Mouthfeel Assessment of Tetra Pak Paper Straws: Exploring the Correlation between Instrumental Measurements and Sensory Evaluation

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MASTER THESIS

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Abstract

The implementation of the Single-Use Plastics Directive has gained significant attention due to the detrimental impacts of plastic pollution, leading to the transition from plastic straws to paper straws for Tetra Pak's portion-size carton packages. However, the acceptance of paper straws could be hindered by negative mouthfeel perceptions, which customers find the difficulties to accurately describe them. Objective measurement approaches, such as instrumental measurement, are expected to provide a comprehensive understanding of the mouthfeel, which can be correlated with subjective preference. Therefore, it is important to ensure that the instruments can accurately predict the results of consumer responses.

The testing methods were developed in this study with the aim of investigating the useful correlations between subjective sensory perceptions and objective instrumental measurements of the mouthfeel on paper straws. Six different variants of paper straws were objectively evaluated for their mechanical and chemical properties related to mouthfeel through instrumental measurements, and their mouthfeel perception was subjectively evaluated through sensory analysis. Correlations between both subjective and objective measurements were identified using Pearson's correlation.

The results indicated that applying a coating material on paper straws effectively reduces water absorption and surface roughness but increases the coefficient of friction. In terms of compressive strength, wet paper straws exhibited significantly lower strength than dry paper straws across all variants. The subjective sensory evaluation revealed that coated paper straws were perceived to be less rough, sticky, dry, and soggy while exhibiting higher sturdiness. Some subjective and objective correlations have been identified in this study, with tactile friction and water absorption demonstrating the most potential in predicting the mouthfeel perception of paper straws. Other properties, including surface roughness, dry compressive strength, and wet compressive strength, only showed a trend of correlations with mouthfeel perceptions without statistical proof. However, further research with more diverse paper straw variants is recommended to confirm the statistical significance of their relationships.

Keywords: mouthfeel, paper straws, correlations, instrumental measurement, sensory evaluation

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List of acronyms and abbreviations

SUP	Single-Use Plastic
CM	Commercial straw
COF	Coefficient of Friction or Friction Coefficient
R_a	Arithmetical roughness average
GMP	Good Manufacturing Practices

1 Introduction

This section presents the company background and problem identification which lead to the project objective and research questions that need to be answered. This section also highlights the scope of the study and delimitations occurred during the project.

1.1 Company Background

Tetra Pak, a pioneer and world-leading food processing and packaging solutions company, was established by Ruben Rausing in 1951 in Lund, Sweden. The company offer several technologies to its customers, including a wide range of complete carton packaging, filling machines, processing solutions and other packaging materials used with carton packages, such as straws, openings, and closures (Tetra Pak, n.d.-c)

The sustainability aspect is a core of Tetra Pak's business, with the idea that the package should save more than it costs. The company, therefore, strongly emphasizes developing innovative solutions and technologies that prioritize food safety, as well as protecting both people and the planet with the slogan "Protects What's Good" This applies not only to the packaging itself but also to the additional materials used with carton packaging, like straws. In Europe, Tetra Pak is the first carton packaging company who introduced paper straws for beverage cartons after the new regulation regarding single-use plastics was implemented. Paper straws from Tetra Pak are recyclable and made only from natural-based materials. With this change, the impact of climate change is reduced by 34% compared to plastic straws (Tetra Pak, n.d.-b; Tetra Pak Global, 2019)

1.2 Problem Identification

1.2.1 Plastics pollution

Plastic is a versatile and durable material that changes many aspects of people's life. It generates enormous convenience and is practical for use in various applications, such as packaging material, especially for food products, as well as used in construction, textiles, consumer products and transportation (Soomro, n.d.; XL Plastics, n.d.). However, the rapid increase in plastic production created numerous challenges in our society, particularly in the environment, where tons of plastic waste deteriorate human and animal health (Plastic Free Foundation, n.d.). The majority of plastic waste comes from single-use plastic products or also known as SUPs (Hale & Song, 2020). SUPs refer to plastic products designed to be used only once or for a brief period and then discarded. The broad usage of SUPs, including plastic bags, straws, beverage containers, and food packaging, has resulted in a remarkable upsurge, creating significant waste that may take several centuries to decompose. Among these products, plastic straws are one of the most concerned because of their high levels of consumption but poor recycling rate since they are often littered in nature. It is estimated that European people consumes over 25.3 billion plastic straws every year, and US people uses approximately 500 million daily, which many of them end up in the ocean, where they can serve a severe risk to marine life (European Commission, n.d.-b; Tembo Paper, 2020)

1.2.2 The Single-Use Plastic Directive

The detrimental effects of plastic pollution and marine debris have emerged as the focus of the public's awareness in recent years, provoking demands for a decrease in SUP consumption. To address this issue, the European Union has taken a leading role by implementing the Single-Use Plastics Directive (Directive (EU) 2019/904), starting on the 3rd of July 2021. This regulation aims to decrease plastic waste and minimize its negative impacts on the environment, especially in marine ecosystems, as well as human health. As a result, the SUPs that have feasible alternatives, which are more cost-effective and eco-friendlier, are not permitted to be sold in the Member States' markets, including plastic straws. This initiative thereby contributes to a significant step towards a more sustainable future and cleaner environment for everyone (European Commission, n.d.-a)

