BREE 495: Engineering Design 3

Design Report:
Cellulose-Based Hygienic Flushable Wipes: Vol. II

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Abstract:

There is an evident need for improvements with the hygienic wet wipes currently on the market. Following the research and assessment of alternatives regarding different wipe designs completed previously in *Cellulose-Based Hygienic Flushable Wipes*, a prototype design was finalized and produced. This prototype design was created to mimic the web forming, bonding and drying methods in order to produce an experimental wipe using an optimal chosen design. Various standardized testing systems, as well as empirical analyses were simulated and performed to ensure the final product meets the criteria required from the Product Needs List (PNL). Overall, three wipe versions A, B and C, were created and tested using the simulated wipe manufacturing systems and evaluations to produce a suitable end-product for consumer use. After evaluating the results between the wipe versions, it was found that wipe C, which was made from hemp and wood pulp fibres, was the most successful, exhibiting foldability, dispersibility, durability and user-friendliness.

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Table of Contents

Abstract

1.0 Introduction 3

2.0 Analysis and Specifications of Wipe Design Process 3
- 2.1 Targeted Problem 3
- 2.2 Targeted Solution 4
- 2.3 Discussion of Overall System Required for Wipe Construction 5
  - 2.3.1 Web Formation: Wet-laid 5
  - 2.3.2 Web Bonding: Hydroentanglement 7
  - 2.3.3 Drying 11
  - 2.3.4 Wetting Solution 12

3.0 Developing Prototype System 14
- 3.1 Fibre Materials 14
- 3.2 Web Formation: Wet-laid 16
- 3.3 Web Bonding: Hydroentanglement 17
- 3.4 Drying 19
- 3.5 Wetting Solution 21
- 3.6 Overall Cost of Prototype System 21

4.0 Prototype End Product 22
- 4.1 Testing Standards 22
  - 4.1.1 INDA & EDANA Testing 22
  - 4.1.2 ASTM Testing: Grab Test 26
- 4.2 Empirical Analyses 27
- 4.3 Occupational Health and Safety 27
- 4.4 Overall Analysis of Results 29
- 4.5 Future Considerations 34

5.0 Practicality of Final Prototype 34
- 5.1 Environmental Considerations 34
- 5.2 Social Considerations 35
- 5.3 Health and Safety Considerations 35
- 5.4 Economic Considerations 36

6.0 Considerations and Future Perspectives 37
- 6.1 Cost Analysis 37
- 6.2 Barriers to Industrial Implementation 38
- 6.3 Risk Management 38

7.0 Conclusion 40

Acknowledgements
References
Appendices

1.0 Introduction

The previous report entitled *Cellulose-Based Hygienic Flushable Wipes* focused on the research and literature involved with the production process of manufacturing a dispersable hygienic wet wipe. Multiple alternative assessments were made regarding the materials and ingredients used as well as its web forming and web bonding techniques. After in-depth evaluation and review, the optimal design was chosen according to the results achieved through the Pugh Chart analyses. These stated that the final product will be made from wood pulp and hemp fibres and be processed through a wet-laid formation and hydroentanglement bonding.

Throughout the development of this product, the central vision was to create a cellulose-based and ecologically friendly hygienic wet wipe that can be easily dispersed in water after it has been discarded, thus deeming it safe for our wastewater systems. The following report discusses in-depth research regarding the optimal experimental design chosen and the steps needed to simulate an industrial manufacturing system. The objectives required throughout the development of this product were to implement the research and decisions made in the previous report to finalize a specific design and follow the required criteria. The main goal was to create a wipe, test and assess its qualities, and construct new versions based on necessary improvements and modifications. It was aimed to construct three different wipe versions, A, B and C, with C being the final and best prototype created.

2.0 Analysis and Specifications of Wipe Design Process

2.1 Targeted problem

As thoroughly discussed in the previous report entitled *Cellulose-Based Hygienic Flushable Wipes,* one of the most commonly used products, the hygienic wet wipe, has significantly impacted global environmental pollution. The report "Reducing household contributions to marine plastic pollution" written by Hann et al. (2018) states that wipes are among the ten most common household items that are majorly problematic within wastewater systems. The large majority of the wet wipes available on the market today are not developed with the capability to be flushed and disintegrate appropriately. However, due to the social habits of consumers, these wipes still find their way into wastewater systems.

The accumulation of such wipes leads to major sewer blockages, damage within the wastewater management facilities. There is also an accumulation of pollution along the coastline affecting the well-being of marine ecosystems and its organisms (Hann et al., 2018; Mendoza et al., 2018). For example, Pantoja Munoz et al. (2018) states that there was a 400% increase in wipe usage in Britain alone over the past ten years, which contributed to the country's 94% increase of wet wipes found on the coastline.

In addition to the accumulation of waste from these wipes, a sizable amount of the pollution within the marine ecosystem is a consequence of the wet wipes being made from plastic polymers. Since many wet wipe producers use a form of nonwoven synthetic plastic, usually made from a mixed blend of polyester fibres, the microplastics found in such wipes can therefore leach their way into the marine environment (Hann et al. 2018) and could potentially affect the pH, salinity, and temperature of the ocean (Mendoza et al., 2018). Overall, synthetic polymers have been known to be an emerging contaminant with ecological consequences in marine environments (Mendoza et al., 2018).

2.2 Targeted Solution

As a means of addressing the aforementioned problem, a solution would be to re-evaluate and modify the design of existing wet wipes. Making modifications to the main contributor of the problem would be the most beneficial method as this would directly affect all the areas needing improvement, namely sewers, waste management facilities and subsequently the environment and its marine ecosystems.

Modifying the design of wet wipes is simply a starting solution to minimizing the issues caused within the industry. Providing an improved design option for wet wipe manufacturers is a small step towards developing a more sustainable future.

The assessment of different product designs was thoroughly researched and conducted in the previous report. More specifically, the alternatives were evaluated using a Pugh Chart analysis with an evaluation criterion focused on the end product's social, economic and environmental sustainability. Throughout the discussion of these analyses, industry codes and standards, as well as the health and safety regulations, were followed and considered. In summary, different methods for web forming (air-laid and wet-laid) and web bonding (hydroentanglement and needle punching) were compared while also contrasting different cellulose-based fibre selections (wood pulp, cotton and hemp) and a multitude of ingredients for the wetting solution.

The final selection demonstrated a means of sustainable web forming and web bonding methods as well as all the materials needed, such as specific fibres and solution ingredients. Ultimately, a wet-laid web forming system was selected alongside a hydroentangled web bonding method to produce a wood pulp and hemp-based hygienic wet wipe. This solution was mainly selected as research demonstrated it to be the most likely to disperse in water, and according to industry standards, it would be considered flushable. More specifically, the development of a plastic-free product that is presumed to disperse similarly to toilet paper will, in turn, improve the overall impacts caused by the majority of marketed wet wipes today.

2.3 Discussion of overall system required for wipe construction

The overall design selected requires a detailed step-by-step manufacturing process encompassing many parameters that ultimately affect the outcome of the wipe product. This design was heavily researched as if it was being produced in an industrial setting to understand better the necessary features needed in the future prototyped production.

2.3.1 Web Formation: Wet-laid

A. *Fibre Type*

There are two fibre types commonly used in the development of nonwoven wipe manufacturing: synthetic and cellulose-based. Generally, this can include fibres such as polypropylene, polyester, cotton, hemp, wood pulp, Tencel or bamboo. For the wet-laid process, the fibre selection is a key aspect as it can affect the stock preparation and web forming steps. For example, if synthetic fibres are chosen for the development of the nonwoven, additional additives would be required to ensure its overall dispersibility during the stock preparation as well as to help properly bond the web in its finishing steps (Hubbe and Koukoulas, 2016). However, following the assessment from the previous report, *Cellulose-Based Hygienic Flushable Wipes*, the use of synthetic fibres will not be discussed. As a result, the discussion of the wet-laid manufacturing practices will be based on the sole use of cellulosic fibres. The advantages of using cellulose-based fibres during the wet-laid process and the assessment of cellulose-based alternatives commonly used in such industrial practices were thoroughly discussed in the previous report. This assessment was based on research demonstrating the industrial use of such fibres in a nonwoven product. More particularly, the fibre alternatives included wood pulp, cotton and hemp.

B. *Fibre Length*

A key factor to any web forming process is the length of the nonwoven fibres chosen. More particularly, different web forming processes within an industrial setting consider different fibre lengths depending on the specific requirements. In general, to ensure a proper formation of a wet-laid nonwoven product, the fibres must have a length of at least 3mm, but a maximum of 10mm (Hubbe and Koukoulas, 2016). Having this length as a standard practice for the development of nonwoven wet wipes allows for a seamless execution of the stock solution as the fibres will properly spread and disperse accordingly (Hubbe and Koukoulas, 2016). Any industrial practice must stay within the range of 3 to 10 mm (Hubbe and Koukoulas, 2016). Overall, cellulosic fibre lengths can be modified in various ways depending on the desired nonwoven end product characteristics as well as the web bonding process.

C. Fibre to Water Ratio

The suspension of the fibres in the aqueous solution requires a specific ratio to promote the development and preliminary formation of the cellulose-based fibre web. This component within the web formation is also known as the fibre to water ratio. The concentration of fibres within the solution can range between 3 to 10% (Hubbe and Koukoulas, 2016). This dilution of the fibres is necessary for them to form an appropriate web once placed on a wire sheet. Other literature, such as Deng et al. (2018), demonstrated a ratio of 1.5%, which is agitated and then diluted again to a ratio of 0.1% as a means of preparing the fibres for the wire sheet.

D. Solution and Agitation Speeds

The stock solution begins with placing the fibres within a water-filled tank. The amount of fibres placed with the water solution is based on the specific fibre to water ratio required of the manufacturing plant. Further, the fibres will be stirred and shaken using an agitator attached to the solution tank (Hubbe and Koukoulas, 2016). Hubbe and Koukoulas (2016) state that the purpose of the agitation step in this process is to break up the clumps of fibres that may have been present or have formed once they were mixed in the aqueous solution. The specific agitation rate can vary with different speeds; some studies have used speeds of 1475 rpm for 20 min (Deng et al., 2018), while others used faster speeds of 2300 rpm for only 10 min (Fages et al., 2012). It has been noted that a faster agitation speed will result in a more significant break up of fibre clusters (Hubbe and Koukoulas, 2016; Shifler, 1985). These differences in agitation speeds can be deduced from both studies using different fibrous materials and their different respective lengths. No current research has stated any specific industry standard or requirements regarding the material characteristics and their effect on agitation needs. The speed at which the agitator is running and the time it is active can be decided based on the particular needs of the nonwoven wipe, such as material selection and fibre length.

Once the preliminary agitation step is complete, the solution of water and fibres will be resuspended into a secondary tank filled with more water as a means of increasing the dilution of the fibre concentration. Once the fibres have been heavily diluted, a secondary agitator is used to ensure quality dispersion of fibres within the solution (Fages et al., 2012). However, the speed of agitation at this step is recommended to be slower than previously used. Once the fibres are suspended appropriately and are all wetted, they will be pumped to a mesh screen where the web will further be bonded (Fages et al., 2012).

E. Mesh Screen and Vacuum

In an industrial setting, following the preparation of the stock solution, the fibres will be pumped onto a surface where the water can seep through. This surface has many names within the industry and in the literature found. Some aliases include wired screen, mesh belt, mesh screen or inclined wire system. For the purpose of this paper, the term 'mesh screen' will be used throughout the discussion of the following processes.

Mesh screens have characteristics such as mesh count, wire diameter and cross-section shape, which help differentiate the screens used in an industry setting. More specifically, mesh count is the measure of how many wires cross each other per square inch, which demonstrates the number of holes through a screen surface. Cross-section shape is the description of how the wires are formed together on the screen. They are either a round cross-sectional shape or a rectangular shape (Xiang et al., 2006). The aforementioned components affect the size of the holes between the wires, ultimately determining the amount of inlet water that gets pulled through by a vacuum and the amount that gets reflected back upon impact with the wires (Xiang et al., 2006). This phenomenon can be expressed through equation (1) below:

$$R_i = 0.16\,(1 - \phi) \cdot 100 \tag{1}$$

where

R_i =the reflected portion of the water brought into the fibre web (%)

ϕ = percentage of open area of the forming wires (%)

Within the industry, the mesh screens used in these practices have been observed to have a R_i value of approximately 16% (Xiang et al., 2006). More specifically, much of the literature available states that a vacuum is used to pull the excess water through the mesh screen post web formation, not many state the pressure at which it runs. However, Xiang et al. (2006) expressed that the vacuum used during their study had a pressure of 4978 Pa.

Overall, the disoriented fibres resulting from the wet-laid web formation are able to lay on a fine mesh screen which provides a forming surface, ultimately creating the baseline structure for the web (Gulhane et al., 2018; Xiang et al., 2006).

2.3.2 Web Bonding: Hydroentanglement

In order to simulate the industrial hydroentanglement process, a thorough analysis was conducted. Hydroentanglement was chosen as a bonding technique due to its ability to strengthen the bonded fibres in nonwovens, while increasing their potential to disperse in wastewater facilities. The components analyzed below vary between hydroentanglement system designs and ultimately affect the outcome of the wipe produced. Such variables include the number of manifolds, jet pressure, jet velocity, the orifice diameter, the line speed and the jet rate of energy.

A. Number of Manifolds

Within a hydroentanglement system, there is a component called a manifold, which is a row of side-by-side water jets. Many studies have alternative names to refer to manifolds, such as jet heads and rows (Deng et al., 2019). Some hydroentanglement systems have multiple manifold units, allowing them to increase the pressure sum on the nonwoven. For example, two manifold units with a water jet pressure of 40 bars will result in a pressure sum of 80 bars (Zhang et al., 2019). It has been demonstrated that the effects of increasing the pressure sum with the number of manifolds significantly impacts the quality of the nonwovens being produced. Studies have additionally mentioned that multiple manifolds positioned in line with one another do not ensure that the water jets from each manifold will respectively puncture the exact same region on the nonwoven (Venu et al., 2017).

All the research found discussing hydroentanglement systems vary drastically regarding the number of manifolds, manifold passes and overall pressure sum. As a result, it can be concluded that no set standard exists within a hydroentanglement system on how the manifold design should be executed. Such design will depend on the required qualities of the nonwoven in discussion as manifolds essentially control the pressure of the system, and the pressure respectively impacts the final outcome of the product.

