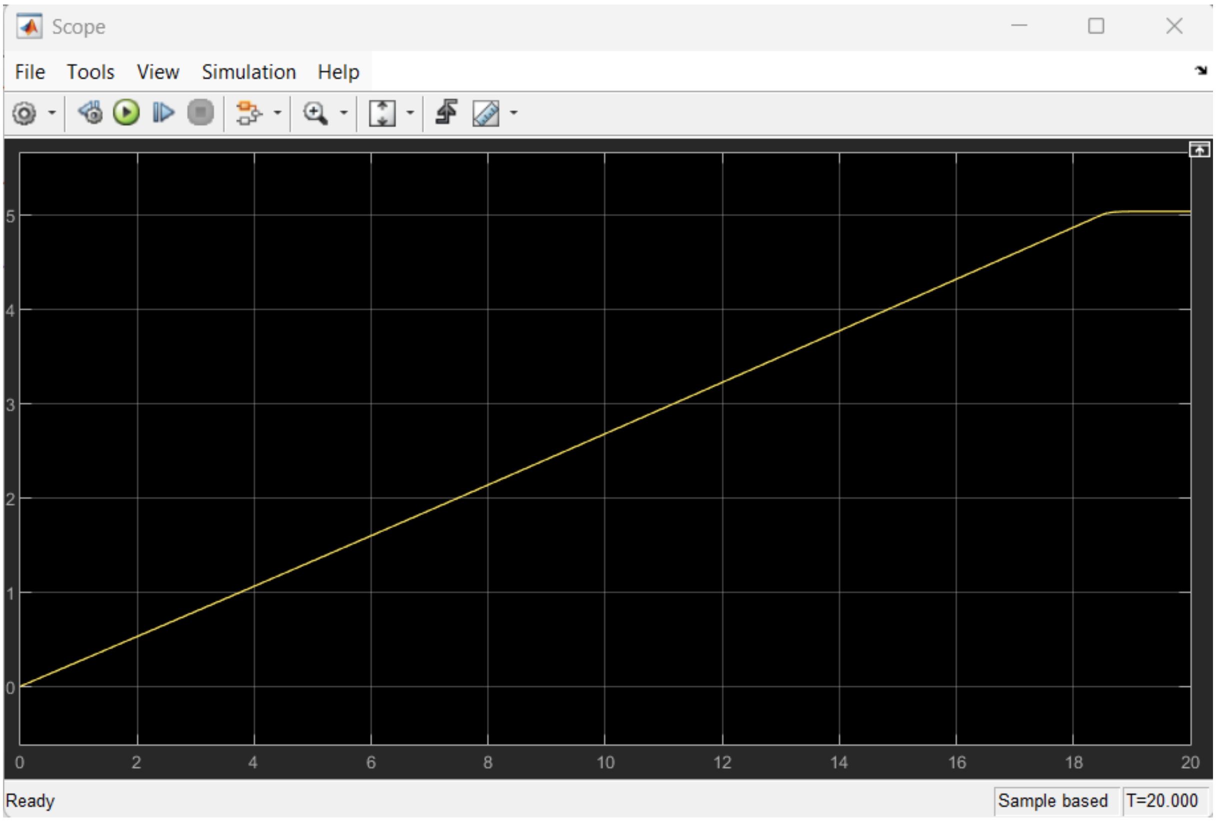


Figure 49: Pressure(bar) vs Time(s) Plot for Scenario 3 of CA System

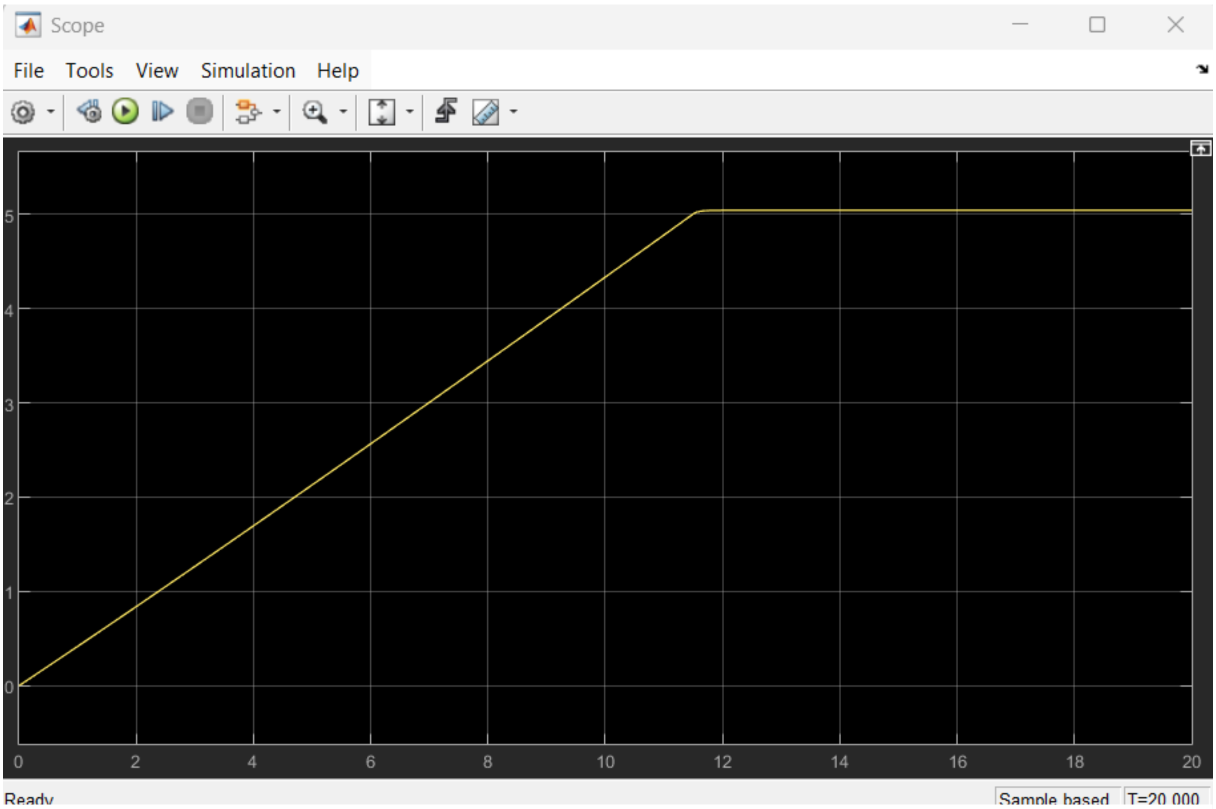


Figure 50: Pressure(bar) vs Time(s) Plot for Scenario 4 of CA System

This modeling can be used as an effective tool to understand the behavior of compressed air systems and optimize system performance. Unlike what is done here, other desired parameters can be selected and the relationship between them can be observed and optimization studies can be performed, studies can be performed with different gas types (argon, nitrogen, etc.) and model verification can be performed with real-time data.

The aim of the Vacuum System modeling is to simulate a vacuum system model using Simscape and analyze the system dynamics. Modeling allows us to predict the physical behavior of the system and to see how the design parameters affect the system dynamically. Simscape's physics-based modeling capabilities were used in this process and allowed the vacuum system design to be realized more quickly and accurately.