1.2.3 Plastic straws replacement and company’s challenges

In response to the recent EU regulations regarding Single-Use Plastics (SUPs) and the rising demand for sustainability, Tetra Pak has contributed to these proactive steps to address the problem of plastic straw waste and littering. The company has consequently introduced paper straws for its portion-size carton packages, replacing the current plastic straw. While switching to paper straws is important for reducing plastic waste, it is also important to address any potential limitations on their usage to ensure that they are a viable and acceptable alternative for consumers. Although the development teams are continuously improving their paper straws to provide the best experience for their customers, there still have been some issues that affect mouthfeel, which might lead to the overall consumer unacceptability. In addition, the difficulty that consumers cannot effectively communicate their precise thoughts or experiences regarding their negative perceptions of paper straws presents a significant obstacle for the company to improve the paper straw texture to meet consumers' needs. It is, therefore, essential to identify and understand the relevant parameters that contribute to the mouthfeel of paper straws and their relationship to the consumer experience. This understanding will enable the development team to precisely create paper straws that fulfill consumers' requirements.

1.2.4 Previous study at Tetra Pak

To better understand the qualitative and quantitative result behind this subjective perception and communicate it precisely, mouthfeel needs to be measured with a practical, objective, and consistent measurement approach. Moreover, to overcome the limitations of time-consuming and expensive sensory evaluations with consumers, instrumental measurements are likely to be adopted as an objective and efficient method to measure several mouthfeel parameters. These measurements are expected to provide a comprehensive understanding of the mouthfeel, which can be correlated with subjective consumer research and panel tests. Hence, it is important to ensure that the instruments can accurately predict the results of consumer responses.

Tetra Pak's development team has investigated the key parameters that may be correlated to mouthfeel perception on paper straws, and they are now finding the objective way to assess their mechanical and chemical properties. Some of the testing methods currently available in Tetra Pak are unsuitable for evaluating the objective properties of final straws or commercial straws as they are designed solely for flat samples or paper sheets. Consequently, alternative testing methods need to be developed specifically for the straws. The development team has discovered some objective tests (described in more detail in the following chapter) that can be used to measure the straw; however, some methods are still missing and need to be developed in the future.

1.3 Thesis Study Purpose and Research Questions

Changing from plastic to paper straws to comply with the legislation represents a big change that can be challenging for both companies and customers to adapt to. Not only difficulties in adapting the production process to make it efficient as plastic straws but this also impacts consumers' acceptability. However, despite the increasing attention towards paper straws, studies related to the quality, stability and mouthfeel perception of this alternative are still scarce. Additionally, identifying the promising attributes and properties that accurately describe mouthfeel is a complex task, yet it is crucial for further development of new paper straw materials which will be able to provide a satisfactory sensory perception for customers.

The objective of this master's thesis is to address the gap in the existing literature regarding the testing methods for assessing the mouthfeel of paper straws and to build upon the work that Tetra Pak has done. Specifically, the research aims to initiate the first trial of the mechanical and chemical tests using the testing methods that have already been discovered previously by the company and develop the new testing methods. Ultimately, the goal is to identify correlations between those objective measurements and subjective sensory evaluation respecting the mouthfeel perception of paper straws.

The strong correlation between objective and subjective measurements could mean that objective testing methods can be used as a quick and effective tool to measure relevant subjective mouthfeel perception of paper straws. Understanding this correlation could help in reducing the requirement for panel tests and aid the development team in quickly examining the mouth feeling of their developed paper straws, thereby aiding in predicting consumer acceptance.

Therefore, these research questions are defined as follows:

1. Are there any strong correlations between the objective instrumental measurement and subjective sensory analysis related to the mouthfeel on paper straws?
2. Which objective instrumental measurement can predict the subjective attributes of the mouthfeel on the paper straw?

1.4 Scope of the study & Delimitations

This research mainly focuses on developing the testing method and exploring the correlations between the instrumental measurements and subjective consumer perception of the mouthfeel on paper straws, using objective tools and sensory evaluation.

This master thesis still has several delimitations that need to be taken into consideration. Firstly, some experimental methods developed and utilized in this research, such as tactile friction, are novel techniques specifically designed to test paper straws. These methods involve numerous intricate steps that need to be carefully executed. It can take several months of experiment and evaluation to find a promising condition that can be used for future analysis. However, with the given limited timeframe (20 weeks), only preliminary testing methods and parameters will be determined, but it may not be feasible to thoroughly verify these new testing methods in this study.

Secondly, there are hygiene restrictions that limit the use of real consumers when performing sensory evaluation since the paper straw samples are in the development process with no safety standard, such as GMP regulations, approval yet. Although a sensory analysis using trained panelists is recommended for analyzing correlations, there is insufficient time to train participants to become suitable panelists for this method. Besides, it requires several materials for the training process, which could take several months to complete. This study, therefore, used untrained consumers instead to reduce the training time. As a result, there is a potential for variability in subjective evaluations of mouthfeel due to personal preferences in sensory perception. It is possible that different panelists may evaluate mouthfeel attributes from different perspectives, which could lead to inconsistent results and reduced reproducibility.

However, this limitation could be addressed by using a standardized evaluation questionnaire with clear instructions for panelists to follow step by step. Additionally, using substantial panelists to have sufficient replication of the tests will help minimize the impact of individual variability on the overall results. By doing this, the results could be able to offer some brief perspective regarding correlations between objective and subjective test methods, which can be used to screen promising objective tests for further study.