B. Jet Pressure

One of the most important factors to the hydroentanglement technique is ensuring a fine high-pressure water jet (Deng et al., 2019), as it is the entangling mechanism for the wet-laid fibres. Much of the literature available discusses the hydroentanglement technique using the pressure normalized in manufacturing practices. These specific pressure values can range from 30 to 50 bar and can have an accumulative pressure sum of 80 bar depending on the number of manifolds or passes through the system (Deng et al., 2019; Deng et al., 2018; Zhang et al., 2019). Some studies have demonstrated the differences between the total water pressures of 80 bar to 250 bar based on the outcome of structural properties and texture of the nonwovens (Deng et al., 2019). The increase of these pressure values was executed by increasing the number of manifolds used in the hydroentanglement system or the number of passes through a manifold.

Increasing the pressure has been known to increase the wet strength of wet-laid hydroentangled nonwovens. The desired fluffy and soft nonwoven texture is also achieved through these high-pressure jets (Deng et al., 2018). However, it was also discovered that increasing the water pressure above 190 bar for some combinations of materials such as wood pulp and hydrophilic polyester resulted in a less dispersible nonwoven. This demonstrated that less water could enter through the material since the bonding remained too strong and compact, significantly decreasing its effectiveness for dispersibility (Deng et al., 2019). Comparatively, other studies have demonstrated that 30 bar pressure jets with a total pressure sum of 60 bar allow for hydroentangled nonwovens made from pulp and Tencel fibres to be disposed of like toilet paper as it has similar disintegration properties (Deng et al., 2018).

Overall, studies have displayed a vast discrepancy between the water pressure required for dispersibility as it ranges from 60 bar to as high as 190 bar. The pressure required in the hydroentanglement process will be dependent on the qualities that manufacturers strive to attain in their nonwovens. As dispersibility is a key component for the nonwovens in question, research has demonstrated that a water pressure range between 60 and 190 bar would be suitable for any manufacturing practice looking to make flushable wipes.

C. Jet Velocity

Next, the jet velocity represents the speed of the water exiting the jet nozzle. Venu et al. (2017) demonstrated the jet velocity through equation (2).

$$V_{jet} = \sqrt{\frac{2P_{jet}}{\rho}} \qquad (2)$$

where

V_{jet} =velocity of jet (m/s^2)

P =jet pressure (Pa)

ρ =density of water at room temperature (kg/m^3)

The following example calculation shows the jet velocity of one type of system in an industrial hydroentanglement setting using one manifold:

$$V_{jet} = \sqrt{\frac{2P_{jet}}{\rho}}$$

$$V_{jet} = \sqrt{\frac{2\,(6\times10^6 Pa)}{998.2\ kg/m^3}}$$

$$V_{jet} = 109.64\ m/s$$

A velocity of $109.64\ m/s$ is not representative of every industrial hydroentanglement process. However, according to the research, a chosen pressure of 60 bar for one pass through a manifold can represent a process where nonwoven dispersibility is the focused main property.

D. Diameter of Jet Orifice

The diameter of the jet orifice is the diameter of the pressurized water stream, which creates the holes within the nonwoven and entangles the fibres. The majority of studies using and testing the effects of hydroentanglement have stated that their orifice diameter ranges between 0.12mm to 0.13mm (Berkalp et al., 2003; Deng et al., 2018; Sawhney et al., 2010; Venu et al., 2017). This diameter was generally consistent amongst all the literature reviewed, concluding that no matter the hydroentanglement system design used, its diameter of jet orifice remained the same.

E. Line Speed

The line speed of the hydroentanglement process is the speed at which the line belt moves across the manifolds and jets. Different manufacturing facilities have different speeds at which their belts move. Within the literature, some studies demonstrated speeds as slow as 6m/min (Seyam and Shiffler, 2005) and 10 m/min with subjecting the fibres to a pressure of 100 bar (Venu et al., 2017). In comparison, others managed speeds of 150 m/min with high pressures of up to 250 bar (Deng et al., 2019). This demonstrates that the higher the water jet's pressure, the faster the belt can roll with the fibres. The fibres are not required to experience entanglement for an extended period of time when subjected to higher pressure water jets. Similarly, the inverse is true as fibres experiencing a lower water pressure will require more time under the jets for entanglement. There exist flaws within the aforementioned literature as slower speeds were not representative of commercial units and were considered weaknesses within the hydroentanglement system design (Seyam and Shiffler, 2005; Venu et al., 2017).

The inconsistencies found in the literature have demonstrated confusion towards the effect of line speeds on the bonding effect of hydroentanglement. There have been no studies that have tested the effects of variable line speeds on the bonding strength of nonwovens or its dispersibility in water. None of the research has specifically gone in-depth with the effect of line speed. However, it can be assumed that the higher the jet pressure, the faster the belt needs to pass through. The reverse is true as well; more reduced pressures require more time under the jets to obtain satisfactory results.

F. Energy

The rate of energy of the system represents the amount of energy required to puncture the wipe per unit of time (seconds). Venu et al. (2017) demonstrated the rate of energy through equation (3).

$$\dot{E} = \frac{\pi}{8}\rho d^2 C_D V^3 \tag{3}$$

where

$\dot{E}$ =energy rate in (J/s)

ρ = density of water at room temperature (kg/m^3)

d =diameter of the jet orifice (m)

C_D = orifice discharge coefficient

$V =$ jet velocity (m/s)

The following example calculation shows the rate of energy for the same system design as explained in *part C,* which shows an industrial hydroentanglement setting using one manifold at a pressure of 60 bar with jet velocity 109.64 m/s. It should be noted that for this report, the coefficient of discharge used, 0.64, is assumed to be the same as that from Berkalp et al. (2003), as their study displayed similar system variables to an industrial unit. Additionally, the diameter of the jet orifice used is 0.00013m as it represents industry standard.

$$\dot{E} = \frac{\pi}{8}\rho d^2 C_D V^3$$

$$\dot{E} = \frac{\pi}{8}(998.2kg/m^3)(0.00013m)^2(0.64)(109.64m/s)^3$$

$$\dot{E} = 5.587\, J/s$$

This rate of energy of $5.587\, J/s$ is an example that demonstrates an industrial hydroentanglement system design for the bonding of dispersible nonwovens.

Overview of Manufacturing Processes

Overall the bonding outcome of a nonwoven product is dependent on various factors within a hydroentanglement process. These variables include the number of manifolds, the jet pressure, the jet orifice diameter, and the line speed. All these factors affect the jet velocity and the rate of energy, two components that strongly affect the physical properties of the wipe, such as strength and texture.

2.3.3 Drying

When discussing the drying mechanisms available in hydroentangled nonwovens manufacturing processes, research shows that the machines used and their parameters considered generally remain consistent. Typically, following the hydroentanglement process, the nonwoven wipes are subjected to a physical roller press to remove excess water (Lehmonen et al., 2020). Furthermore, the belt from the hydroentanglement process will then proceed to move through a drying process, which can either be drum drying or hot through-air drying (hot cylinders or hot air) (Gulhane et al., 2018; Zheng, 2003). Both are conventional and commonly used methods with the sole purpose of drying the fabric (Zheng, 2003). Research has more frequently discussed using air drum dryers and has stated that the heating temperature is approximately 150 ℃ (Deng et al., 2019). The industrial practice of drying is not the most intensely discussed component of the nonwoven manufacturing process, and this is presumed to be because the drying process does not have many parameters to consider. As well, the time under which the nonwovens are spent drying is not a variable that is discussed in any literature. Nonetheless, it can be concluded that this time variable is subject to change with the ultimate goal in mind that the drying process is to simply have a dry nonwoven that can move on to the following step in the system. Overall, this entails having a final dry wipe that is dried enough so that the water has been evaporated, but not too much where the fibres are burnt under the dryer.

2.3.4 Wetting Solution

The liquid composition which moistens the nonwoven wipe is referred to as the wetting solution. Several parameters are considered to ensure adequate moisture content, quality and overall safe usage for contact with the skin. Such parameters include the solution ingredients, their specific ratios in the solution, the overall wet-to-dry ratio and methods of employing such solution onto the nonwoven wipes.

A. *Solution Ingredients*

For the wetting solution to be stable, effective, and safe for consumers, it is required to incorporate various ingredients. This set of ingredients include a solvent, surfactant, humectant, emollient, preservative, pH adjuster and emulsifier (Droid, 2019), all of which contribute their own unique purpose.

All of the alternative examples of said ingredients were assessed in the previous report *Cellulose-Based Hygienic Flushable Wipes.* This assessment was based on research demonstrating industrial practices and the common ingredients used. In overview, for a solvent, deionized water is most commonly used in industrial practices as it dissolves many substances and is considered readily available (Pregozen, 1992; USGS, 2020). Further, preservatives are necessary to prevent unwanted chemical changes and protect the product over time from contamination. They also help maintain the colour, consistency and safety of the product ingredients (Anderson, 2019). Typical preservatives include GeoGard Ultra as well as grapefruit seed extract (Coop Coco, 2020a). In addition, emulsifiers are needed to prevent the separation of polar and non-polar ingredients such as oil and water. Examples of emulsifiers are olivem 1000 and glyceryl stearate (Bárány et al., 2000; Coop Coco, 2014).

The following ingredients are primarily used to maintain a safe cleansing solution for the skin. Surfactants have a range of options, with some being very alkaline in pH and others being more neutral. Typical surfactants used include a neutral option such as coco-betaine (Coop Coco, n.d.a) and more alkaline options such as coco glucoside and decyl glucoside (Coop Coco, 2019; Coop Coco, 2020c). Further, humectants promote the attraction of water from the surrounding environment to the outer layer of skin, potentially resulting in a hydrating effect. These include vegetable glycerin, propylene glycol and aloe vera gel (Coop Coco, 2015; Coop Coco, 2020b; Coop Coco, n.d.c). Emollients create a barrier over the skin, reducing water loss to increase moisture levels. Suitable emollients include olive squalane, caprylic triglyceride and avocado oil (Coop Coco, n.d.b; Mungali et al., 2021; Park et al., 2013).

Lastly, pH adjusters are of great importance as they help balance the overall pH of the solution. Depending on the choice of certain ingredients such as surfactants, accompanying ingredients (acidic or basic) would be necessary to add to adjust the formulation. Typically an acidic ingredient is required to be incorporated in wetting solutions used in wet wipes, as it helps to balance out the alkaline surfactant. This can be achieved using citric acid as it is soluble in water and adequately adjusts the pH to 3.5 to 4.5, considering it appropriate for human skin contact (Pregozen, 1992).

B. Final Wetting Ratio

The amount of wet solution present compared to that of the dry nonwoven material (wet-laid hydroentangled fibre) is known as the final wetting ratio (Klofta et al., 2015). An ideal wetting ratio, wet to dry, is said to be 0.80 or less (Klofta et al., 2015). Other sources have mentioned that an appropriate wetting ratio can range from approximately 2 to 5 times the weight of the nonwoven substrate, with 3.5 times being most preferred (Pregozen, 1992). This ratio allows for the adequate distribution of the wetting solution upon contact with the skin while ensuring the stability of the nonwoven during its shelf-life.

C. Method of Employing Solution

In an industrial setting, the wipes are distributed through a packing machine and are wetted with a particular ratio, cut, folded, packaged and sent for distribution. The wetting solution is distributed through nozzles as a method of impregnating the nonwoven wipe. Such nozzles allow the wipe to stay clean and sterile by reducing the risk of contaminants. Other methods of distribution include spraying, padding or printing the wetting solution onto the nonwoven wipes (Pregozen, 1992). These techniques are known as "online wetting systems" or "online impregnation" in the industry (SES, 2017; Temcon, 2020). The amount of wetting solution distributed between each individual wipe, also known as the wetting solution ratio, is controlled using a lube pump with a flow meter (Temcon, 2020). Overall, this method of employing a wetting solution provides the wipe with a hygienic and even distribution as a means of completing the end product deeming it suitable for the retailing market.

Overview of Manufacturing Processes

Overall the wetting solution required for a nonwoven product is dependent on the ingredient selection, the ratio of said ingredients, the final wetting solution ratio and its method of employment. These factors are generally constant throughout many nonwoven wipe manufacturing processes; however, they can vary depending on the specific producer or the client's needs.

3.0 Developing Prototype System

The prototype system was developed to mimic as closely as possible the industrial system. The wet laid, hydroentanglement and drying procedures were achieved with a hand blender, large bucket, mesh screen, oral irrigator, a custom built drying box, and a wetting solution (see Appendix A). The following section will discuss in detail how each component was tailored to replicate the industrial system and achieve the most authentic nonwoven hygienic wipe.

3.1 Fibre Materials

The prototype wipe was made from hemp fibres and wood pulp. The hemp fibres were supplied from Bast Fibre Technologies, a company that specializes in the production of hemp fibres for wipes and other nonwoven fabrics manufacturing. At Bast Fibre Tech, the hemp is grown from dicotyledon plants' seeds (BFT, 2020). The company also states that the plants are grown responsibly and are cultivated following standards and procedures (BFT, 2020). Once the plants are grown, they are harvested and carefully decorticated to achieve the bast fibres intact, improving their absorbency (BFT, 2020). The fibres are later cleaned by passing through a wetting process that will also separate them (BFT, 2020). Bast Fibre Tech also states that they “naturally modify the fibres” to improve their properties of cohesion, absorbency, and length (BFT, 2020). After this process, the fibres are then sold to companies as raw materials for manufacturing nonwoven and woven products (BFT, 2020).

Furthermore, three different sources of wood pulp were used in the construction of the wipes. For the first prototype, standard computer paper and brown paper towel were shredded and then soaked in water. However, the paper was not in a fibrous or pulp composition as the team did not yet have access to a blender or other equipment to transform the paper into a pulp. Therefore, the paper was cut into as small pieces as possible. The second prototype was made with regular toilet paper as its wood pulp source. The team had access to a handheld blender and was able to create wood pulp from the toilet paper by first soaking the paper then grinding it into a suspended pulp using the blender. Lastly, wood pulp fibres were generously provided by Dr. Marie-Josée Dumont for the final prototype. These fibres were also blended using the handheld blender.