Vacuum systems generally aim to create a low-pressure area by removing gas from the environment. As seen in Figure 51, this system is modeled using elements such as gas properties, a constant-volume chamber, a pipeline, a flow rate source, and a pressure sensor.

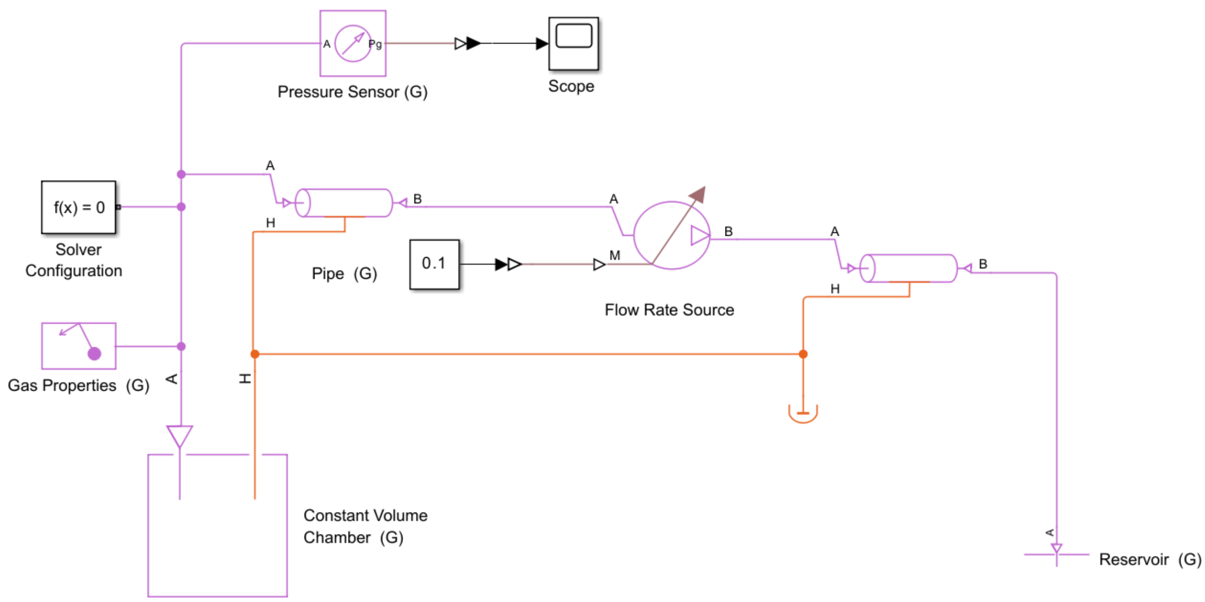


Figure 51: Modeling of Vacuum System in Simscape Environment

This simulation was also conducted under different scenarios. The first scenario aimed to understand the effect of the flow source, the second scenario aimed to understand the effect of the length of the pipes and finally the effect of the tank volume on the pressure in the tank. These parameters are shown in Table 7. Gas was selected as the ideal gas. The flow in the pipes is assumed to be laminar. Heat transfers in the system are neglected. The simulation time was set as 10 s.

Figures below show the parameters and initial conditions of the components in the modeling.