Finally, paper is a hygroscopic material, meaning that it is essential to control the surrounding environment as much as possible to ensure that all measurements, including sensory analysis, are consistently performed.

2 Theoretical Framework

In this chapter, the relevant studies including the background of drinking straw and theories behind this research are described.

2.1 Drinking Straws

2.1.1 History of drinking straws

Drinking straws have existed for thousands of years, with evidence of their use dating back to ancient times, which is made from natural materials such as plant stems. It facilitates an easy drinking solution for consumers, provides more hygiene while drinking beverages, as well as help the disabled to have safe liquid consumption (Nunez, 2020). The modern drinking straw was first invented and patented in the late 19th century by Marvin Stone. He created a cylinder tube by wrapping strips of paper around a pencil and gluing them together. His straws then began to be mass-produced two years after his invention (Gibbens, 2018).

Until the 1930s, plastic straws were introduced and became more popular due to their affordability and durability. They have been mass-produced since the 1960s and are still market leaders until today (Gibbens, 2018).

2.1.2 New alternatives

Despite several advantages of plastic straws, including their durability, water resistance and low cost, the world has become more aware of the environmental impact of plastic waste, i.e., microplastics from degraded plastic wastes, which affects the ecosystem and human health. Plastic straws are then banned from several countries. However, there are arguments said that these restrictions do not consider the needs of patients and disabled people. It is crucial, therefore, to find alternatives to SUP straws that can meet these requirements while minimizing environmental damage (Qiu et al., 2022; Wong, 2019). Fortunately, a range of eco-friendly and sustainable options are more available on the market nowadays, for instance, paper straws, bamboo straws, metal straws, silicone straws, glass straws, etc. (Gibbens, n.d.)

With the push for eco-friendly options, paper straws have gained immense popularity among consumers as disposable straws. Consumers consider that paper straws are better than plastic straws in terms of their impact on the environment (Takou et al., 2019). Besides, paper straws offer an array of benefits such as customization flexibility, longer shelf-life and more. However, the downside is that they can become soggy and easily collapse once wet, leading to potential customer dissatisfaction.

In response to the problem of material durability, people have started exploring more durable options like bamboo straws, metal straws, or glass straws. Bamboo straw apparently gives the most environmental sounds as bamboo grows rapidly, producing oxygen even before it is mature enough for production (Qiu et al., 2022). However, it can be hard to completely clean and may absorb flavors of the drinks. On the other hand, metal straws are made using stainless steel, aluminum, or titanium, making them durable and reusable. But the drawback is that they might leave a metallic taste and can transfer heat from hot beverages (Gibbens, n.d.).

Inevitably, the selection of straw material will depend on personal preferences and requirements. Despite the fact that there are various alternative options available on the market apart from paper straws and consumers will get used to these options in the upcoming years, they are not viable to use for replacing the plastic straws attached to the packages like paper straws did.

2.2 Paper Material and Some of its Properties

Paper is a thin sheet material primarily used for various purposes such as writing, printing, cleaning, or packaging. It is produced from cellulose pulp by processing cellulose fibers obtained from various sources such as wood, rags, grasses, cotton, rice, or wheat straw in water. Cellulose fibers will form a network during the paper manufacturing process (Montibon, 2010), creating a surface, as shown in Figure 1. Paper production typically consists of three main processes: pulping, forming and dewatering. The paper used to be produced manually as individual sheets until Louis Robert invented the Fourdrinier paper machine in 1799. This machine can shape cellulose pulps into continuous paper rolls, which will be used for subsequent production processes (Hiziroglu, n.d.).

In order to make paper, pulp as a raw material can be produced through two methods: chemical pulping (bleaching) or mechanical pulping. Mechanical pulping does not remove lignin from the fiber. Chemical pulping, in contrast, uses various chemicals to break down the lignin from cellulose fiber to make pulp, thereby affecting the properties of paper that are associated with mouthfeel perception (Hiziroglu, n.d.). The bleached paper will have a higher density, smoother surface and lower microbial load.

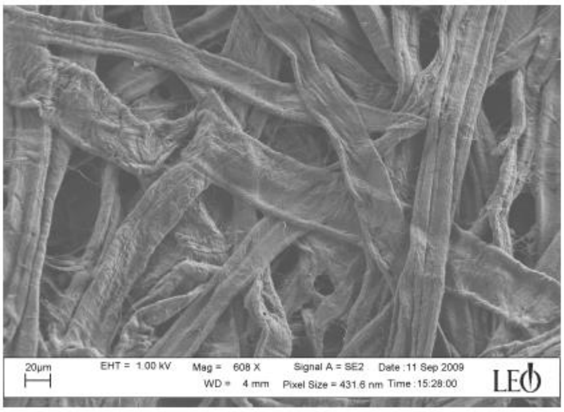

Figure 1 Paper surface on the scanning electron microscope (SEM) (Montibon, 2010)

A number of characteristics of paper used for evaluating its quality can be classified into different categories as follows (Akram et al., 2017):

Physical properties: basis weight or gram, bulk and density, thickness, friction, moisture content, roughness, formation, conditioning of paper etc.

Strength properties: bursting strength, compressibility, hardness, surface strength, tensile strength, wet strength, tear resistance etc.

Electric properties: conductance, dielectric constant, dielectric strength, pH, porosity, air resistance etc.

Optical properties: opacity, brightness, whiteness, color, gloss, finish etc.