To determine the weight of a hygienic wipe, a generic brand wet wipe was dried overnight to remove its moisture and was weighed the following day. The wipe's dry weight was approximately 3 g, while its area was 277.5 cm^2. The generic wipes proportion of dry mass to the surface area of the wipe will be equal to the proportion of the prototype's dry mass to its surface area, as illustrated in equation 4.

The wipe dry mass to surface area is calculated as follows:

$$\frac{m_{generic\ dry}}{A_{generic}} = \frac{m_{prototype\ dry}}{A_{prototype}} \qquad (4)$$

where

$m_{generic\ dry}$ = dry mass of the generic wipe (g)
$m_{prototype\ dry}$ = dry mass of the prototype wipe (g)
$A_{generic}$ = surface area of the generic wipe (cm^2)
$A_{prototype}$ = surface area of the prototype wipe(cm^2)

The following equation was used to determine the dry mass required to produce one wipe according to the values given by the generic wipe brand used:

$$A_{screen} = L \times W = 20.3\ cm \times 27.9\ cm = 566.37\ cm^2$$

$$A_{generic} = L \times W = 18.5cm \times 15cm = 277.5cm^2$$

$$A_{prototype} = L \times W = 18\ cm \times 13\ cm = 234\ cm^2$$

$$\frac{A_{generic\ dry}}{A_{prototype\ dry}} = \frac{3\ g\ of\ fibre}{x\ g\ of\ fibre}$$

$$m_{prototype\ dry} = \frac{234\ cm^2 \times 3g}{277.5\ cm^2} = 2.53\ g$$

$$m_{for\ entire\ screen} = \frac{566.37\ cm^2 \times 3g}{277.5\ cm^2} = 6.1\ g$$

The results shown from the calculations indicate that the dry fibre mass required to produce one wipe would be 2.53 g, and the dry mass of fibre required to fill the entire screen would be 6.1 g. To ensure a proper dimensioned wipe with uniform edges, the entire screen will be filled with fibres, and following the drying, the wipe will be cut to the desired dimensions.

The hemp to wood fibre ratio was determined experimentally during the first manufacturing session. The parameters used to determine the ratio included: appearance, softness, flexibility, durability and dispersibility. It was speculated that hemp would give softness and structure to the wipe, and the wood pulp would help ease dispersibility. The ratio of hemp fibre to wood pulp chosen was 2:1. This ratio was chosen based on experimental trials that yielded satisfactory results of the factors mentioned above. Using this ratio, the mass of fibres required to occupy the entire screen was 4 g of hemp and 2 g of wood pulp. The hemp fibres and wood pulp were weighed using a kitchen scale. Following an experimental test, it was observed that not all fibres that are suspended are caught by the mesh screen, it was estimated that half of the fibres were not caught. An insufficient amount of fibres would lead to an incorrect wipe weight and thickness. To resolve this issue, an additional 3 g of fibres were added, hemp fibres were weighed to approximately 6 g, while the wood pulp fibres were weighed to 3 g. Therefore, a total of 9 g of fibres were weighed per wipe produced, instead of the original estimation of 6 g. This quantity allowed for enough suspended fibres to fill the entire screen without losing a large amount of the fibres. After the fibres were weighed, they were cut and blended. The hemp fibres were cut to lengths ranging from 3 to 10 mm as recommended by the industrial standards. The wood pulp was added to water and blended using a handheld blender to turn it into a pulp and ensure it was suspended in water.

3.2 Web Formation: Wet-Laid

Following the weighing of the dry fibres, the blended wood pulp fibres were added to the hemp fibres and agitated together in a bucket of water until a suspension was observed. The fibre-water suspension ratio had a theoretical value of 0.1% fibre to water by volume (Deng et al., 2018), however, during experimental trials it was observed that the suspension ratio was invalid when applied. The suspension ratio used in practice was 0.05% fibre to water. The bucket was filled with about 12 L of ambient temperature water with the fibres then added in. The fibres were then agitated for about a minute or until a good fibre suspension was observed. This was demonstrated by the fibres being separated from each other and entirely surrounded by the water.

Following, a paper-making screen was used to mimic an industrial mesh screen as it closely represented small enough holes in a high count meshing. This mesh screen was then dipped into the bucket with the suspended fibres at an angle of approximately 40 to 50 degrees. The screen was then fully immersed in the water to allow the suspended fibres to lay on top of the screen. It was then lifted just under the water surface allowing the laid fibres to shape onto the screen and arrange themselves so that they may lay uniformly. When the shape and arrangement of the fibres on the screen were deemed appropriate, the screen was lifted straight up out of the water and placed on a drying rack. A rolling pin was then used to press out excess water from the screen and was then vacuumed with a hose placed directly under the rack to suction out any remaining excess water.

The mesh screen used allows for a certain amount of inlet water to get pulled through by the vacuum and a certain amount that gets reflected back upon impact with the wires. The mesh screen had an open area of forming wires of approximately 60% and the R_i value was calculated using equation 1:

$$R_i = 0.16\,(1 - \phi)$$
$$R_i = 0.16\,(1 - 0.6)\ \cdot\ 100$$
$$R_i = 6.4\,\%$$

where

R_i =the reflected portion of the water brought into the fibre web (%)

ϕ =the open area of the forming wires(%)

The results demonstrated an R_i value of 6.4%. As the industrial value of R_i is 16%, the mesh screen used in this system did not completely match those used in industrial settings. This could be due to the fact that the mesh screen used had holes that were too large.

3.3 Web Bonding: Hydroentanglement

After the excess water had been removed, the hydroentanglement process began. For the hydroentanglement process, a minimum pressure of 60 bar (6 MPa) was required according to the value indicated in Deng et al. (2018). Additionally, a water jet diameter of 0.13 mm was required in accordance with the orifice dimensions reported in industrial systems (Berkalp et al., 2003; Deng et al., 2018; Sawhney et al., 2010; Venu et al., 2017). Therefore the highest pressure device with a small orifice that was accessible for the purpose of this project was an oral irrigator (dental water flosser) device. The water flosser device claimed to be able to reach pressures of up to 0.862 MPa and had a water jet orifice measured at around 0.6 mm in diameter. Due to the larger water jet diameter, the final product was expected to display larger holes than desired, however, the team deemed this result acceptable. Furthermore, the trade-off for water pressure was also deemed to be acceptable as in an industrial setting the fabric would be subject to high-pressure jets for a very small amount of time. However, for this project, the time variable was adjusted. More specifically, in order to compensate for the difference in pressure, the fibres were subjected to the oral irrigator's lower pressure for a longer time period. The water used for this step had an average temperature of 36 ℃. During the experimental trials, it was observed that the oral irrigator's highest setting resulted in holes too big for the project's requirements. Therefore, the pressure level of the device was set at a pressure of 88 psi. The conversion of 88 psi to pascals was based on values from Çengel et al. (2019) as demonstrated below:

$$88\,psi \times \frac{6.894757\,kPa}{1\,psi} = 606.7386\,kPa = 606.7386 \times 10^{3}\,Pa$$

Interpolating from Çengel et al. (2019), the density of water at 36℃ is 993.04 kg/m^3. The increase in water temperature has the capability of decreasing the density of water which would, in turn, affect the jet velocity. This is expressed below using equation 2:

$$V_{jet} = \sqrt{\frac{2P_{jet}}{\rho}}$$

$$V_{jet} = \sqrt{\frac{2\,(606.7386 \times 10^{3}\,Pa)}{993.04\,kg/m^{3}}}$$

$$V_{jet} = 34.957\,m/s$$

With the experimental system, the jet velocity was concluded to be 34.957 m/s. When compared to that of the jet velocity found in an industrial system, it demonstrated how a decrease in pressure can significantly affect the speed of water hitting the nonwoven wipe by being slower.

As well, the path of the water jet is demonstrated in figure 1. After that path has been followed, any areas on the wipe that seemed uneven were passed over again with the water jet. Going over these sections of the wipe can be similar to increasing the manifold passes as the added pressure helps to compress and bond these sections accordingly. These adjustments were done until the evenness of the wipe was satisfactory (i.e. until no unevenness could be observed upon examination). The time it took to complete a single pass of the hydroentanglement process was on average 2 seconds for its width and 4 seconds for its length. The mesh screen had a length of 30 cm and a width of 20 cm. This timing can be referred to as the experimental version of line speed and can be expressed as follows:

$$Width\colon\ 20\,cm \times \frac{1\,m}{100\,cm} = 0.2\,m \div \left(2\,seconds \times \frac{1\,min}{60\,secs}\right) = 6\,m/min$$

$$Length\colon\ 30\,cm \times \frac{1\,m}{100\,cm} = 0.3\,m \div \left(4\,seconds \times \frac{1\,min}{60\,secs}\right) = 4.5\,m/min$$

An average line speed of 5.25 m/min was best attempted to be used on the prototype wipe. When compared to other industrial systems or studies discussing line speed, the line speed used seemed very slow and inadequate, however, it was concluded that it was sufficient enough for hydroentanglement to occur on the prototype wipe.

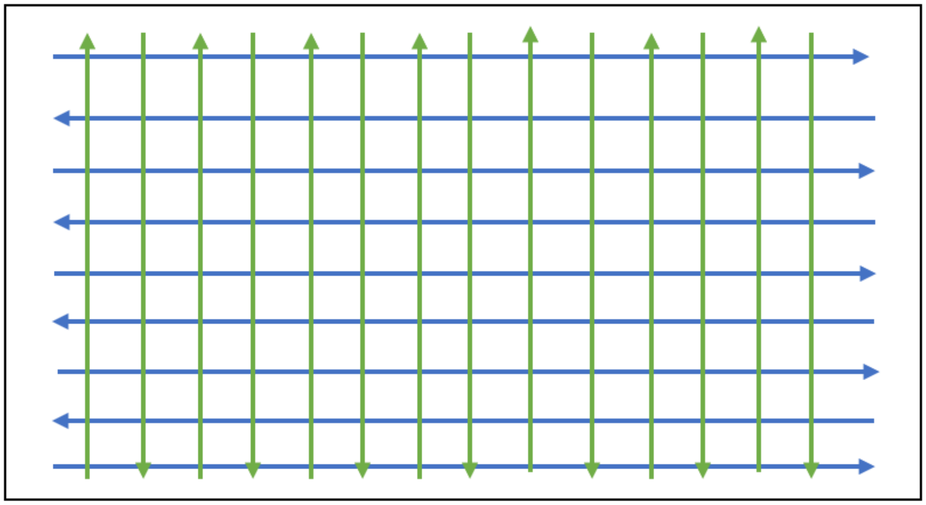

Figure 1. The trajectory of the water jet represented by green (width) and blue (length) paths (Bucci, 2021)

After the hydroentanglement process, excess water was required to be removed again. This time, a rolling pin was used to ring out the water from the wipe in order to mimic the industrial rollers that the wipe fabric would pass through in a manufacturing process. After the wipe passed under the roller, the wipe was vacuumed once again to remove as much water as possible to accelerate the drying time. The wipe and screen were placed on the drying rack so that the screen refrained from damage during the vacuuming process. The vacuum was placed under the drying rack and drew out the excess water for about 20 seconds. The total energy rate for this process was calculated using equation 3:

$$\dot{E} = \frac{\pi}{8}\rho d^2 C_D V^3$$

$$\dot{E} = \frac{\pi}{8}(993.04 kg/m^3)(0.0006m)^2(0.64)(34.957 m/s)^3$$

$$\dot{E} = 3.838 J/s$$

The value of the energy rate of 3.838 J/s resulted in a smaller value than that of an industrial hydroentanglement process. However, it should be noted that in the industrial settings, systems are designed for efficiency; while the hydroentanglement processes performed in this project were experimental and an attempt to emulate the industrial process. Though there is a difference of 1.749 joules per second, an improvement to approach the energy rate of the industrial process would be to increase the pressure and decrease the diameter of the jet orifice.

3.4 Drying

During a typical industrial process, the drying of the wipe is done in an oven. Therefore in order to imitate this process as best as possible, a contained drying system was constructed as illustrated in figure 2. A lid made from aspenite wood was constructed and also added. The box was built from melamine composite wood for the sidewalls, and solid pine for the base, which was nailed together using a brad nailer. The interior lip that held the rack on the inside of the box was softwood and also nailed to the sidewalls using a brad nailer. During the construction of the box, it was decided that adding a thin sheet of rubber gasket to the edges would be an improvement on the planned design as shown in figure 2. Adding the gasket along the outer edge would create a seal to minimize heat loss around the edges and to not allow any loose fibres to slip out and become airborne.

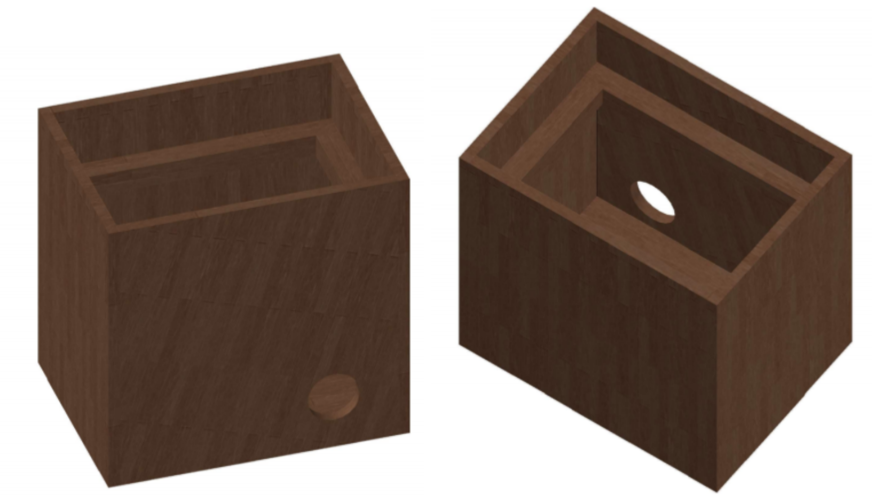

Figure 2. The constructed contained drying system (Bucci, 2021)

The dimensions of the drying system were designed to hold the drying rack and screen depicted in figure 3. However, during construction, a slight deviation from the plans was experienced as it was concluded that it would be more suitable if the dryer was closer to the screen. Therefore a hole, with an approximate diameter of 0.0572 m for the dryer, was drilled using a hole saw 0.1905 m from the base. To use the system, the drying rack was placed on the lip of the inside of the box; then the screen with the wet entangled fibres followed. The lid was placed on top of the outer edge and a heavy object was placed on top of the lid to seal it. Further, a conventional hair dryer was used as a heat source. The hair dryer was inserted into the hole while on a high heat setting and created optimal hot air conditions required to dry the wipe. While the hair dryer is active, air needs to escape the box. Therefore the heavy object was placed slightly offset on top of the box’s lid so that the built up air in the box would force the lid slightly up. As the air is forced up, a small gap between the lid and gasket would appear to release some air. The duration of the drying period was on average 12 minutes in duration.