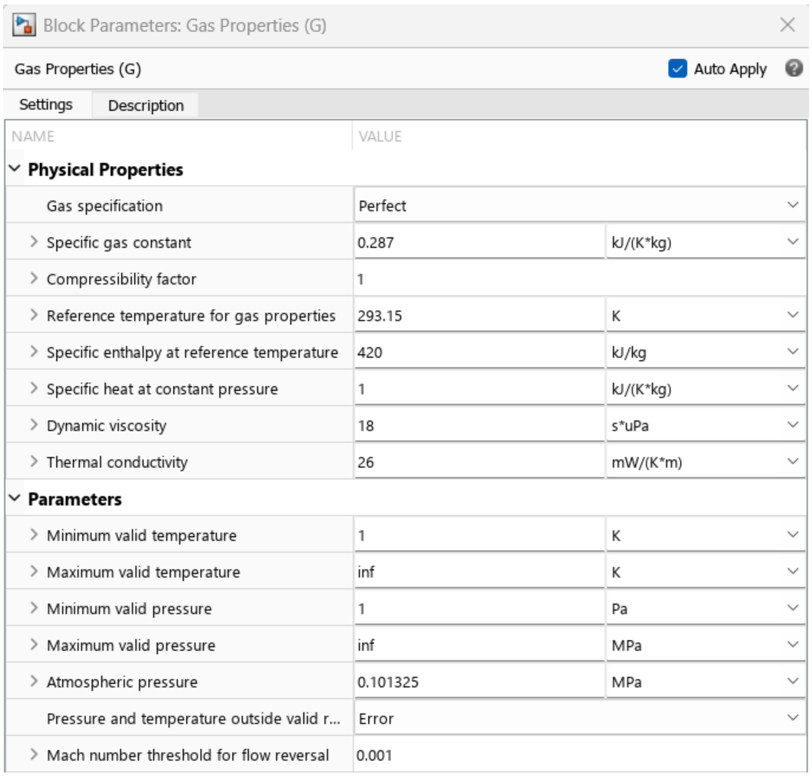


Figure 52 : Properties of the Gas Used in the Vacuum System Modeling

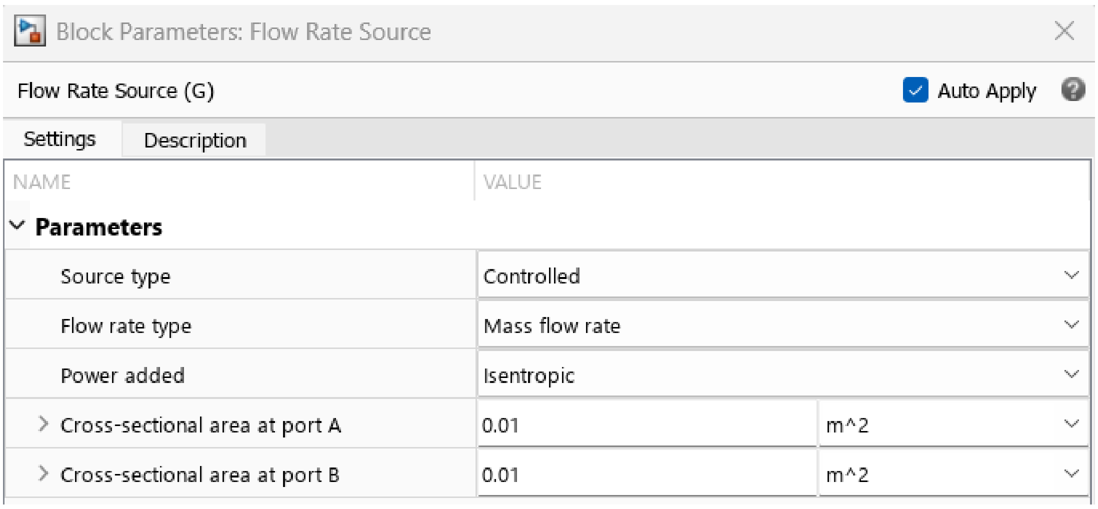


Figure 53: Properties of the Flow Rate Source Used in the Vacuum System Modeling

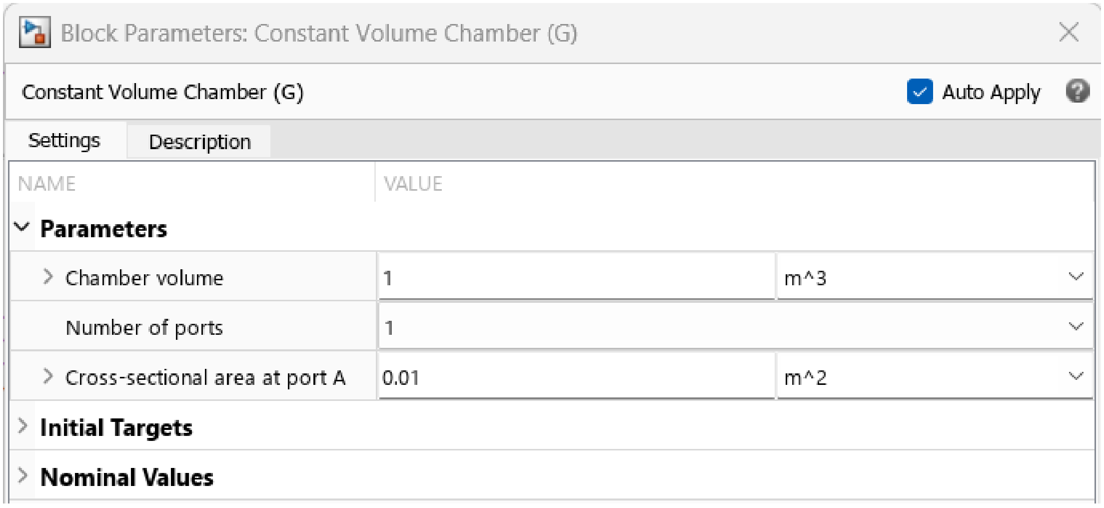


Figure 54: Properties of the Constant Volume Chamber Used in the Vacuum System Modeling