Thermal properties: thermal conductivity, specific heat capacity, water absorption

Miscellaneous properties: ash content, dirt content, print quality, printability etc.

However, some paper properties used in this study are described as follows:

2.2.1 Physical properties

2.2.1.1 Friction

The frictional property of paper can be described using the coefficient of friction (μ or COF), which refers to the resistance between two surfaces sliding against each other (Akram et al., 2017). A lower coefficient of friction means that less force is required to slide the object across a surface. This can be calculated using the following equation, where μ is dimensionless as it is a ratio of forces.

$$\mu = \frac{Friction\ force, (F)}{Normal\ force, (N)}$$

Figure 2 depicts the free-body diagram of the force used in this equation. The size of frictional force between two surfaces is affected by both the materials and the nature of the surfaces in contact and the normal force's size. Furthermore, the direction of the frictional force always opposes the direction of the applied force based on Newton's third law of motion (Bird & Chivers, 1993).

Typically, frictional force can be divided into two categories:

(1) Static friction force: It is the resisting force that prevents the object from moving when applying force to it. This will make the object remains stationary.

(2) Dynamic or Kinetic friction force: It is the resisting force that occurs when the object is already in motion. It is generally lower than the static friction force (Bird & Chivers, 1993).

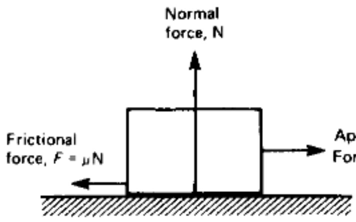

Figure 2 The free-body diagram of the force (Bird & Chivers, 1993)

2.2.1.2 Roughness

Roughness property in paper or paperboard refers to the uneven surface that is created when cellulose fibers form a network during paper manufacturing (Montibon, 2010), as seen in Figure 1. It turns up as one of the most important properties in paper manufacturing as it can affect printability, the amount of necessary coating and ink absorbability. In addition, it is also linked to the glossiness and frictional feature of the surface, which impacts the appearance and tactile quality. The coating is commonly applied to printing paper in order to improve the smoothness of the surface; however, the amount of coating material is determined by the surface quality of base paper or paperboard (Alam et al., 2012).

According to the study of Kajanto et al. (1998), roughness can be classified into three components. These components are (1) optical roughness, which is less than 1 μm (2) micro-roughness, which ranges from 1 to 100 μm; and (3) macro-roughness, which ranges from 0.1 to 1 mm. However, surface roughness can be measured in several ways, including contact or non-contact methods.

The mechanical stylus is one of the examples of contact method. To measure surface roughness, a probe equipped with a diamond-tipped stylus is used to scan across the irregular surface. The results are then displayed in µm, including arithmetical roughness average (R_a), root mean square roughness (R_q), and average maximum height of surface profile (R_z) (Alam et al., 2012). The schematic of R_a is shown in Figure 3. However, the drawback of this method is that the sample will be damaged during the measurement.

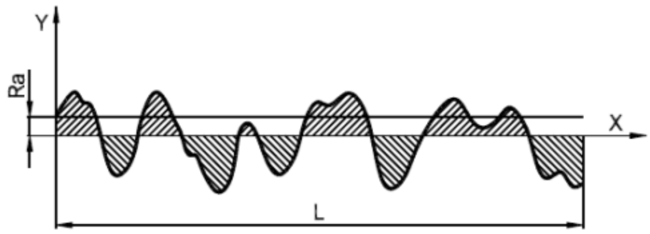

Figure 3 Schematic of roughness average (Ra) (Pino et al., 2010)

In contrast, optical methods can be used to measure roughness without contacting the surface. These methods have become more popular due to concerns about sample damage (Keyence, n.d.). Moreover, it can be used to measure in-line without disturbing the process. The assessment of roughness relies on the interaction between light and the surface of the paper, with the light scattering approach is one of the optical methods. When a surface is rougher, it scatters more light compared to a smoother surface (Pino et al., 2010).

2.2.2 Thermal properties

2.2.2.1 Water absorption and wetting property

Water absorption is one of the thermal properties of paper besides thermal conductivity and specific heat capacity (Akram et al., 2017). It is closely related to the wetting behavior of the paper. Since the cellulose fibers that make up paper are hydrophilic, the paper network also tends to be hydrophilic. This allows the paper to absorb water or moisture from the humid environment, causing the paper to swell and consequently leading to a decrease in mechanical strength. The ability of paper to resist water penetration can be affected by the chemical composition of the surface as well as its topography. To improve its hydrophobicity, coating materials – either natural or chemical – can be applied to the paper surface. This treatment enhances the paper's water resistance and ability to withstand water exposure (Montibon, 2010; Zawawi et al., 2013).

The wetting property of paper can be evaluated by determining the contact angle between a liquid and the paper surface, both static contact angle (immediately after liquid droplets touch the surface) and dynamic contact angle (when droplets absorb over a period of time). The static contact angle uses for assessing the paper's ability to repel liquids, while the dynamic contact angle uses for assessing the spreadability and absorbability of liquid on the paper’s surface (Gómez et al., 2014). A water contact angle measurement below 90° indicates a surface that is hydrophilic, while a high-water contact angle, usually above 90°, indicates a more hydrophobic surface. However, if the water contact angle exceeds 150°, the surface is considered as superhydrophobic or ultra-hydrophobic. The degree of water contact angle is shown as theta (θ). The lower the theta, the more spreadability of the water droplet across a surface (less hydrophobic), as seen in Figure 4 (Mattone et al., 2017; Zawawi et al., 2013).