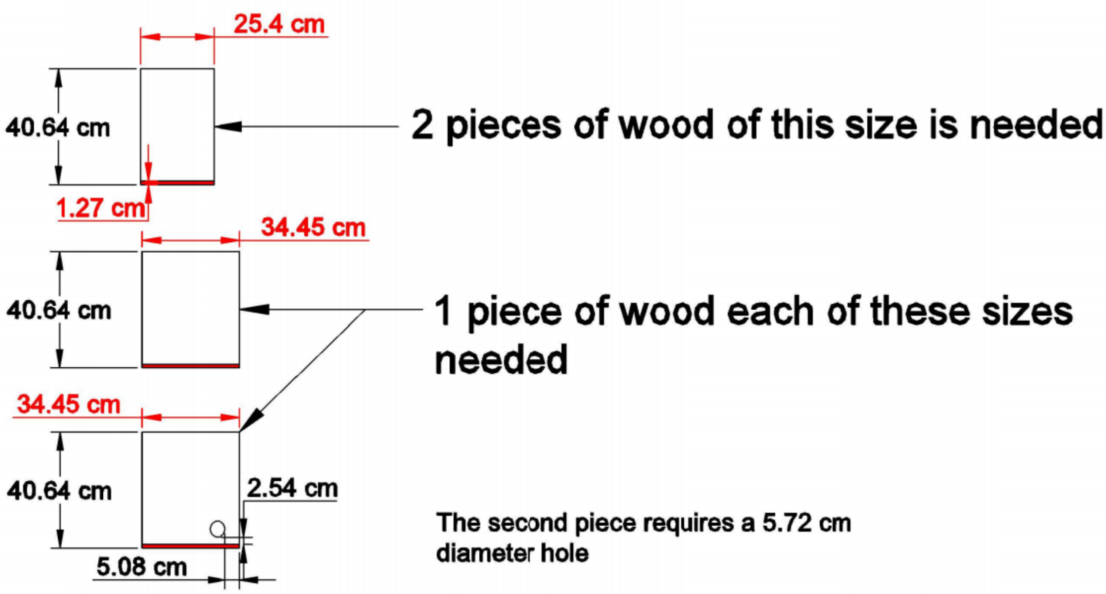

Figure 3. Dimensions of the drying system (Bucci, 2021)

The wipe was then carefully peeled off the screen and examined. Observations were additionally noted down along with any issues regarding the techniques, equipment and materials used.

3.5 Wetting Solution

In order to prepare the wetting solution, the following ingredients and their respective proportions were used:

- 64% Distilled water
- 5% Vegetable glycerin
- 12% Caprylic/capric triglycerides
- 2% Olivem 1000
- 15% Coco glucoside
- 2% GeoGard Ultra
- Citric acid to balance the pH to 5.5

The formulation and method of the wetting solution was obtained from tertiary sources, which included supplier websites (Coop Coco, 2014; 2015; 2020a; 2020c; n.b.d) and informational videos (Lee, 2019) as no primary sources were available for this topic. The method of preparation first involved a water phase and an oil phase. A third phase for the surfactant, preservative and pH balance was also included. The formulation had a total volume of 60 mL, which was the estimated volume required for the testing procedures of the project. To start the formulation, the water phase was made, 38 mL of water and 3 mL of glycerin was poured into a

150 mL beaker and mixed until combined. As for the oil phase, 7.2 mL of caprylic/capric triglycerides and 1.2 mL of olivem 1000 were poured into a new 150 mL beaker and mixed until combined. Both beakers were placed into a water bath at 70 degrees celsius for 20 minutes in order to sterilize both solutions. Once the solutions were sterile, the water phase was then poured into the oil phase and the solution was blended using an immersion blender. Finally, for the third phase of the formulation, 9mL of coco glucoside was added into the solution and stirred gently. The pH was measured using a pH meter and was adjusted to 5.5 using citric acid. Following this, the preservative GeoGard Ultra, was added in at 1.2 mL and the solution was stirred until the preservative was combined. To conclude the preparation, the wetting solution was placed in a spray bottle to evenly distribute the solution onto the wipe right before testing procedures. Each side of the wipe sample was sprayed 5 times prior to testing, this allowed for a dry to wet ratio of 0.8 or less.

3.6 Overall Cost of Prototype System

The overall cost of the prototype totaled to $218.73 (see Table B1). The raw materials supplied for the construction of the wipes were graciously provided by Bast Fibre Tech and Dr. Marie-Josée Dumont at no cost. Equipment to construct the wipe, such as the oral irrigator, the drying rack, the paper-making screen and temperature gun, were purchased from Amazon, as it was the most economical option for the team. Further, the equipment needed for the testing of the wipe, such as the simulated toilet pipes (P-trap and drain-line) and pH meter were purchased from Réno-Dépôt and Amazon respectively. The ingredients for the wetting solution were purchased from Coop Coco as this supplier was economically appropriate and had a wide variety of options. The budget for the production and testing of this prototype was funded by the Bioresource Engineering Student Society (BESS) Innovation & Design Fund. As well, any other equipment used in the construction and testing phases of the project were previously owned and supplied by the members of this project.

4.0 Prototype End Product

Following the prototyped wipe manufacturing process, the end products received will be subject to testing as a means of meeting the requirements of the product needs list (PNL) as illustrated in Table 1. These evaluations include standardized INDA & EDANA testing, empirical analyses as well as the consideration of its overall occupational health and safety.

Table 1: Hierarchical Product Needs List

1. **Flushability** 1.1 Easily dissolvable for municipal sewage systems 2. **User Friendly** 2.1 Safe ingredients

2.2 Affordable
2.3 Non-abrasive
2.4 Gentle cleansing
2.5 Appropriate size

3. **Durable**
   3.1 Tear resistant
   3.2 Pathogen resistant

4. **Flexible**
   4.1 Foldable

5. **Low Environmental Impact**
   5.1 Plastic free
   5.2 Sustainable
   5.3 Biodegradable

4.1 Testing Standards

4.1.1 INDA & EDANA Testing

In order to properly define flushability, INDA & EDANA tests for toilet bowl and drain-line clearance, slosh box disintegration and settling were the ones evaluated for the wipes developed.

A. *Toilet Bowl and Drain-line Clearance Test*

INDA & EDANA Guidelines

As a means of evaluating the behaviour of a nonwoven wipe through a toilet and drain-line system, the FG501.R1(18) toilet bowl and drain-line clearance test was used. This test requires both a toilet and drain-line, and was meant to simulate one toilet system used by a family of four during a period of 2 days (INDA & EDANA, 2018). For nonwoven wipes, a sequence of 35 flushes is required to properly replicate the use of the toilet under such conditions. More specifically, this sequence is required to be repeated: flushing with the wipe and water only, flushing with the wipe, water and simulated fecal matter (SFM), as well as flushing with the wipe, water and toilet paper (INDA & EDANA, 2018). The test must continue throughout the entirety of the simulation as the products being flushed must successfully exit the drain-line after 35 flushes. Further, to determine the passing rate of this test, the nonwoven wipe cannot clog the system (toilet and drain-line) for a maximum of one simulated flush (INDA & EDANA, 2018).

Model Simulation

In order to simulate the FG501.R1(18) test, a small-scale mock system was created. As it was difficult to obtain a real-life toilet and drain-line system, a floor P-trap and an attached open funnel aluminum bowl served as substitutes (fig. 4). More specifically, based on Canadian toilet systems, it was concluded that the drain-line pipe diameter typically has a minimum value of 3 inches or 7.62 cm (Brenner, 2018). Therefore, the P-trap setup was set to follow these dimensions as a means of ensuring a proper mock simulation. As well, the length of the drain-line used was 57.15 cm long. In addition, the aluminum-based funnel bowl was created to illustrate the shape of a typical Canadian toilet bowl and best simulate the movement of water.

As the design did not account for a real toilet with a set flushing system, once the setup was complete (see figure C.1), the amount of water required to simulate a single flush was calculated. A single flush is equivalent to 5 litres of water (Plumbing Paramedics, 2018). Therefore, following the instructions of the *INDA & EDANA simulation*, 35 flushes each with 5 litres of water was poured alongside the wipe. As the number of wipes produced was limited, the team decided to simulate one sequence of the 35 flushes using only water with a whole wipe. A catchment basin was placed at the end of the exiting pipe of the P-trap to see the disintegration of the wipe following the flush sequence. The catchment basin was drained every 5 flushes as a means of determining whether there were any particles from the wipe left after a sequence of 5 flushes. This helped to determine whether the wipe was being flushed out accordingly and whether there were any clogs.

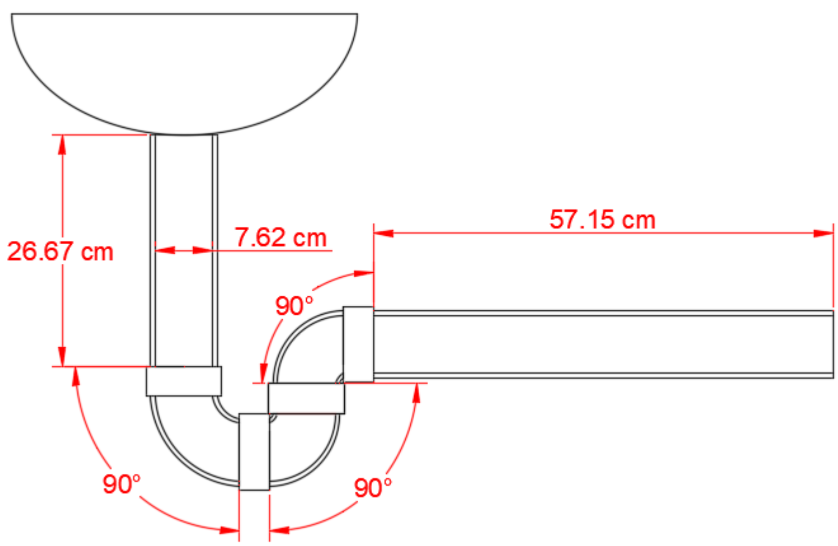

Figure 4. Sketch of toilet bowl and drain-line clearance test (Bucci, 2021)

B. Slosh Box Disintegration Test

INDA & EDANA Guidelines

To analyze the disintegration behaviour of a nonwoven wipe during the process of agitation which occurs in toilet bowls and wastewater pipes, the standard FG502.R1(18) slosh box disintegration test was used. More specifically, this test is conducted in a 2 L basin of tap water, where the nonwoven wipe is agitated at a rate of 26 rpm for a total of 60 minutes (INDA & EDANA, 2018). Following, the basin was then poured out onto a 12.5 mm perforated sheet as a means to measure the ratio of disintegrated wipe which passed through the holes compared to that remaining on its surface (INDA & EDANA, 2018). The remaining wipe is then dried and weighed, then compared to its original dry weight. For the test to be fully confirmed, it must be replicated at least six times. Finally, to achieve a passing rating, the remaining dry weight must not exceed 40% of the starting weight for at least 80% of the replicates tested (INDA & EDANA, 2018).

Model Simulation

To successfully imitate test FG502.R1(18), a strip of the cellulose-based wipe created was weighed dry and used. This test was not performed six times as the availability of wipes was limited. The strip was placed into a bowl filled with 2 L of tap water, was covered with a lid and agitated manually for 1 hour. The rotational speed of 26 rpm was difficult to mimic exactly as there was no means of measuring this precise value. However, this was not neglected as the simulation aimed to achieve an agitation rate of approximately 2.7 radians per second (around 3 full circle movements per second) as per equation 5.

$$Radians = 26\,rpm \times \left(\frac{2\pi}{1\,rev}\right) \times \frac{1\,min}{60\,sec} \quad (5)$$

$$Radians = 2.7227\,rad/s$$

After the hour of agitation elapsed, the fluids of the bowl were passed through a 10 mm hole strainer. The material that remained on the surface of the strainer was transferred to another clean bowl to dry completely and was then reweighed. The passing result of the test was conducted using equation 6, where only a maximum of 40% of the wipe's post-test dry weight would be remaining on the strainer's surface (INDA & EDANA, 2018).

$$w_f \leq 0.4\,(w_i) \quad (6)$$

where

w_i =weight of original wipe (prior to test)

w_f =weight of remaining wipe (post test)

C. *Settling Test*

INDA & EDANA Guidelines

As a means of determining the nonwoven's ability to settle in the systems of a wastewater treatment facility, the FG504.R1(18) settling test was used. This test was constructed by using a water-filled transparent cylinder with measured markings alongside its length to determine the distance travelled by the wipe (INDA & EDANA, 2018). More specifically, a cylinder with a 20 cm diameter and a minimum height of 35 cm was required. The wipes are initially rinsed with water and then placed into a 1 L beaker filled with tap water, which was then poured into the transparent cylinder. Over the course of 24 hours, the wipe's displacement behaviour in the cylinder was observed and calculated to determine the average settling rate (INDA & EDANA, 2018). In an industrial setting, this test would have been conducted 10 times, each with a different wipe to determine accurate results. Overall, the passing rate for this test would require 95% of the wipe to not rise more than 30 cm from the bottom of the cylinder within the full 24 hour period nor exceed a settling rate of 0.1 cm/s (INDA & EDANA, 2018).

Model Simulation

Simulating the FG504.R1(18) test was completed using a 50 cm high clear vase with a diameter of 18 cm. A metric measuring tape was attached alongside the length of the cylinder as a means of observing the graduations of the wipe over time. The cylinder was filled with enough water leaving room for an additional 1 L to be further added in. Next, the wipe was rinsed with tap water and was then placed in a separate bowl filled with 1 L. This was then transferred directly to the clear vase and recorded a total volume of 48 cm. The 24-hour timer began immediately after observing its initial settling behaviour (see figure C.2).

4.1.2 ASTM Testing: Grab Test

As a means of defining durability according to the PNL (Table 1), the grab test was conducted to determine the product's tear resistance.