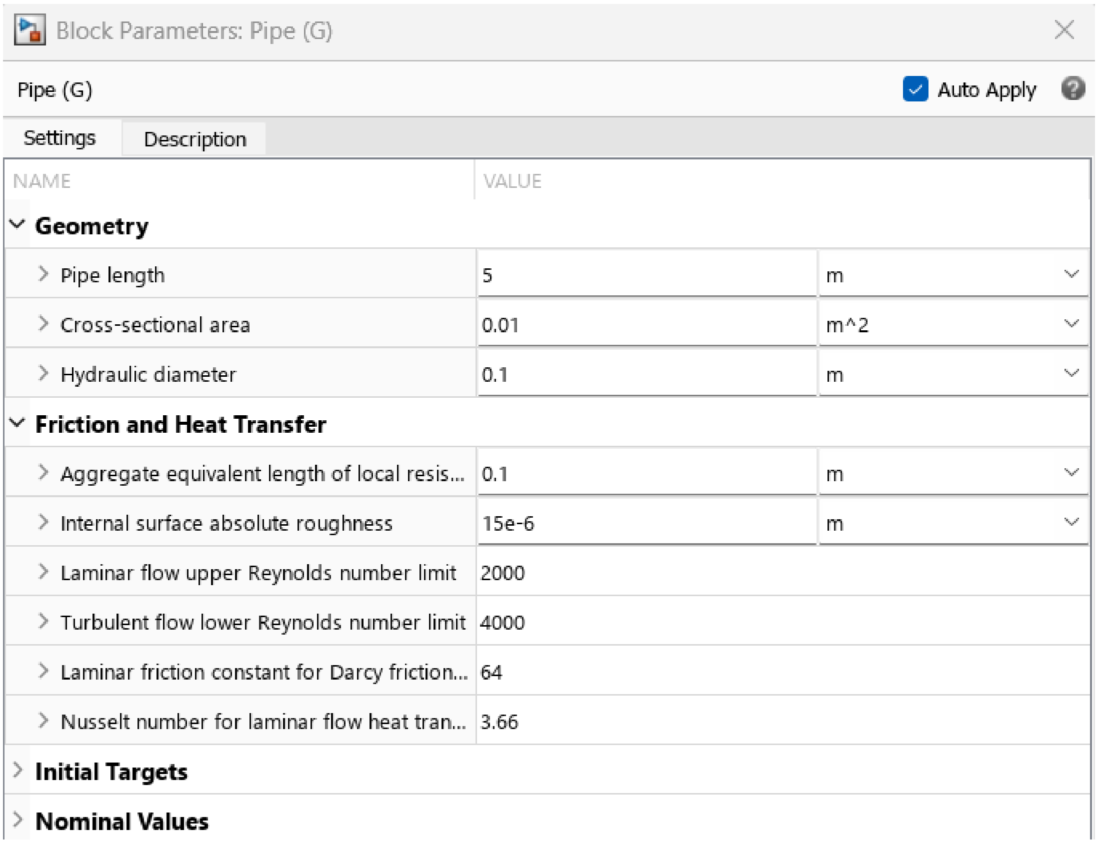


Figure 55: Properties of the Pipes Used in the Vacuum System Modeling

Table 7: Table of Parameters with Different Scenarios for The Vacuum System

	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Flow Rate Source (Kg/S)	0.01	0.03	0.01	0.01
Pipe Length (M)	5	5	10	5
Tank Volume (L)	400	400	400	200
Initial Vacuum Tank Pressure (Gauge Pressure) (Bar)	0	0	0	0