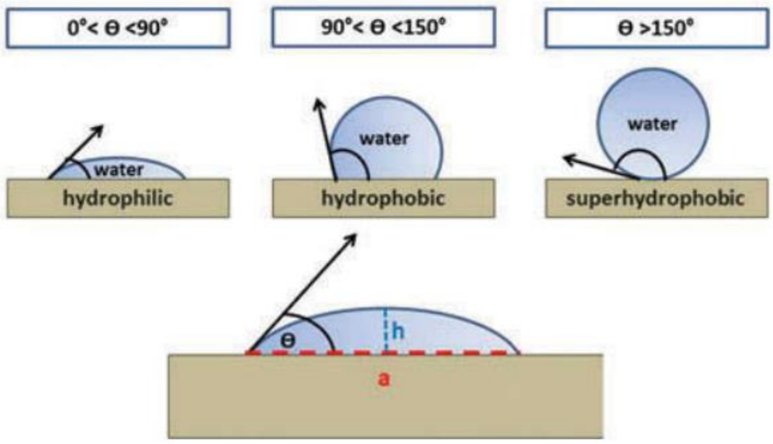

Figure 4 The degree of water contact angle of a liquid droplet to define the surface properties (Mattone et al., 2017)

Water absorption can be measured on the paper sheets by using Cobb Test. It is one of the testing methods used to test the capacity of paper to withstand water penetration by quantifying the amount of water absorbed by paper or paperboard. The higher water absorption results in the lower performance of the paper as it cannot maintain its strength and integrity (Zendano, 2021). Figure 5 depicts the paper sample set in the machine, where water is poured inside the ring with a set-up period of 60 or 180 seconds (Cobb 60 or Cobb 180). The result of water absorption is then determined by the area of the sample material (Smithers, n.d.).

Figure 5 The setting of the Cobb Test (Smithers, n.d.)

2.2.3 Strength properties

2.2.3.1 Compressive strength

The fundamental testing method used to evaluate this mechanical property is the compression test. It is used to determine the behavior of testing material while it is compressed under the applied crushing load. The compression test is commonly performed by applying compressive pressure to the cuboid or cylindrical sample using the universal testing machine (Figure 6) equipped with a specific fixture. The results are then plotted as a stress-strain curve (Figure 7) that helps to identify a number of properties, including the elastic and compressive fracture properties as well as modulus of elasticity, proportional limit, compressive yield point, compressive yield strength, and compressive strength (Chua et al., 2017; Instron, n.d.). Compression strength is defined as the ability to resist the loads before failure (Jaya, 2020). It tends to vary inversely with tensile strength. However, it is important to determine these properties of a material in order to assess its suitability for specific applications and to predict the strength and integrity of product during the production or development (Chua et al., 2017).

The compression test is usually used to measure the ability to withstand compressive forces of brittle material, including metals, plastics such as plastic pipes and water bottles, ceramics, composites, and corrugated materials such as cardboard (Instron, n.d.). Therefore, it could be able to measure the compressive strength of paper straws as well.

Figure 6 The Universal Testing Machine (Instron, n.d.)

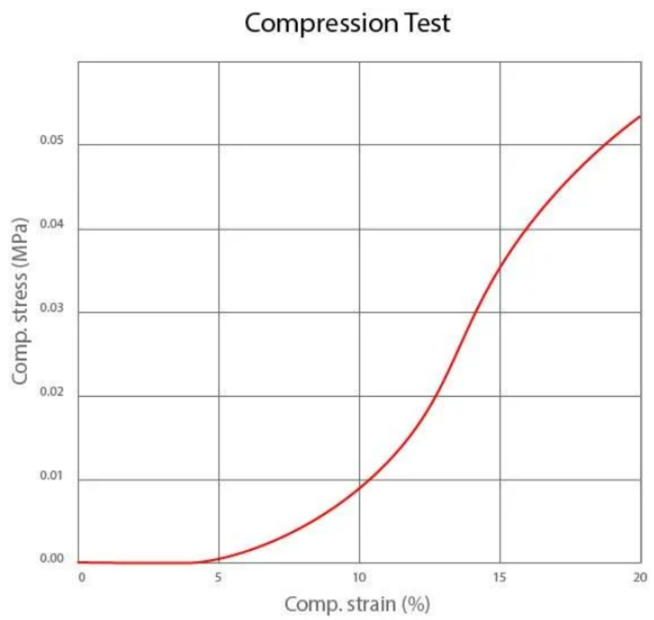

Figure 7 A stress-strain curve (Instron, n.d.)

2.3 Tetra Pak Paper Straws

Currently, Tetra Pak has several types of straw used with its portion-sized packages, such as sensory straw, straight straw, telescopic straw, U-straw, and Z-straw for its customers to choose depending on the viscosity of the product, size and shape of the package. Paper straw, as a focus of this study, is one of the sustainable development programs of the company to address the problem of plastic straw and littering. A straight, U-shaped and telescopic paper straw are the three variants that can be used with its portion-sized packages, which U-shaped paper straw is the variant that is the most common (Tetra Pak, n.d.-a).