ASTM Guidelines

Another test conducted on the nonwoven hygienic wipes was the ASTM D5034: standard test method for breaking strength and elongation of textile fabrics, also known as the grab test. The following is a method used to determine the breaking strength and elongation of a sample piece of the nonwoven cellulose-based wipe through the use of a universal testing machine (UTM). The strips used in this procedure are needed to be cut to minimum dimensions of 10 cm by 15 cm. The gage length required by the standard is approximately 7.5 cm between the two grips (ASTM, 2017). Furthermore the loading rate that is applied to the samples should be about 30 cm per minute. The standard also listed other measures in place to ensure that a sufficient uniformity of the force is applied to the samples. Measures also exist to ensure that the pressure of the clamps is even across the sample while also maintaining no slippage of the wipe in the clamps (ASTM, 2017). According to the standard, the amount of time it takes for a wipe to break should be roughly 20 seconds and when it does, it should not occur within half a centimetre of the clamps (ASTM, 2017). The standard also states that this given time-to-break is arbitrary and is solely a suggested time, as each manufacturer may have specific requirements (ASTM, 2017).

Model Simulation

During the simulation, a deviation from the standard was necessary as the UTM used for the testing only allowed for samples that were 1 to 4 cm wide by 10 cm long. Each sample was cut and then measured individually, the measurements of each wipe were all slightly different and therefore needed to be taken into account (see Appendix D.1). The changes in dimensions were input into the UTM and taken into account in the calculations.

Five wipe tests were performed for each sample, which included wipes A, B and C when dry as well as samples B and C when wet. Unfortunately, due to time and experimental constraints a limited quantity of wipe A was available for testing and, therefore, it was not tested under wet conditions. Even though the standard required for the textile to be wetted prior to testing, the team agreed that the wipe should be tested under both wet and dry conditions. As required by the standard, the wipe was mounted into the UTM and the grip distance was set at 7.5 centimetres. The wipe was then marked off and the line was examined after each test to confirm that none of the wipes experienced slipping. The UTM also conformed to the requirements of the standard by applying a crosshead speed of 30 cm per minute until the wipe broke.

This test was used to measure each sample's overall durability and tear resistance as the UTM system applied a tensile load and computed the displacement, stress, strain at the maximum load along with each tests' Young's modulus. The UTM was able to measure the textile's displacement under a tensile load, which represents the change in length of the fabric (Callister and Rethwisch, 2015). This tensile stress refers to the force applied on a certain area, in SI units and is measured in N/m^2 (Callister and Rethwisch, 2015). On the other hand, the strain was obtained by the ratio of the change in length over the original length of the specimen, which in this case was set at 7.5 cm (Callister and Rethwisch, 2015). Further, the tensile strength represents the maximum stress on a strain-strain curve (Callister and Rethwisch, 2015). Another parameter that was measured by the UTM machine is the Young's modulus, which establishes a relationship between stress and strain and refers to the material's ability to withstand change in length while under a tensile load. This is also commonly referred to as the modulus of elasticity (Callister and Rethwisch, 2015).

4.2 Empirical Analyses

Following the standardized testing that ensures the flushability and durability requirements of the wipe, it is also necessary to apply direct and indirect observations to the product. In the case of these nonwoven hygienic wipes, such empirical analyses will ensure that the wipes meet the main targets of the user-friendliness and flexibility categories.

In detail, the wipes produced must uphold certain standards of texture and feel to ensure its overall softness and non-abrasiveness. This was observed by the physical touch to the skin of the final product, which includes the wipe being saturated with the wetting solution. Alongside this wetting solution, it was made with properly formulated ingredients to be gentle on the skin and provide cleansing properties to remove mild oil, germs and dirt, while not inducing any form of irritation or harsh smells. As well, the final wipe size and flexibility were observed through folding the wipe and attempting to mimic its use by consumers. Furthermore, the characteristics of the wipes produced were imaged in the scanning electron microscope (SEM). The images provided by the SEM (see figure E) helped determine and confirm visual differences between the wipe samples.

4.3 Occupational Health & Safety

The occupational health and safety of the product and its development was not included in the PNL. It is not a criterion that is subject to consideration as all facilities are required to abide by these ethics.

Industry Regulation

The occupational health and safety guidelines for nonwoven wet wipes were briefly discussed in the previous report *Cellulose-Based Hygienic Flushable Wipes*. Additionally, as a means of ensuring Good Manufacturing Practices (GMP) in relation to hygienic wet wipes, the Government of Canada refers to the guidelines set forth by the Food and Drugs Act (FDA), the International Cooperation on Cosmetic Regulation as well as the International Standards Organization (ISO) Guidelines on GMP for Cosmetics (Government of Canada, 2014). GMPs encompasses the standards required for the development of high-quality products through all the industrial processes namely, manufacturing, testing, storage, handling and distribution (Government of Canada, 2014). In this context, hygienic wet wipes are defined as cosmetics and will be following such safety and quality requirements (Government of Canada, 2020).

To ensure the development of a safe product within a healthy industrial environment, establishment instructions are used as guidelines. More specifically, areas such as buildings, equipment, materials, records, laboratory controls and staff are all prepared and inspected (FDA, 2020; Government of Canada, 2014). The requirements for buildings entail its adequate construction and proper ventilation. The equipment used is well maintained, operates appropriately and is routinely cleaned and sanitized when necessary. Materials are ensured to be labelled appropriately and free of contamination. Further, records are necessary throughout the manufacturing process as they ensure the organization of all equipment and materials used, and document the quality of the supplies. Laboratory controls require the finished products to be tested in order to determine if they meet the standards set by the industry. Lastly, the staff involved must be qualified and properly trained to be part of such industrial processes. The staff must partake in protocols to ensure their own health and safety as well as that of the finishing product. More specifically, the individuals involved must sport protective clothing, gloves and hair ties (FDA, 2020; Government of Canada, 2014).

Model Simulation

For the development of the hygienic wet wipe in question, the GMPs set forth by the Government of Canada as well as the establishment instructions were followed to the best capability. As this project was created on a smaller scale, it only took into consideration the industrial processes of manufacturing and testing. Noting that the project's processes were done in a global pandemic, careful distancing measures as well as sanitation were strongly established. For manufacturing, the cellulose-based nonwoven hygienic flushable wet wipes were developed in the McGill Macdonald Campus Technical Services Building. This building's structure allowed for a well-ventilated, large and open space for product development. As well, all spaces used within the shop were properly cleaned and sanitized prior to use. Next, the equipment used to develop the design system was newly purchased or already owned but was ensured to be in proper condition and cleaned for reduced potential contamination. As well, throughout the entire production and testing procedures, detailed records of the machines, materials used, as well as end product results through empirical and standardized testing were recorded in an organized journal. This also ensured that the laboratory controls required for this specific product such as the INDA & EDANA guidelines, the ASTM standard and overall empirical testing met the requirements set forth by the PNL displayed in Table 1. Finally, those involved in the wipe production and testing procedures took the necessary health and safety measures to protect themselves and mainly produce a safe and high-quality end product. More specifically, all members of the team wore protective clothing, gloves and hair ties. As well, face masks, distancing measures and proper sanitizing practices were consistently implemented as per health code recommendations of the COVID-19 protocols.

4.4 Overall Analysis of Results

The following section discusses the results of all the testing conducted in the aforementioned section. More specifically, these results were analyzed and assessed in order to determine the appropriate modifications needed to improve one wipe version to the next, ultimately creating the best final wipe. A visual representation of wipe version A, B and C can be seen in below in figure 5.

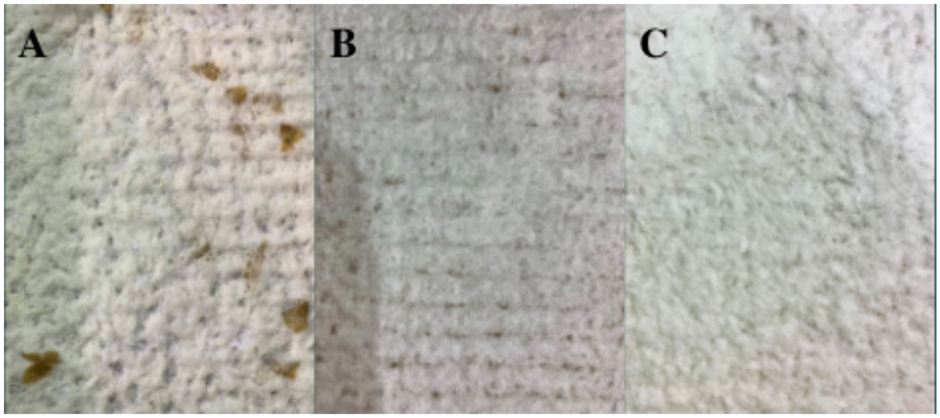

Figure 5. Visual representation of Wipe A, B and C

Wipe Version A

Toilet Bowl and Drain-line Clearance Test (Result: Pass)

No real problems were demonstrated in wipe A through this test as there was no clogging observed. In addition, the water exiting the P-trap system clearly showed broken down pieces of the original wipe. It should be noted that pieces of the wipe were already noticed to fall through the end of the P-trap pipe system after a single flush. The exiting water from each flush thereafter also contained pieces of what looked like disintegrated fibres. It took a total of 15 flushes for the entire wipe to have exited the P-trap system. The remaining 20 flushes seemed to have only clean water, indicating that no wipe was left within the pipes clogging the system.

Slosh Box Disintegration Test (Result: Fail)

Wipe A had an initial dry weight of 1.3 g pre-testing. As the final dry weight of wipe A came to be 0.8 g, it was concluded through the use of equation 6 that wipe A exceeded 40% of its starting weight as 0.8 g is not less than or equal to 0.52g, thus not successfully passing the test.

$$w_f \leq (0.4)\, w_i$$

$$w_f \leq (0.4)\,(1.3)$$

$$w_f \leq 0.52g$$

Settling Test (Result: Fail)

Wipe A was placed in the cylinder and remained afloat at the top throughout the entire duration of the examination. There was no initial sinking and overall, it stayed above the 30 cm limit, deeming the test unsuccessful.

Grab Test

This wipe version was only tested under dry conditions (no wetting solution) due to limited supply. It had an average break force of 0.429 N and the shortest elongation with an average displacement of 5.819 mm. The Young's modulus of this version was the second highest with a mean of 0.399 MPa. The results of these samples stress and strain graphs can be seen in figure D2.1. These results suggest that the wipe had a good capacity to be tear resistant according to the requirements of the PNL however it did not have much stretch to it implying that it is not very flexible. It should also be worth noting that this version was the thickest which may explain its high break force.

Empirical Analysis

Wipe A exhibited poor texture characteristics as both surfaces were rough to the touch, scratchy and lacked an overall pleasant appearance. As well, the paper pulp fibre used was unsuccessful in behaving as a complimentary fibre source to hemp. More specifically, the pulp from the paper did not blend appropriately and left noticeable large pieces. This was presumed to have led the wipe to be of rougher texture, less flexible and non-uniform. Additionally, the wipe displayed large holes which was a result of the parameters chosen during the hydroentanglement process, thus leading the wipe to be visually displeasing.

Overview

Overall, wipe A demonstrated no issues regarding its flushability as it displayed proper dispersable capabilities within the P-trap system. However, it did fail with the slosh box disintegration and settling tests as the wipe did not fully disintegrate nor settle. The success from the drain-line clearance test was assumed to be derived from the force of a mimicked toilet flush, which in this model simulation was large quantities of water being poured down the pipe. Although there were failed tests, the flushability standards of wipe A can overall be deemed sufficient, as the real-life forceful flow of wastewater to treatment facilities contain many components that would facilitate the breakdown of wipe. However, according to the results obtained from the grab test, this version did not meet the requirements of flexibility or tear-resistance that the team was aiming to achieve. Lastly, the physical characteristics of wipe A displayed a need for improvement as it lacked an overall soft feel and uniform appearance.

Modifications Required

It was evident that the choice of blended white paper was not a suitable wood pulp fibre choice. It was decided that the next wipe version will use thoroughly blended toilet paper as the wood pulp source to best mimic short individual fibres. Furthermore, the hydroentanglement process will be done with warmer water and a lower jet pressure to help soften the fibres and reduce the entanglement hole size. With these modifications, wipe B is expected to perform better in the slosh box disintegration and settling tests, as toilet paper will blend better with the hemp, potentially allowing for a more uniform wipe.

<u>Wipe Version B</u>

Toilet Bowl and Drain-line Clearance Test (Result: Pass)

The results of this test were almost identical to that of wipe version A. However, it took a total of 11 flushes for the wipe to fully exit the drain-line. Similarly, the wipe post drain-line was broken up into small pieces of fibre, with a few chunks clumped together remaining in the water.

Slosh Box Disintegration Test (Result: Pass)

Wipe B had an initial dry weight of 1.5 g pre-testing. As the final dry weight of wipe B came to be 0.5 g, it was concluded again through the use of equation 6 that wipe B did not exceed 40% of its starting weight, thus successfully passing the test.

Settling Test (Result: Fail)

Wipe B initially sunk to the bottom of the cylinder, however rose above the 30 cm limit throughout the entire 24-hour time period which overall indicates that this wipe did not pass the test.

Grab Test

This version of the wipe was tested under dry and wet conditions. The dry wipe performed the best under loading and was able to withstand the greatest amount of force. The mean break force was 0.715 N with the average stress and strain being 0.027 MPa and 0.135 mm/mm respectively (see figure D2.2 for the stress-strain graph). It also showed to have good stretching abilities as it had an average elongation of 10.129 mm. The wipe's mean Young's modulus was recorded at 0.433 MPa, which was higher than version A.

Wipe B was also tested when it was conditioned with the wetting solution. It had a greater elongation which was expected due to the wetting solution acting as a plasticizer within the wipe (Dumont, 2021). However its average break force decreased to 0.355 N and the average Young's modulus also decreased to 0.123 MPa (see figure D2.4 for the stress-strain graph). This suggests that the wetting solution provided the wipe with more stretch and flexible properties however, it also weakened its overall tear resistance. Furthermore, it was observed that the tearing within wipe B began where there were holes or a thinner area of the wipe.