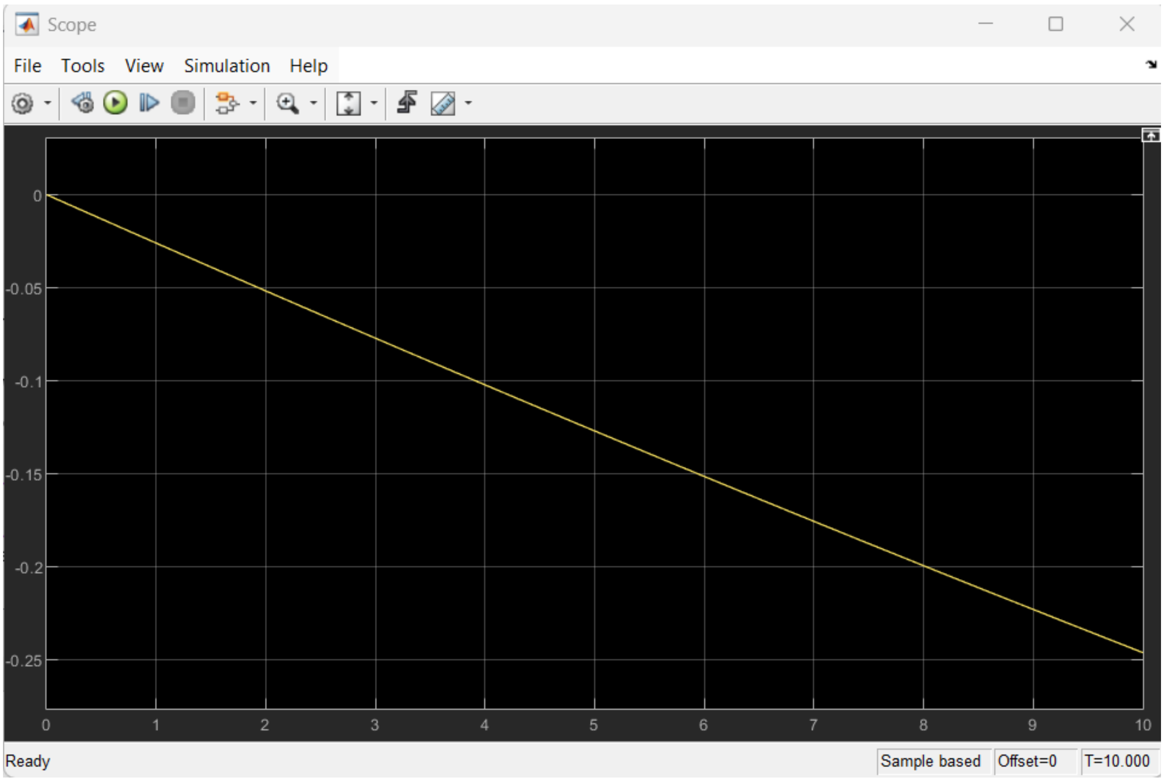


Figure 56: Pressure(bar) vs Time(s) Plot for Scenario 1 of Vacuum System

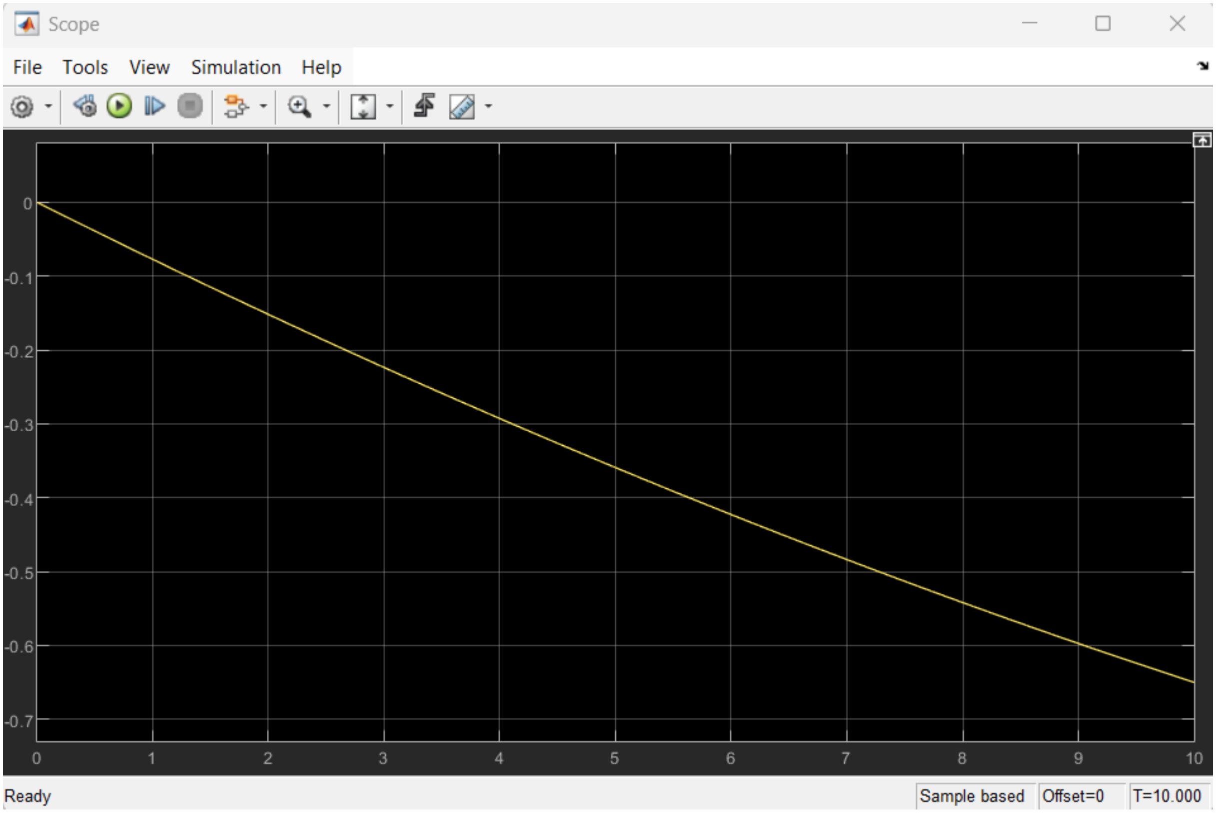


Figure 57: Pressure(bar) vs Time(s) Plot for Scenario 2 of Vacuum System

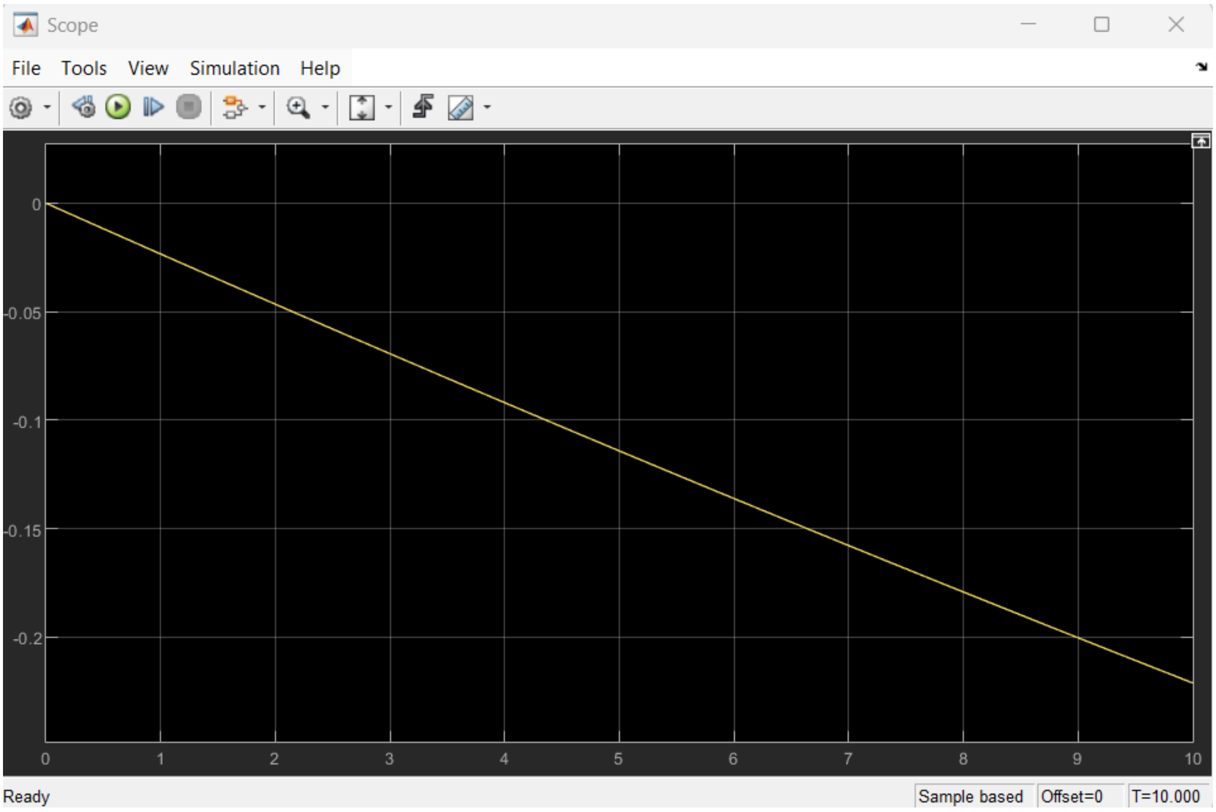


Figure 58: Pressure(bar) vs Time(s) Plot for Scenario 3 of Vacuum System

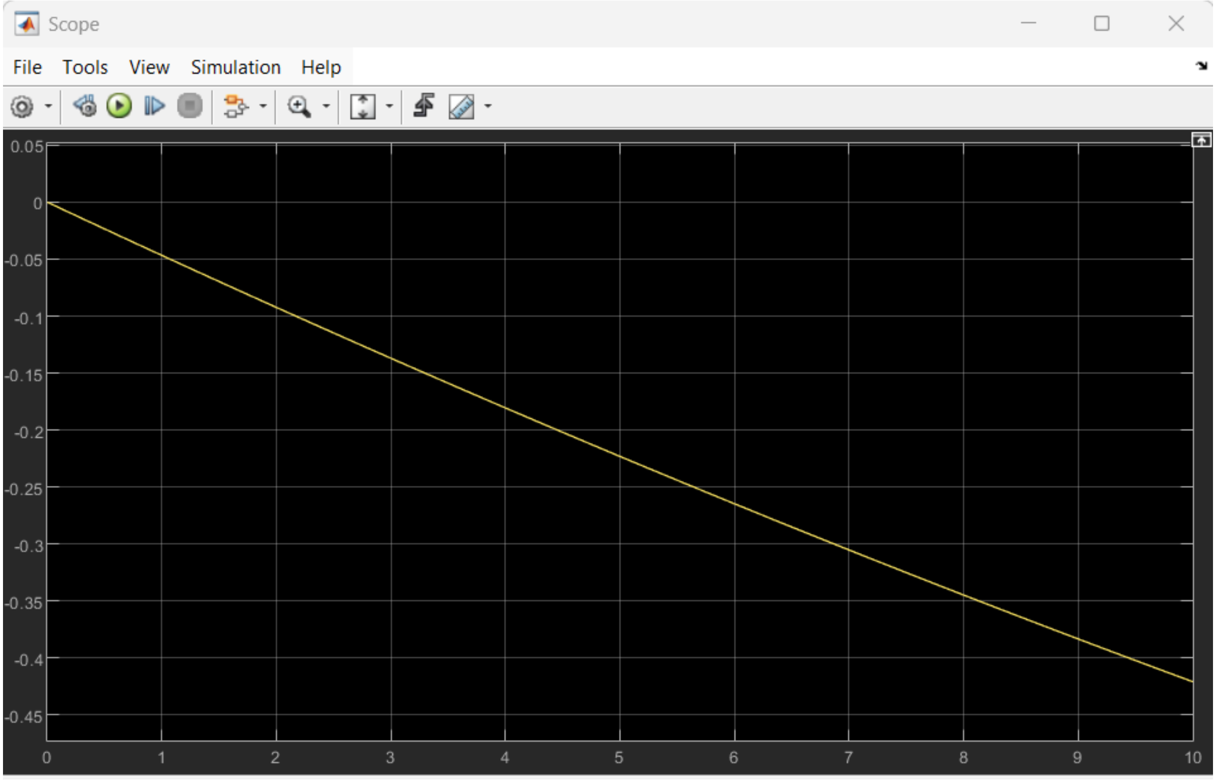


Figure 59: Pressure(bar) vs Time(s) Plot for Scenario 4 of Vacuum System

The model successfully reflects the gas dynamics, but it may not be realistic to assume that the flow velocity in the pipes is completely laminar. For a more detailed model, temperature effects and compressibility of the gas can be considered. The system can be optimized by changing the parameters.

The production of molded pulp packing material, use of compressed air and vacuum systems should be optimized for the increase in production efficiency and quality management (in molding) operation. These systems are very important as they are at the core of fundamental processes like correct pulp placement in molds, removing extra water and molding the final shape of the product. Original modeling study carried out aiming at several ultimate goals. Since compressed air and vacuum systems are a significant energy consumer, the application with the main goal of improving their energy efficiency. Modelling these systems will allow for unnecessary energy use to be minimized and energy improvement opportunities identified.

Secondly, the modelling study can be enhanced to guarantee that product quality remains at a consistent level through improvements in modeling. If vacuum levels are adequate, the pulp is adequately spread on the mold and presents a controlled use of compressed air lowers damaging products release of the mold. Accessing these quality standards by modelling gives the parameters necessary which have minimum influence on these in real systems as well and modeling can aid in process to be optimized such that the most suitable operating parameters of the systems will be chosen thus production speed will be increased.

Overall, the fundamental principles of modelling compressed air and vacuum systems for improvement in energy efficiency, product quality and process optimization of production process in bound to mould pulp packaging production. It will also serve to facilitate the enhancement/ reinforcement of existing systems and enable the construction of new systems, in compliance with the sustainability route of molded pulp packaging production.

5. CONCLUSION

This thesis presents an investigation into molded pulp packaging, a sustainable alternative to conventional materials like expanded polystyrene. The study integrates a detailed exploration of product properties, production processes, and tooling techniques with experimental analyses and computational modeling to propose advancements in the field.