Tetra Pak's paper U-straw is a tube-formed straw made from double layers of paper, sticking together with water-based glue (Figure 8). This results in a different seaming pattern when compared to several straws on the market since it has only one straight line of the outer seam. Other straw producers commonly use winding technology. U-straws are corrugated and bent at a certain height in the machine to form a U-shape. The end of the straw was then cut as a sharp tip used for piercing the pre-punched hole of the carton package.

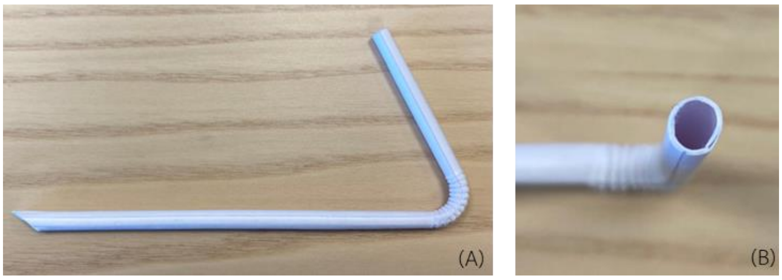

Figure 8 Tetra Pak's U-shape paper straw (A) and double layers of paper straw (B)

2.3.1 Consumer research

Consumer research is defined as *"the study of people's opinions about products or services, and about what products or services they want or will buy"* (Cambridge Dictionary, n.d.). It helps firms to understand customers' psychology, needs, and purchasing behavior during the development of the new product (Bhat, n.d.). Proper consumer research enables the company to define the brand position from the consumer's perspective (Robinson & Chiang, 2002).

Like many other companies, Tetra Pak recognizes the importance of understanding consumer preferences and their behaviors. Thus, consumer research has been conducted with most of Tetra Pak's products, of which paper straw is one of the examples. Through this consumer research, the company gain insights into both sustainability aspects and the satisfaction of its customers when using paper straws.

With that, it can guide product development people to develop products that meet consumer needs and expectations.

2.4 Mouthfeel & Sensory Evaluation

2.4.1 Oral sensation

The mouth is considered as one of the most sensitive organs in the human body due to its substantial nerves and receptors. It is made up of various types of tissues, such as skin, muscle, and teeth, which are responsible for controlling essential functions such as eating, drinking, speaking and oral perception. The somatic sensations that occur inside the mouth are referred to as oral somatosensory awareness. These sensations are enacted through a combination of stimulations, including touches, pains, and thermal changes such as warmth or coldness, perceived from the objects in the mouth like food, beverage, or oral device. These signals are then sent to the receptors and subsequently transmitted to the brain, where they are presented as the mouthfeel. However, the concept of mouthfeel is complex as it involves not only physical sensation but also emotional and hedonic evaluations of sensory experience. As a result, it has been challenging to study mouthfeel quantitatively (Haggard & de Boer, 2014).

2.4.2 Sensory evaluation and relevant sensory techniques

Sensory evaluation is a scientific approach that employs humans as measuring tools to assess product or food characteristics, such as texture, flavor, taste, odor, appearance, etc., through their five senses, including sight, smell, taste, touch, and hearing. Sensory evaluation has been used to prove the acceptability of food quality by integrating it with technological and microbiological safety. However, it has also emerged as a powerful tool for ensuring consumer acceptance of new products in recent years (Ruiz-Capillas & Herrero, 2021). In this study, sensory evaluation will be used to evaluate the mouthfeel of paper straws.

Sensory evaluation can quantitatively and qualitatively explain the feeling of products in multiple ways using different sensory techniques, which can be divided into three groups as follows:

(1) Discrimination Analysis is used to find the differences between products. Examples of the tests are the triangle test, duo-trio test, and pair comparison test.

(2) Descriptive Analysis is used to differentiate the product in specific sensory attributes. Example of the tests includes Quantitative Descriptive Analysis or QDA.

(3) Affective Analysis is used to quantify consumer preferences or level of liking or disliking towards products. It is also known as acceptance tests, preference tests or hedonic tests (Lawless & Heymann, 2010)

Given that the objective of the study is to gain a better understanding of mouthfeel perception, the descriptive analysis technique is believed to be more relevant in this context. Therefore, this technique will be adapted to use in this study.

Descriptive analysis serves as a critical tool in sensory evaluation, providing both qualitative and quantitative descriptions of a product's sensory attributes. In this approach, a unique evaluation questionnaire is developed for each product to assess the differences in specific sensory dimensions among product samples. This questionnaire usually consists of a list of sensory attributes and their intensity scale, where participants will indicate the strength of their attitudes or opinions using defined verbal labels that are given at the end point of the scale (Scherpenzeel, 2022). Generally, participants will go through the training sessions to ensure calibration and mutual understanding of the product and sensory attributes before conducting the analysis. In many cases, a sample size of approximately 8-12 participants is considered sufficient (Lawless & Heymann, 2010; Svensson, 2012).

The effectiveness of descriptive analysis has been demonstrated across various applications, including quality control, formulation optimization and product development. The information obtained through this technique often aligns with consumer preferences. Moreover, it facilitates the analysis of the correlation between sensory and instrumental measurements, allowing for a more comprehensive understanding of a product's sensory characteristics. It is worth noting, however, that descriptive analysis can be time-consuming and costly. Thus, it is typically employed for important matters rather than daily evaluations (Gomide et al., 2021; Svensson, 2012).