Empirical Analysis

Wipe B exhibited a better texture than wipe A as it was less scratchy, but still coarse. The visual appearance of the wipe was pleasant and looked even, and no pieces of unblended wood pulp were visible. As well, the wipe was flexible, but sturdy. It was speculated that these characteristics were obtained by thoroughly blending toilet paper as a wood pulp fibre, using warmer water and by using a higher jet pressure during the hydroentanglement process. The blended toilet paper fibres also allowed for a more even texture and flexibility. Lastly, the hydroentanglement holes were smaller than those presented in wipe A, leading to a more appealing look.

Overview

Overall, wipe B demonstrated improvements over wipe A regarding its flushability as it succeeded this round in both the drain-line clearance test and the slosh box test. It seemed as if the changes made to the pressure in the hydroentanglement system allowed for better dispersibility with the agitation presented in the slosh box examination. Additionally, slight improvements were made regarding the settling test as the wipe did settle to the bottom at the beginning of the evaluation however, it did eventually float above the 30 cm line within the 24 hours. Additionally, this version of the wipe was more tear-resistant as it was able to withstand the greatest amount of force on average. Although the overall texture of wipe B improved compared to that of wipe A, further modifications could be made to refine its user-friendliness as a means of making it more marketable.

Modifications Required

The choice of blended toilet paper resulted in improvements, however in order to further maximize the performance of the product as well as its behaviour in the standardized tests, it was decided that conventional wood pulp would be best as it best represents industrial practices. Additionally, another component that would aid in the overall texture of the product is glycerol and would be added during the suspension step and agitated with the fibres. The new wood pulp fibres was kindly sourced by Dr. Dumont, an assistant professor in the Department of Bioresource Engineering at the University of McGill. All other parameters involved in the wipe manufacturing system such as the hydroentanglement pressure will remain unchanged. The addition of glycerol will also hopefully have an impact on the wipe's ability to settle as it will contribute to increasing the density of the product. With these modifications, wipe C is expected to perform better and have an improved overall finish

<u>Wipe Version C</u>

Toilet Bowl and Drain-line Clearance Test (Result: Pass)

The results of this test were almost identical to that of wipe versions A and B. However, it took a total of 10 flushes for the wipe to fully exit the drain-line. This wipe post drain-line seemed as if it was completely disintegrated as the physical structure of the wipe was clearly broken up into its fibrous components.

Slosh Box Disintegration Test (Result: Pass)

Wipe C had an initial dry weight of 1.5 g pre-testing. As the final dry weight of wipe C came to be 0.6 g, it was concluded through the use of equation 6 that wipe C did not exceed 40% of its starting weight, thus successfully passing the test.

Settling Test (Result: Pass)

Wipe C instantly sunk to the bottom and over the course of the 24-hour time period it remained at the bottom which indicates that this wipe successfully passed the test.

Grab Test

Wipe version C was also tested under dry and wet conditions. The dry condition wipe was quite strong as well as its mean break force resulted in a value of 0.665 N (stress and strain at max load was 0.024 MPa and 0.152 mm/mm respectively (see figure D2.3 for the full graph)). It also had an average Young's modulus of 0.285 MPa and mean elongation of 11.412 mm. No large gap between wipe B dry and wipe C dry break forces were noticed nor their elongations, however their Young's modulus differed.

It was found that wipe B when dry had the highest average break force, stress and Young's modulus. However, the conditioned wipe C had the largest average elongation, stretching 22.116 mm, which corresponds to 30% of its original length. The largest elongation recorded was 42% its original length. This data shows that after being wetted with the cleansing solution the wipe was able to exhibit stretching and flexible properties. However the break force was the lowest of the wipes with a mean of 0.342 N (stress and stress at this load were 0.013 MPa and 0.295 mm/mm (see figure D2.5 for the full graph)). This version also had the lowest recorded Young's modulus with an average of 0.103 MPa.

Empirical Analysis

The final product of wipe C had the best overall finish compared to the others previously produced. It resulted in a much softer and uniform texture, as well as a more proportional size and shape. The hydroentanglement holes were less noticeable, the wood pulp fibres were seamless and the wipe was not rough. Although the changes made to wipe B did demonstrate improvements, the wipe still did not reach the empirical standards of those sold on the market currently.

Overview

Overall, wipe C demonstrated improvements compared to both wipe A and B. Its flushability results demonstrated success with the changes made throughout the testing process. When looking at all the wipe samples, they all did not reach the time threshold required by the standard as their time-to-break was recorded at 2.458 seconds and not 20 seconds. However, despite not meeting the breaking time requirements, the results of this test demonstrated that the dry version of this wipe was quite tear resistant as it could withstand more force and the conditioned wipe was the most flexible of any of the other prototypes. The empirical analysis of wipe C was best overall, however when demonstrating this product on an industrial scale, its softness, texture and visual appearance could still be modified compared to those on the market today. As this product is meant to be developed for personal hygienic uses, all user-friendliness factors are very important for marketability and customer satisfaction.

4.5 Future Considerations

As wipe C is the final product developed in this design, it is recommended that any further wipe versions be made under proper industrial practices. As this design was experimentally produced and tested on a small scale basis, it is not representative of its full potential. Therefore, any modifications required for further development should be made with proper processing equipment such as an industrial hydroentanglement system and a complete overview of all the standardized testing. Due to the time restraints of this project, the current global pandemic as well as the access to industrial equipment and materials, not all of the required standardized tests were performed. INDA, EDANA & ASTM have a longer set of evaluations for determining flushability than those used in this project as they require heavy industrial machinery, materials, labour and extensive time. Those selected to be used in this project allowed for a broad flushability assessment of the wipe versions produced and considered them the most important with respect to the aspect of the PNL.

In relation to empirical analyses, the experimental results presented through the examinations were carried out using the team's own personal assessment. In future considerations, when the time, budget and materials are available, supplementary standardized tests for adequate durability, texture and feel are recommended to produce a suitable marketable product. Furthermore, an in-depth analysis of SEM images could be performed to identify the effectiveness of the bonding technique and the structural weakness of the nonwoven textile.

5.0 Practicality of Final Prototype

5.1 Environmental Considerations

Throughout the development of the wipe in question, many important environmental aspects were taken into consideration to limit the product's overall impact. As previously mentioned in the following report, the wet wipe industry has caused significant damage to the environment through their lack of dispersibility within toilet systems, ultimately creating major sewage system blockages (Hann et al. 2018). These wipes causing the blockages also contribute to environmental pollution through plastic accumulation in marine ecosystems due to their material composition (Hann et al. 2018; Mendoza et al., 2018). Throughout the entirety of the design process of this project, ensuring the product was made with cellulose-based fibres became an important concept to maintain. Although the source of the wood pulp fibres may have varied throughout the modifications made between the wipe versions (A, B & C), it was essential for them to remain cellulose-based as it was a key component of the project design. According to the test selection for this experimental project design, the final product prototype succeeded in being a cellulose-based hygienic wet wipe with the ability to disperse accordingly in municipal toilet systems. The design produced, which included a wet-laid hydroentangled hemp and wood pulp fibre blended wet wipe, could be demonstrated as an appropriate option for environmental improvement regarding the wet wipe industry.

Further, the machinery processes used throughout the industrial production of the wipe are presented as energy intensive, mainly the hydroentanglement system. Although this system uses an excess of water, it is known to recycle the water for reuse in the system (Moyo, 2012). As the development of the prototype wipe was an experimental process and required a self-made system of the design requirements, there was no excess use of resources such as materials, energy, water and produced an overall minimal amount of waste.

5.2 Social Considerations

Within the industry of hygienic wet wipes, it was evident that there existed a need for improvement within the product, as consumers habitually flush down wipes that are not designed to be broken down appropriately. Thereby, significantly damaging sewers and wastewater management systems. The new design in this project would ultimately contribute to a positive social change as it increases the sustainability of the current habits of consumers. More specifically, from the results obtained following the testing practices chosen for this project, the final wipe C seemingly demonstrated the ability to be flushed appropriately, while simultaneously having user-friendly qualities. Therefore, this would indicate that by using the final prototype wipe C product, consumers need not change their disposal habits.

In addition, the development of this wipe involves positive social considerations as the modifications made upheld the user-friendliness criterion. This criterion was important to follow throughout the development of the prototypes as a means of gaining the trust of consumers and maintaining social acceptance of such a newly designed product. The development of this product undertook three different prototypes with multiple forms of testing and evaluations to ensure the best quality was yielded for appropriate marketability and customer satisfaction.

5.3 Health and Safety Considerations

The health and safety parameters considered throughout the development of this product encompass the systems impacted by its disposal behaviour, as well as those involved in its production and those using it.

To affirm that these requirements were met, it was necessary for the final prototype product to undergo specific standardized testing as well as industry codes of practice. However, the final prototype produced was constructed under an experimental setting, therefore not all of the appropriate tests were completed. The evaluations chosen to be completed in this project were a product of the resources and time available. This indicates however that the final product is seemingly flushable, but cannot be stated as legally flushable until all tests are measured and acquired. For the safety of its users as well as wastewater facilities and systems, it is required that the next steps following the preliminary wipe design would need more extensive industrial standard testing as it would ensure the proper labelling of flushability for appropriate consumer use.

In terms of ensuring the safety of the product's consumers, the design took into consideration several important parameters such as fibre types and wetting solution ingredients. The final version of the product uses both industrial grade wood pulp and hemp fibres, which inherently increases its overall product quality. As well, the entire design of the product including its web forming and web bonding processes were carefully chosen for the development of a personal hygiene product. Further, the wetting solution used following these processes was meticulously developed as the ingredients that were chosen ensured a safe cleansing product that could be used in hygienic sensitive areas (further explained in section 6.3). These ingredients also allow the product to preserve itself accordingly, certifying its quality is maintained over a long period of time.

In addition, throughout the entirety of the production process, many occupational health and safety precautions were seriously implemented as per mentioned in subsection 4.3. This was critical to stipulate the safety of those involved in the production of the various wipes as well as the physical product developed. Further, given the circumstances of the current pandemic, heavy health regulations were also set in place in all facilities used.

5.4 Economic Considerations

The following report discusses a wipe design using a prototype of a model simulation of a typical industrial wipe manufacturing system. This being said, it is important to consider that the economics throughout the development of this product is not representative of that of a real-life industrial process. However, with the development of this product being unique with only using cellulose-based fibres, wet-laid and hydroentangled techniques, it does not rely on any new and expensive technology within an industrial setting. This hypothesized design leads to presumed reasonable economic production choices, for a reasonably priced product.

Cellulose-based wipes have a niche market in the industry, however incorporating a label of flushability brings forth a wide variety of consumers. As well, with a corresponding product marketing plan, the successful exposure of a cellulose-based hygienic flushable wipe can be achieved and generate economic advantages. It is only through the appropriate application of design methods within an industrial setting that a true cost analysis can be conducted and compared to other marketed wipes.

As this design was completed in an experimental setting, the development of this product took into account the individual costs of material selection, ingredients as well as the resources needed for the simulated web formation and bonding techniques. The overview of the cost analysis of the experimental product is thoroughly discussed in the following section.

6.0 Considerations and Future Perspectives

6.1 Cost Analysis

The hemp fibres that were used in this project were degummed hemp and a total of one kilogram of hemp was obtained from Bast Fibre Tech. Unfortunately, they did not provide the cost of one kilogram of hemp. However, the calculations will be based on bulk quantities to simulate an industrial supply and are demonstrated in detail in Appendix F.1. For a bulk purchase of 595 kg of degummed hemp, the cost would total to approximately $11.26/kg (Bulk Hemp Warehouse, 2021). If this were compared with the cost of the prototype, it would come out to $32.85 per kilo (Bulk Hemp Warehouse, 2021). Further, the wood pulp was another ingredient used in the creation of the wipes and typically costs around $1.63 per kilogram according to Natural Resources Canada (2021). However, the supplier site Alibaba (2021) demonstrates that wood pulp can be purchased for $1396.53 for 20000 kg. As each wipe is known to weigh roughly 3 g (with a 2:1 ratio of hemp to wood pulp), this can produce around 1,000 wipes. Therefore, to produce 1000 wipes, it would cost a total of $22.59 in materials for the bulk quantities simulating industrial costs. In the case of our prototype the cost of materials would be $67.33.

In addition to the materials, the cost of the wetting solution ingredients for 60 mL of solution is described in Appendix F.2. The cost of the cosmetic ingredients were according to the tab from the supplier Coop Coco and distilled water from Walmart. The total cost to produce 60 mL of wetting solution totaled to $0.74 (see Appendix F.2). This amount of wetting solution would be sufficient enough to fill 2 bottles of solution. In order to dampen each wipe with the solution, 1 mL was used. Therefore, one wipe is worth $0.0123 of wetting solution. To summarize, without including the cost of labour, the total cost to manufacture a single wipe is demonstrated in Appendix F.3.

As the system produced was experimental and in a non-industrial setting with inefficiencies, the cost to produce a single wipe for this project was almost triple that if it were to be made in bulk within an industrial setting (not including the added cost of labour and cost of machinery and systems). Furthermore, in future considerations, the cost of labour is important to consider. For example, the prototype created took two people in non-industrial work conditions four and a half hours to be able to produce three wipes. Assuming the cost of labour for each worker is the minimum wage of $13.50/hour in Quebec, the price of each individual wipe would be unsustainable and unrealistic. However, in an industrial setting, wipes would be manufactured more efficiently demonstrating an increased number of wipes per unit of time.

6.2 Barriers to Industrial Implementation

Fortunately, nonwoven techniques such as wet-laid and hydroentanglement have already been in practice in the industry and the machinery system have already been developed (ANDRITZ, 2019). The industrial line configuration for wipes illustrated in figure 6 represents a unified unit of all systems required to make a nonwoven wet wipe. The modelled and experimental prototype system created did not exhibit a seamless production line as each step was executed independently from one another. The most important adjustment to consider would be the fibre input. The fibres used were not synthetic, therefore they had different properties and could pose different challenges than the current marketed wipes. However, it has been noted that the combination of wet-laid and hydroentanglement allows for the use of biodegradable materials, with no additives, to make nonwoven textiles (ANDRITZ, 2019). In terms of bulk material supply, hemp fibre and wood pulp can have consistent quality and availability of supply (Galembert, 2003.; Jones & Brischke, 2017.; Manaia et al., 2019). Furthermore, the use of cellulosic fibres for nonwoven textiles can improve the fibre dispersion and bonding, the textile's absorption, softness, and colour (Hubbe & Koukoulas, 2016). There are no major barriers to implementing our design industrially, the supply of fibre and the machines required are present and available.