Through an extensive literature review, the thesis captures the evolution of molded pulp packaging, discussing its historical context, material classifications, and inherent advantages and disadvantages. The analysis delves into the production line and tooling aspects, offering insights into the operational intricacies that shape the mechanical and environmental properties of molded pulp products. Key comparisons with EPS, including cushioning properties, stress-strain relationships, and degradation behavior, further underscore its potential as a viable and eco-friendly packaging solution.

In the experimental phase of this study, tensile tests were conducted on different samples of molded pulp materials to evaluate their mechanical performance. The results demonstrated notable differences in mechanical properties, primarily attributed to the pressing methods and fiber density. These findings underscore the importance of manufacturing techniques in achieving tailored material characteristics suitable for diverse packaging applications.

In the modeling phase, MATLAB Simscape was utilized to simulate the energy efficiency of compressed air systems integral to the production line. The simulations provided valuable data on optimizing vacuum and compressor performance, reducing energy consumption, and improving overall process sustainability.

This comprehensive approach not only deepens the understanding of molded pulp packaging but also bridges the gap between theoretical knowledge and practical application. Future research could extend these findings by incorporating novel additives, improving production techniques, and refining system simulations to enhance the scalability and efficiency of molded pulp packaging technology.

6. REFERANCES

[1] About MoldedFiber- International Molded Fiber Association n.d.

[2] Mrittika Debnath, Roman Sarder, Lokendra Pal, and Martin A. Hubbe. Debnath et al. (2022). “Molded pulp packaging review,” BioResources. Bioresources 2022;17:3810–70. https://doi.org/10.15376/biores.17.2.Debnath.

[3] Pros and Cons of Molded Pulp Packaging 2021.

[4] Martin L. Keyes. Machine for molding articles from pulp. 1904.

[5] M. Koppelman and S. Cooper. Packaging for fragile articles 1922.

[6] S. Price and E. C. Sloan. Package 1940.

[7] R. Wever, C. Boks, H. Van Es, A. Stevels. Multiple Environmental Benchmarking Data Analysis and its implications for design: a case study on packaging. International Symposium on Environmentally Conscious Design and Inverse Manufacturing 2005. https://doi.org/doi:10.1109/ECODIM.2005.1619353.

[8] R. Wever, D. Twede. The History of Molded Fiber Packaging; a 20th Century Pulp Story 2007.

[9] M.A. MacGregor. Wet Pressing Research in 1989 – An Historical Perspective, Analysis and Commentary. Trans of the IXth Fund Res Symp Cambridge, 1989 2018:511–86.

[10] Kit L. Yam, editor. The Wiley Encyclopedia of Packaging Technology. John Wiley & Sons, Inc., Hoboken, NJ, USA; 2009.

[11] Kristian Søllner. A system and a method for producing a molded article, such as a bottle 2016.

[12] Karim Y.P. Martínez, Eli A.V. Toso, Reinaldo Morabito. Production planning in the molded pulp packaging industry. Computers & Industrial Engineering 2016:554–66. https://doi.org/10.1016/j.cie.2016.05.024.

[13] Matthew P. Westman, Leonard S FifieldLeonard S. Fifield, Kevin Simmons, Tyler A. Kafentzis. Natural Fiber Composites: A Review. US Dept of Energy 2010. https://doi.org/10.2172/989448.

[14] Khandoker S. Salem, Ved Naithani, Hasan Jameel, Lucian Lucia, and Lokendra Pal. Lignocellulosic Fibers from Renewable Resources Using Green Chemistry for a Circular Economy. Global Challenges 2021;4. https://doi.org/10.1002/gch2.202000065.

[15] D. Fengel, M. Stoll. Crystals of cellulose grown from TFA solution. Wood SciTechnol 1989;23:85–94. https://doi.org/10.1007/BF00350610.

[16] Alavi, S., Thomas, S., Sandeep, K. P., Kalarikkal, N., Varghese, J., and Yaragalla, S. Polymers for Packaging Applications. Apple Academic Press 2014. https://doi.org/10.1201/b17388.

[17] J. Pere, E. Pääkkönen, Y. Ji, E. Retulainen. Influence of the Hemicellulose Content on the Fiber Properties, Strength, and Formability of Handsheets. BioResources 2019;14:251–6. https://doi.org/10.15376/biores.14.1.251-263.

[18] van de Wouwer, D., Vanholme, R., Decou, R., Goeminne, G., Audenaert, D., Nguyen, L.,Höfer, R., Pesquet, E., Vanholme, B., and Boerjan, W. Chemical Genetics Uncovers Novel Inhibitors of Lignification, Including p-Iodobenzoic Acid Targeting Cinnamate-4-Hydroxylase. Plant Physiology 2016;172:198–220. https://doi.org/10.1104/pp.16.00430.

[19] Wang, Q.-L., Xiao, S.-L., Shi, S. Q., and Cai, L.-P. Effect of light-delignification on mechanical, hydrophobic, and thermal properties of high-strength molded fiber materials. Scientific Reports 2018;8:2–11. https://doi.org/10.1038/s41598-018-19623-4.

[20] Gouw, V. P., Jung, J., Simonsen, J., and Zhao, Y. Fruit pomace as a source of alternative fibers and cellulose nanofiber as reinforcement agent to create molded pulp packaging boards. Composites Part A: Applied Science and Manufacturing 99 2017:48–57. https://doi.org/10.1016/j.compositesa.2017.04.007.

[21] Chen, J., Qin, Z., Xu, Z., Wu, L., Wei, Y., Wang, X., and Duns, G. J. Utilization of an invasive species (Spartina alternifolia) in the molded pulp industry, 2012, p. 137–46.

[22] Ehrhardt, S., and Leckey, J. Fluid resistance: The sizing of paper. Make Paper Products Stand Out: Strategic Use of Wet End Chemical Additives, TAPPI Press; 2020, p. 53–75.