2.5 Pearson's Correlation

Pearson's correlation is a statistical method used to qualify the strength of a linear relationship between two continuous variables (Statistics Solutions, n.d.). It was first introduced by Karl Pearson in 1896 and has become one of the most widely used statistical measures in research such as social and behavioral sciences, theory testing, instrument validation, reliability estimation and other multiple disciplines (Salkind, 2010).

Pearson's correlation coefficient (r) aims to draw the most suitable straight line that best describes the whole data of two variables and illustrates the deviation distance between the actual data and the line of best fit, known as the degree of correlation. The r value can vary from −1 to +1, with a value of 0 meaning that there is no relationship between the two variables. The direction of the relationship is marked by the sign of r value, either plus (+) or minus (-). Figure 9 shows the direction of the correlation value (r). A value higher than 0 shows a positive correlation, meaning that while one variable increases, another variable also tends to increase. A value lower than 0 shows a negative correlation, meaning that while one variable increases, another variable tends to reverse or decrease (Laerd statistics, n.d.).

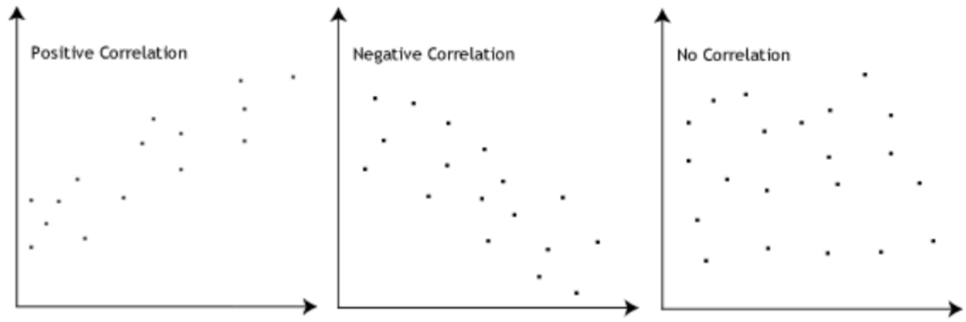

Figure 9 The direction of Pearson's Correlation (Laerd statistics, n.d.)

However, the strength of the relationship or degree of correlation can be indicated by comparing the value to 1 or -1, depending on the direction of the correlation, whether it is a positive or negative correlation, respectively. The closer the coefficient value to 1 or -1, the stronger the correlation. This can also be seen by examining the variation of data points to the line of best fit using the graph. Examples of different relationships and their r value are shown in Figure 10. It can be clearly seen that if the data points have small variations around the line, the r value will be closer to 1 or -1. In contrast, the r value will be closer to 0 if the data points have big variations away from the line (Laerd statistics, n.d.; Statistics Solutions, n.d.).

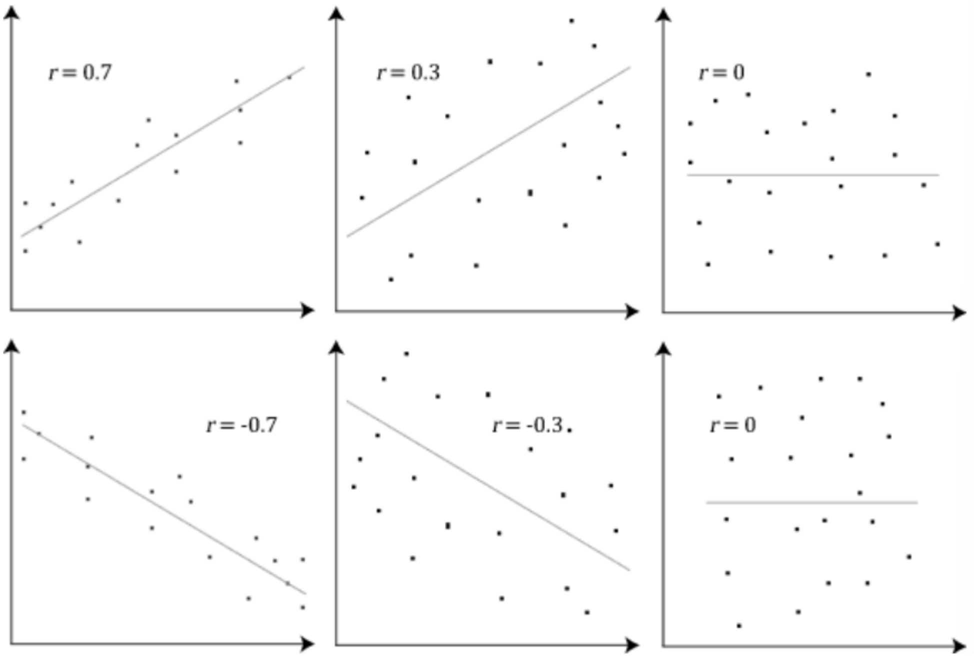

Figure 10 Different relationships and their correlation coefficients (Laerd statistics, n.d.)

The degree of correlation can be separated into three levels: high, moderate, and low. The high degree has a value ranging from ± 0.5 to ± 1, meaning that it has a strong correlation. Moderate degree has a value ranging from ± 0.3 to ± 0.49, meaning that it has a medium correlation. The last, low degree, has a value below ± 0.29, meaning that it has a poor correlation (Statistics Solutions, n.d.).

One of the key advantages of Pearson's correlation is its simplicity and ease of interpretation. The two variables can be measured in completely different units and scales, but the scales should be either interval or ratio scales. Moreover, it does not matter whether those variables are dependent or independent variables. They can be plotted either on the x-axis or y-axis, in which the r value will be the same.