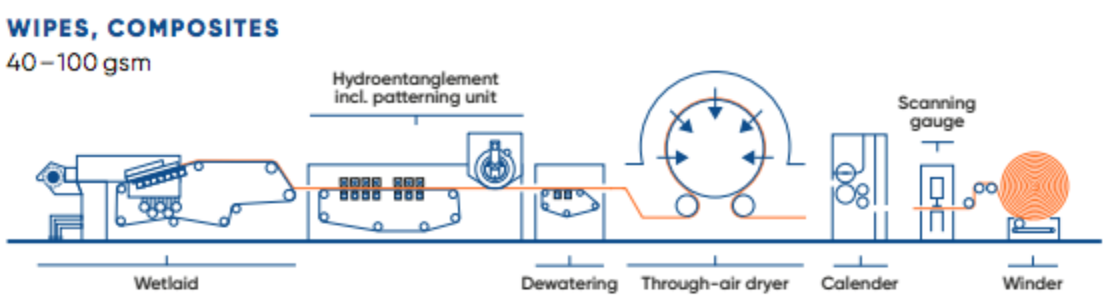

Figure 6. Complete unified industrial unit for nonwoven wet wipes (ANDRITZ, 2019)

6.3 Risk Management

The risks associated with the production line of the wipe manufacturing process are relatively low, as each individual step was completed autonomously with careful detail. In addition, if this project were to be implemented in an industrial manufacturing setting, the process expresses an even lesser risk as the machinery has been carefully developed and programmed to function efficiently and safely.

As the current marketed wipes are known to contain synthetic plastics within their material composition, the biomaterial created throughout the course of this project was specifically designed to be made completely out of natural cellulosic fibres while still being flushable (i.e. wastewater system safe). Most of the literature on wipes, that end up in wastewater systems, focus on the pollution that the wipes' microplastics cause to marine ecosystems. Therefore the team constructed a plastic-free wipe, ultimately mitigating the concern of plastic pollution resulting from their disposal. There has also been concerns about the cellulosic fibres' interaction in marine environments and if there is a risk of these fibres negatively impacting aquatic organisms. According to Suaria et al. (2020), there has been no evidence that the consumption of cellulosic fibres by marine organisms in the wild has caused illnesses. Illnesses due to the fibres including plastics fibres have only been found in invertebrates in controlled lab studies (Suaria et al., 2020). Hemp and wood pulp fibres are biodegradable though it is still unclear to scientists if these fibres properly degrade in marine ecosystems (Henry et al., 2019; Suaria et al., 2020). However this study notes that the chemicals and plastics present in the wipes pose the greatest risk (Suaria et al., 2020).

Therefore, the focus of the risk assessment associated with the final product is more likely to result from the ingredients in the wetting solution. More specifically, there is potential risk associated with the solution as it could directly affect consumers during use and other organisms post disposal. However, the wetting solution was meticulously created with these risks in mind. Regarding the risk of affecting marine life, Rodrigues et al. (2020) state that coco glucoside is biodegradable in seawater and poses a small risk of lethality to aquatic organisms. GeoGard Ultra also has low marine toxicity, and is not known to bioaccumulate in ecosystems (Coop Coco, 2020a).

In relation to the risks that could affect consumers, according to the safety data sheet provided by the supplier, GeoGard Ultra is not known to cause irritation to the skin (Coop Coco, 2020a). Moreover, citric acid, caprylic/capric triglycerides and vegetable glycerin are also consumed as food additives, and therefore pose little to no risk to human and animal health in terms of irritation or toxicity (Becker et al., 2019; Fiume et al., 2014; Traul et al., 2000). However it has been stated by Fiume et al. (2014), that citric acid may increase skin vulnerability to sunburn if not chemically formulated appropriately. Furthermore, the ingredient olivem 1000, also known as cetearyl olivate, is an alkyl ester that chemically results from olive oil, but is historically known to have a maximum concentration of 0.3-3% in products (Fiume et al., 2015). Therefore, the team only used 2% of concentrated olivem 1000 in the prototyped product in order to stay within the known concentration limits of this ingredient. Overall, when following the recommended guidelines, olivem 1000 can be considered a safe and non-irritating cosmetic ingredient (Fiume et al., 2015).

In overview, the risks regarding the safety of wastewater treatment systems, consumers and marine life were taken into consideration throughout the assessment of alternatives, production and testing processes needed to complete the development of a prototype nonwoven wet wipe.

7.0 Conclusion

Overall, this project aimed to improve the wet wipes available on the market today by producing a cellulose-based hygienic flushable wipe designed for the benefit of the wastewater treatment facilities, environment and consumer use. As a team, this project was deemed successful on an experimental basis with the results of the final prototype C. Even though the true results of this experiment are not known due to its lack of equipment, testing methods and resources, it was a victorious preliminarily step to a much larger project. Optimally, if this project can be pursued on a larger scale, the team would aim to develop a prototype using the appropriate industrial equipment and testing methods. These advanced technologies will permit to decrease the cost of production and efficiently produce large quantities of uniform wipes.

Even though the development of this project was conducted on an experimental platform, this was a stepping stone to creating a change within the wet wipe industry. More specifically, the design of a cellulose-based hygienic flushable wipe will positively affect the industry by encouraging other scientific research to occur within this field by representing a unique design which causes minimal damage post disposal.

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Appendices

Appendix A
Prototype System

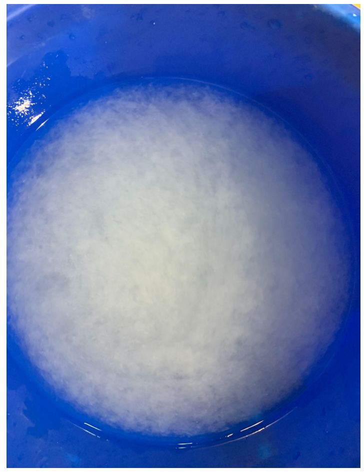

Figure A1. Woop pulp fibres suspended.

Figure A2. Hemp and wood pulp fibres suspended.

Figure A3. Fibres laid onto mesh screen.

Figure A4. Dental Flosser for Hydroentanglement


Figure A5. Drying Box

Appendix B

Design Project Cost

Materials	Reason	Cost	Supplier	Calculation of taxes	
P-trap	Testing	$16.09 (with tax)	Reno Depot		
Toilet pipe	Testing	$10.22 (with tax)	Reno Depot		
Rack, screen, water flosser	Wetlaid and hydroentanglement	$84.77 (with tax)	Amazon		
Emulsifier	Wetting solution	$ 6.59 (without tax or shipping)	Coop Coco	$6.97 (minus 8% discount, plus 15% tax)	
Olivem 1000	Wetting solution	$ 14.29 (without tax or shipping)	Coop Coco	$15.12 (minus 8% discount, plus 15% tax)	+ $8.79 shipping
Citric Acid	Wetting solution	$ 8.89 (without tax or shipping)	Coop Coco	$9.40 (minus 8% discount, plus 15% tax)	
pH meter	Checking pH of wetting solution	$ 16.99 (without tax or shipping)	Amazon	$17.40 (calculated with 15% tax)	
Screen and temperature gun	Wetlaid and for preparing the wetting solution	$49.97 (with taxes)	Amazon		

Reno Depot (pipes)	$	16.09
Reno (pipes)	$	10.22
Amazon (rack, water flosser, screen)	$	84.77
Coop Coco (wetting ingredients)	$	6.97
Coop Coco (wetting ingredients)	$	15.12
Coop Coco (wetting ingredients)	$	9.40
Coop Coco (shipping)	$	8.79
Amazon (pH meter)	$	17.40
Amazon (screen and thermometer)	$	49.97
Total (with all taxes and shipping)		**$218.73**