[23] Liu, T.-H., Wang, Y., Zhou, J., Li, M.-Y., and Yue, J.-Q. Preparation of Molded Fiber Products from Hydroxylated Lignin Compounded with Lewis Acid-Modified Fibers Its Analysis. Polymers 2021 2021;13. https://doi.org/10.3390/polym13091349.

[24] Bildik Dal, A. E., Hubbe, M. A., and Pal, L. Cationic emulsions of maleic anhydride derivatives of oleic and abietic acid for hydrophobic sizing of paper. TAPPI Journal 2020 2020;19:281–90. https://doi.org/10.32964/TJ19.6.281.

[25] Strazdins, E. Theoretical and practical aspects of alum use in papermaking,. Nordic Pulp & Paper Research Journal n.d.;4:128–34. https://doi.org/10.3183/npprj-1989-04-02-p128-134.

[26] T. Noguchi, M. Miyashita, J. Seto, and M. Kawano. Development of moulded pulp materials for the packaging of electronic equipment 1998:161–8. https://doi.org/10.1002/(SICI)1099-1522(19970501/30)10:3<161::AID-PTS391>3.0.CO;2-1.

[27] Y. J. Sung, J.-Y. Ryu, H. J. Kim, T. K. Kim, and B. K. Song. Improvement of Drainage at Wet Pulp Mold Process. Journal of Korea Technical Association of The Pulp and Paper Industry 2004.

[28] G. B. Gavazzo, R. Lanouette, and J. L. Valade. Production of molded pulp at laboratory scale. Progress in Paper Recycling 2005;14:20–5.

[29] B.-U. Cho, J.-Y. Ryu, and B.-K. Song. Factors influencing deflaking kinetics in repulping to produce molded pulp. Journal of Industrial and Engineering Chemistry 2009;15:119–23. https://doi.org/10.1016/j.jiec.2008.08.003.

[30] I. Park, J.-N. Kim, D. Kim, and Y. Lee. Effects of Mixing Ratio of ONP and OCC on Physical Properties of Pulp Molds for Cushion Packaging Materials. Journal of Korea Technical Association of The Pulp and Paper Industry 2008;40.

[31] S. Li, G. Sun, R. Yang, and L. Ding. Preliminary Study on Molded Pulp Products byUsingBlast FurnaceSlag Fibre. Proceedings of International Conference on Pulping, Papermaking and Biotechnology, 2008, p. 132–5.

[32] X. Wang, X. Shi, H. Xu, and H. Yuan. The Research on Dyeing Performance of Meliorated Pulp with Chitosan for Producing Color Molded Pulp Products Packaging Food. Research Progress in Paper Industry and Biorefinery: 4th ISETPP 2010:2026–9.

[33] W. Sridach. Preparation and characterization of moulded pulp container made by hot compression moulding. IPPTA: Quarterly Journal of Indian Pulp and Paper Technical Association 2014;26:89–95.

[34] Aguerre, Y. S., and Gavazzo, G. B. Lignocellulosic Recycled Materials to Design Molded Products: Optimization of Physical and Mechanical Properties. Journal of Materials Science and Engineering A 2016;6:222–31. https://doi.org/10.17265/2161-6213/2016.7-8.005.

[35] Howe, E. The Re-invention of Molded Pulp. Rochester Institute of Technology 2010:1–13.

[36] Paine, F. A. Moulded pulp, expanded polystyrene, moulded and thermoformed plastic containers. The Packaging User's Handbook 1991:313–47. https://doi.org/10.1007/978-1-4613-1483-7_16.

[37] H. Ji, H. Wang, J. Chen. Mechanical behaviors of molded pulp material. Proceedings of SPIE - The International Society for Optical Engineering 2008. https://doi.org/10.1117/12.839376.

[38] S. Gurav, A. Bereznitski, A. Heidweiller, P. Kandachar. Mechanical Properties of Paper-Pulp Packaging. Composites Science and Technology 2003;63:1325–34. https://doi.org/10.1016/S0266-3538(03)00104-0.

[39] H. Ji, H. Wang. Short Span Compressive Stress-Strain Relation and Model of Molded Pulp Material. Key Engineering Materials 2010:202–5. https://doi.org/10.4028/www.scientific.net/KEM.450.202.

[40] L. Carlsson, C. Fellers, A. De Ruvo. The mechanism of failure in bending of paperboard. Journal of Materials Science 1980:2636–42.

[41] M. A. Sek, M. Minett, V. Rouillard, B. Bruscella. A new method for determination of cushion curves. Packaging Technology and Science 2000;13:249–55. https://doi.org/10.1002/pts.517.

[42] Y. Ou and Q. Huang. Study on the photo degradation of pulp mold container. Journal of Applied Polymer Science 2003;87:2052–6. https://doi.org/10.1002/app.11392.

[43] P. Bajpai. Recycling and Deinking of Recovered Paper. Elsevier Science, London 2014.

[44] B. L. Huo, K. Saito. Multidimensional Life Cycle Assessment on Various Moulded Pulp Production Systems. Packaging Technology and Science 2009;22:261–73. https://doi.org/10.1002/pts.852.

[45] T. K. Das, C. Houtman. Evaluating chemical-, Mechanical-, and bio-pulping processes and their sustainability characterization using life-cycle assessment. Environmental Progress 2004;23:347–57. https://doi.org/10.1002/ep.10054.

[46] S. Mousavi, S. Kara, B. Kornfeld. Energy Efficiency of Compressed Air Systems. Elsevier BV 2014. https://doi.org/10.1016/j.procir.2014.06.026.

[47] K. Taheria,, R. Gadow. Industrial compressed air system analysis: Exergy and thermoeconomic analysis. CIRP Journal of Manufacturing Science and Technology 2017:10–7. https://doi.org/10.1016/j.cirpj.2017.04.004.

[48] Victoria O. Garcia. General Pressurization Model in Simscape. California State University, Northridge 2010.