Table B1. Total Design Project Cost Calculation

Appendix C

Testing System Images

Figure C1. P-trap system

Figure C2. Settling Test

Appendix D

Testing with UTM

Appendix D.1

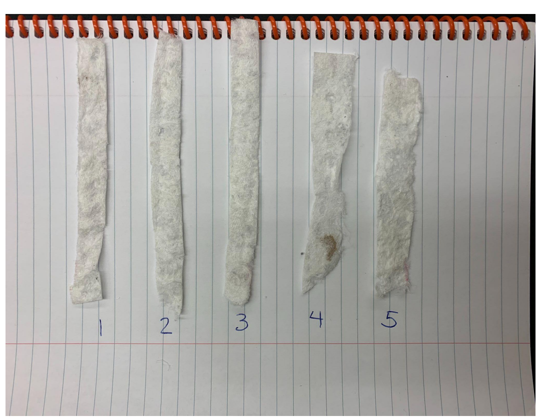

Figure D1.1 Wipe A

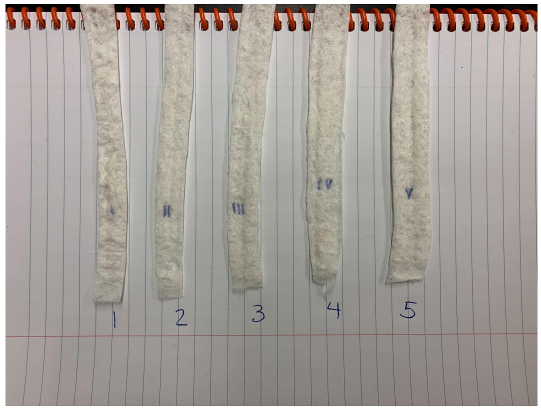

Figure D1.2 Wipe B

Figure D1.3 Wipe C

Appendix D.2

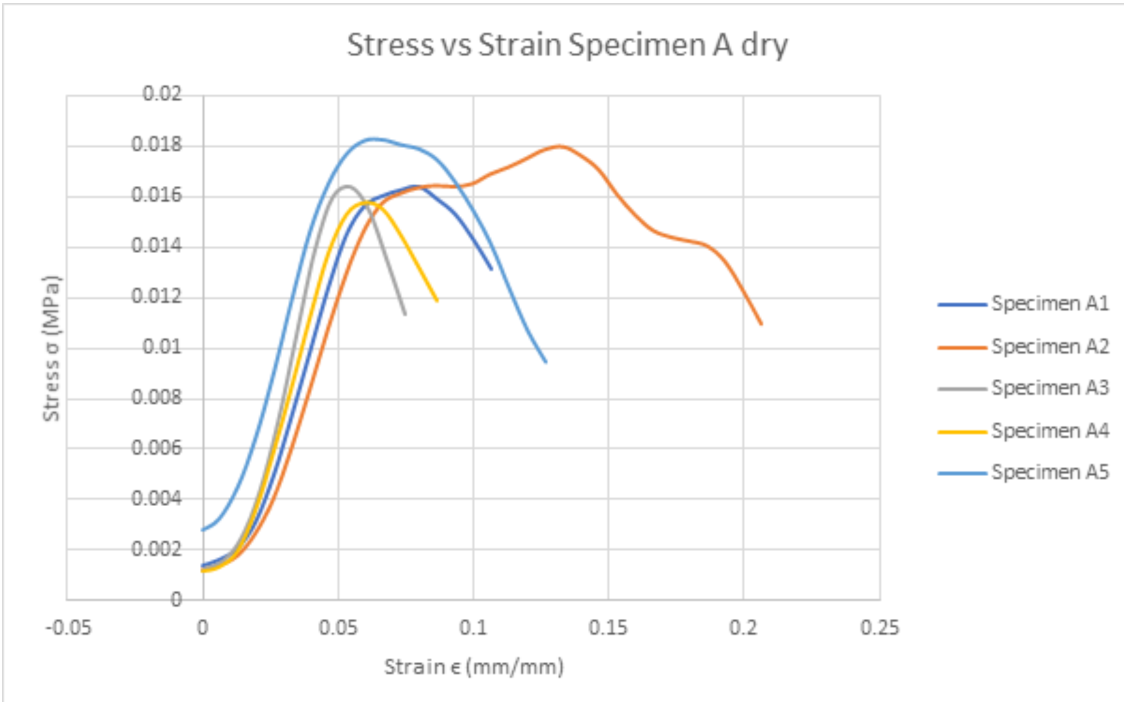

Figure D2.1 Stress vs Stress Graph Specimen A Dry

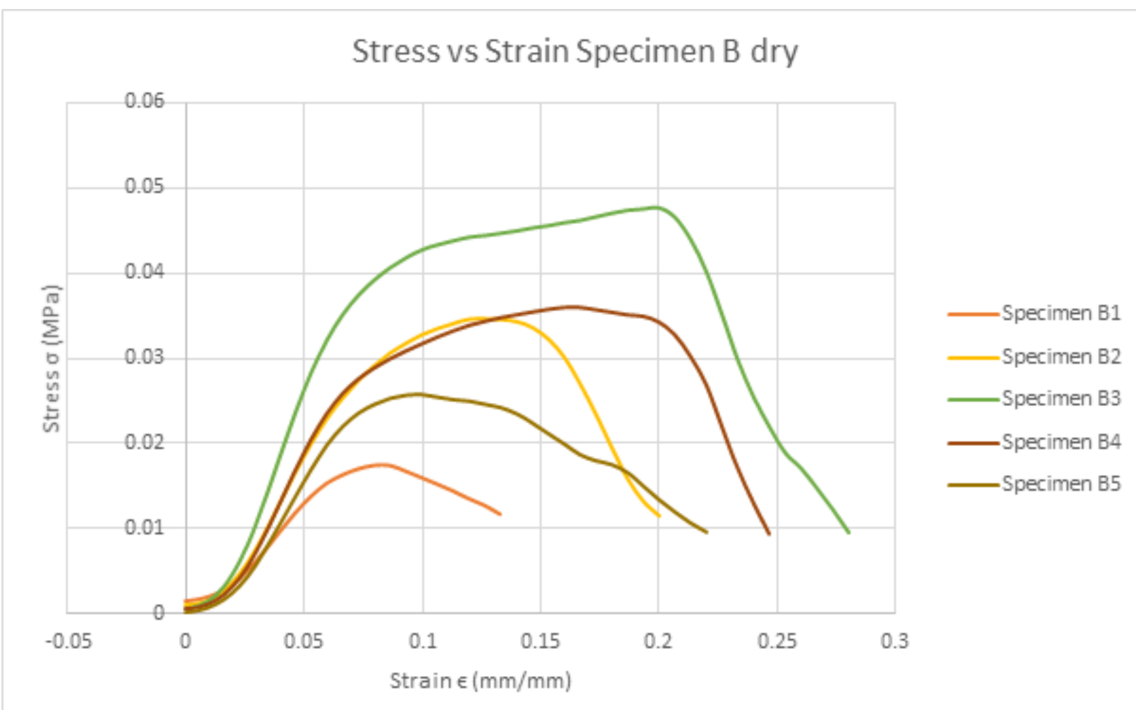

Figure D2.2 Stress vs Stress Graph Specimen B Dry

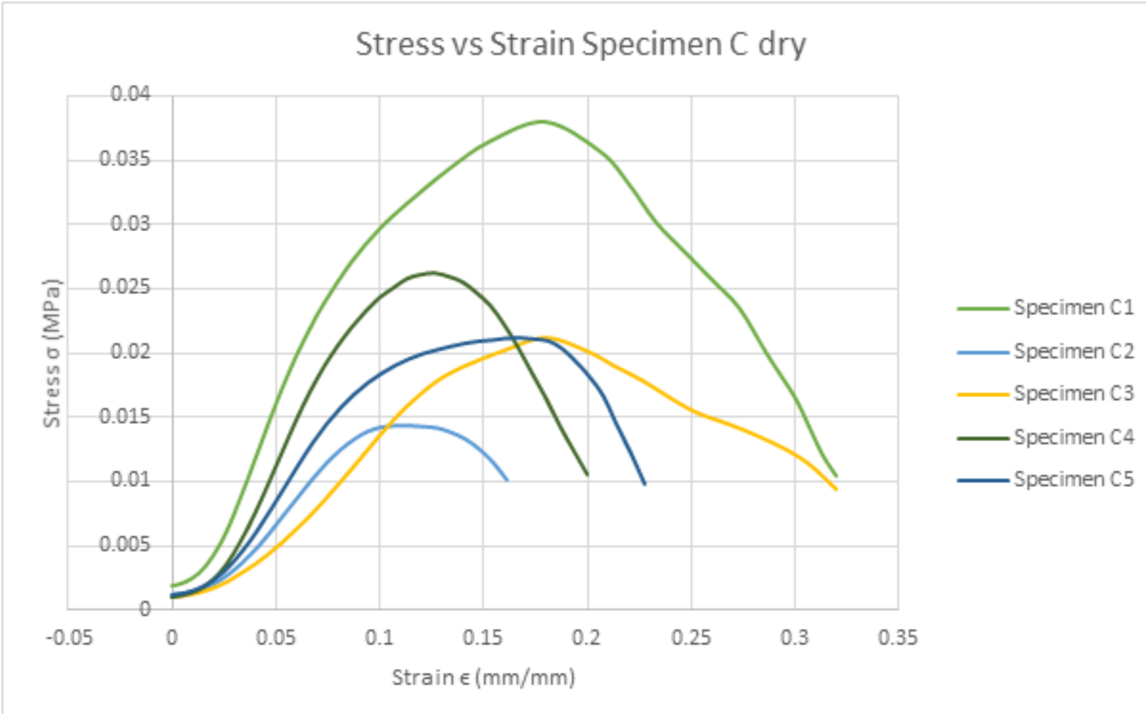

Figure D2.3 Stress vs Stress Graph Specimen C Dry

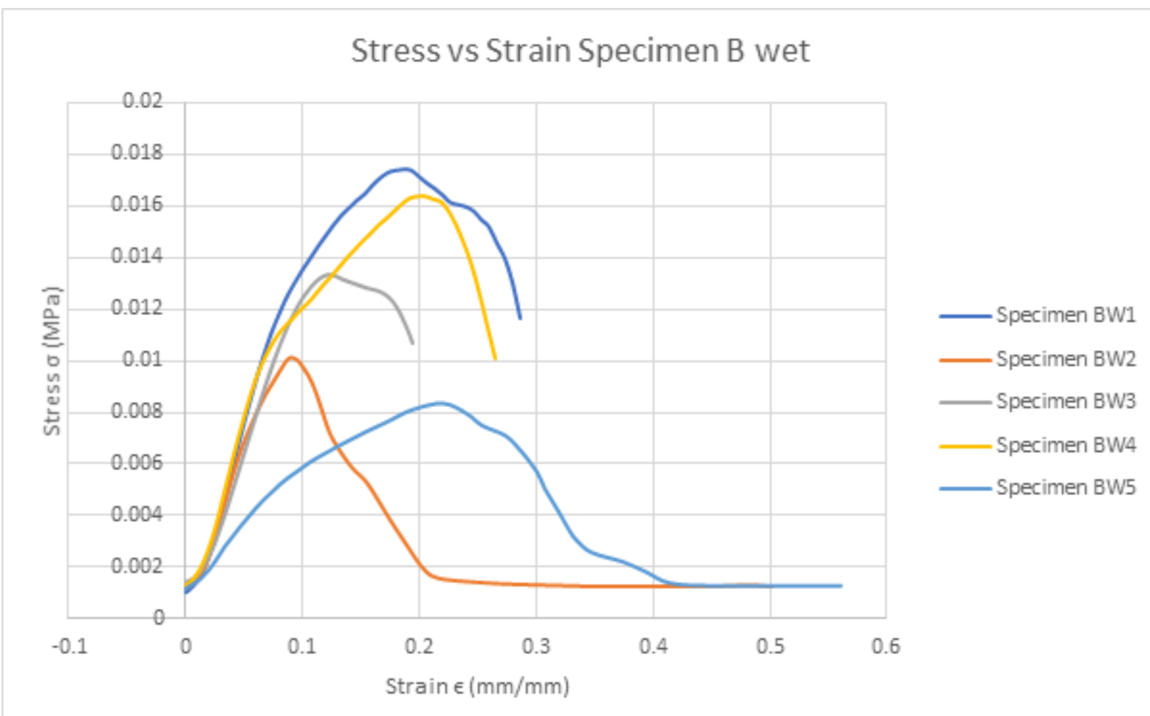

Figure D2.4 Stress vs Stress Graph Specimen B Wet

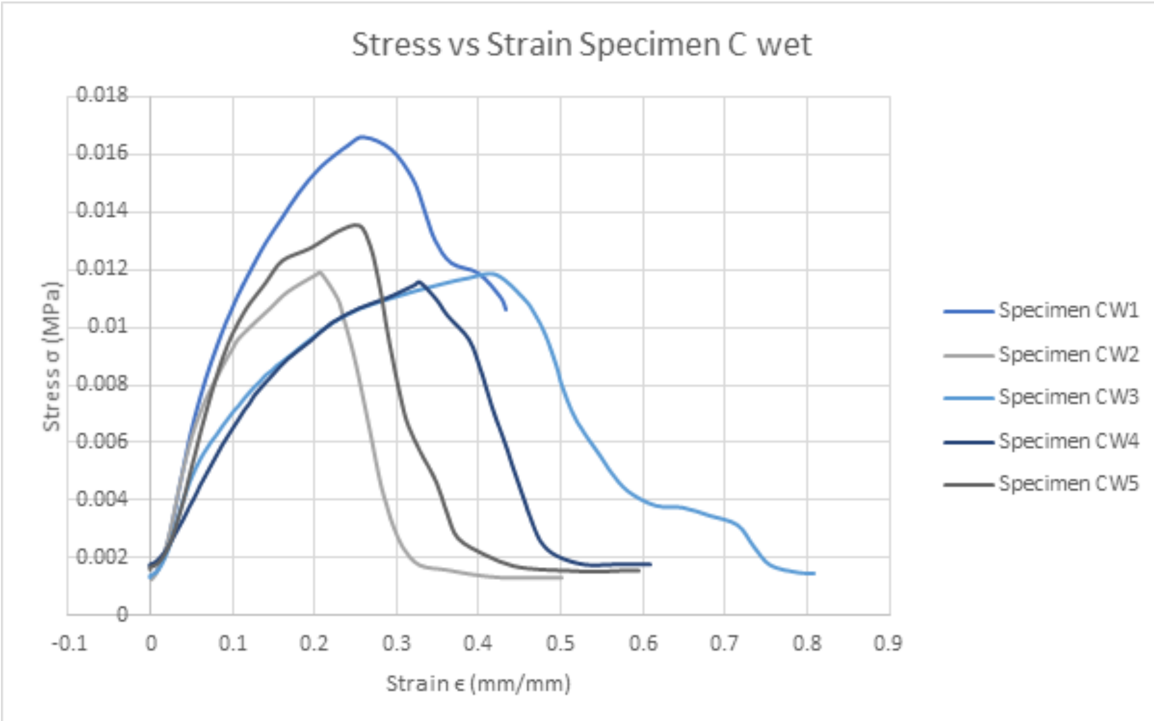

Figure D2.5 Stress vs Stress Graph Specimen C Wet

Appendix E

SEM Images

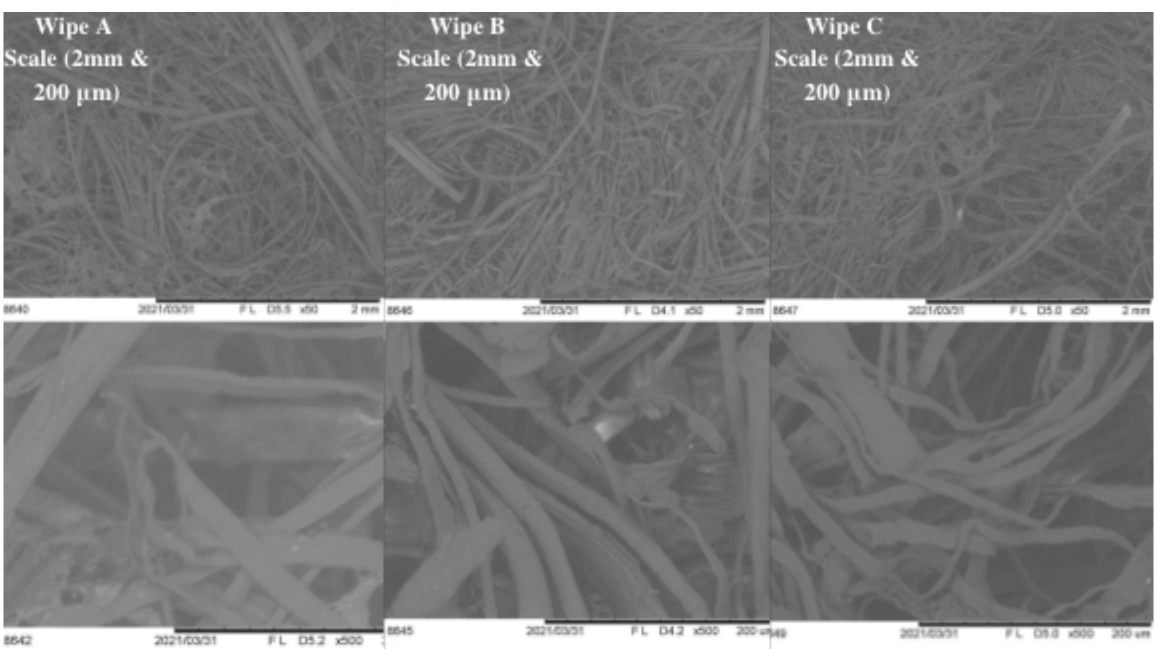

Figure E. Scanning Electron Microscope Images for Wipe A, B and C.

Appendix F : Calculations

Appendix F.1
Prototype and Industrial Cost of Fibres

Industrial cost of hemp

$$\frac{\$11.26}{kg} \times 2\,kg = \$22.52/\,1000\,wipes$$

Prototype cost of hemp

$$\frac{\$32.85}{kg} \times 2\,kg = \$65.70/\,1000\,wipes$$

Industrial cost of wood pulp

$$\frac{\$1396.53}{20000kg} \times 1\,kg = \$0.0698/\,1000\,wipes$$

Prototype cost of wood pulp

$$\frac{\$1.63}{kg} \times 1\,kg = \$1.63/\,1000\,wipes$$

Total cost of industrial materials to produce 1000 wipes

$$\$22.52 + \$0.0698 = \$22.59$$

Total cost of prototype materials to produce 1000 wipes

$$\$\,65.70 + \$\,1.63 = \$67.33$$

Appendix F.2
Wetting Solution Cost per 60 Wipes

Distilled water:

$$\frac{\$0.97}{4000\,mL} \times 38\,mL = \$\,0.0092$$

Vegetable glycerin:

3 mL used for solution and 5 mL used for wet-laid process to soften fibres

$$\frac{\$34.29}{4000\,mL} \times (3\,mL + 5\,mL) = \$\,0.06858$$

Caprylic/capric triglycerides:

$$\frac{\$329.19}{19000\,mL} \times 7.2\,mL = \$\,0.1247$$

Olivem 1000:

density is 1.055 g/mL (Nuiy Nature, 2020)

$$\frac{\$49.39}{500\,g} \times 1.055\,\frac{g}{mL} \times 1.2\,mL = \$\,0.125$$

Coco glucoside

$$\frac{\$52.49}{4000\ mL} \times 9\ mL = \$\ 0.1181$$

GeoGard Ultra:

density 4 oz = 113.4 g (Coop Coco, 2020)

$$\frac{\$58.29}{250\ g} \times \frac{113.4\ g}{4\ oz} \times \frac{1\ oz}{29.57\ mL} \times 1.2\ mL = \$\ 0.2682$$

Citric acid

This was the only ingredient measured in grams as it came in powder form and varied for each solution (it was used as a buffer). However the average amount used per 60 mL bottle was weighed to be 3g.

$$\frac{\$8.89}{1000g} \times 3\ g = \$\ 0.02667$$

Total

$$\$0.0092 + \$0.06858 + \$0.1247 + \$0.125 + \$0.1181 + \$0.2682 = \$0.74$$

cost per 60 wipes.

Appendix F.3
Total Industrial and Prototype Cost per Wipe

Cost of solution per wipe

$$\frac{\$0.74}{60\ mL} \times 1\ mL = \$0.0123$$

Industrial cost per wipe

$$\frac{\$22.59}{1000\ wipes} = \$0.02259 + \$0.0123 = \$0.03/wipe$$

In packs of 250 wipes

$0.03 × 250 = $7.50

Prototype cost per wipe

$$\frac{\$67.33}{1000\ wipes} = \$0.06733 + \$0.0123 = \$0.08/wipe$$

In packs of 250 wipes

$0.08 × 250 = $19.91