Misinterpretation of data arising from the use of Pearson's correlation, regarding its accuracy in non-linear relationships, can be one of the limitations as it typically uses to reflect the strength of a linear relationship. The reflection of the true relationship between variables may be altered due to this issue. It is better to check the type of relationship between two variables by plotting a graph, for example, a scatter plot, before using Pearson’s correlation. Other statistical approaches, Spearman's rank correlation and Kendall's tau correlation, for example, have been therefore suggested as alternatives to cover this limitation. They are preferred options for better describing non-linear relationships (Cohen, 2008; Laerd statistics, n.d.).

3 Materials and Methodology

This chapter describes the materials, equipment, and testing methods used in the experiment.

3.1 Straw Specimens

The study evaluated the mouthfeel perception of six different variants of paper straws (Figure 11) using both objective (instrumental) and subjective measurements. Five specimens were provided by Tetra Pak, while the remaining one was commercial straw (CM) which can be found in the existing market. Table 1 depicts the name of the variants of paper straw involved in this study, including their application of the coating, seaming orientation and outer diameter (mm).

All Tetra Pak paper straws are made from the same paper substrate, with differences perceived in seaming orientation and the coating material. They were all coated solely on the outside of the straw. Clear differences between Tetra Pak straw and commercial straw are the structural design of the straw and the type of coating material. However, both paper type and material used for coating paper straws cannot be disclosed in this study. Tetra Pak straw is a tube-formed straw, having only one outer seam, whilst the commercial one is a winded straw, having several outer seams along the straw, as shown in Figure 11. The differences in the seaming orientation of Tetra Pak paper straw are shown in Figure 12.

Figure 11 also illustrates that the corrugated part of each straw is not identical. This study, however, used Tetra Pak specimens that was not yet corrugated for instrumental measurement. Additionally, the corrugated part of commercial straws was also cut before conducting the experiment since the corrugated part is more vulnerable and could potentially affect the results. All straws were kept in the controlled environment room (23 ± 2 °C, 50 ± 5% RH) at least 24 h prior to the measurements.

Table 1 List of the variants of paper straws used for instrumental and subjective measurements

Name	***Coating***	***Seaming orientation***	***Outer Diameter (mm)***
R	Without coating	Inner - outer seams form 180° angles	4.5
CC	With coating	Inner - outer seams form 30° angles	4.5
SC	With coating	Inner - outer seams form 30° angles	4.5
W9C	With coating	Inner - outer seams form 180° angles	4.5
W12C	With coating	Inner - outer seams form 180° angles	4.5
CM	With coating	Winded straw	4.6

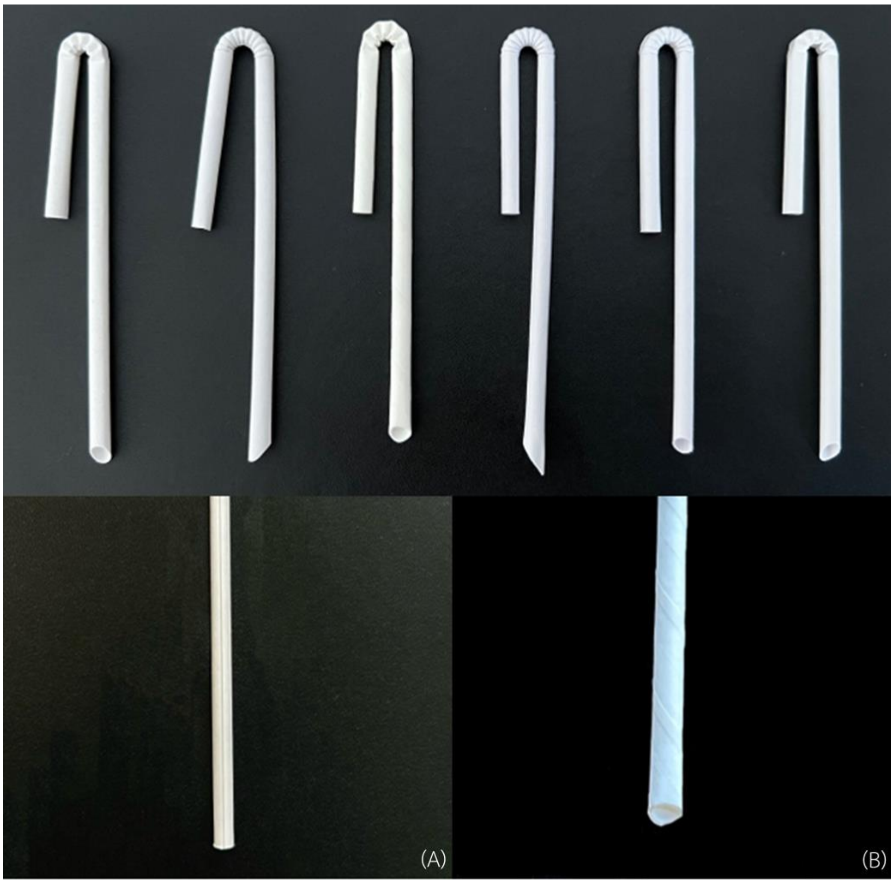

Figure 11 Six different variants of paper straws used in the study. (Up) From left to right: R, CC, SC, W9C, W12C, CM. (Down) Tetra Pak's tube-formed straw (A) and Commercial winded straw (B)

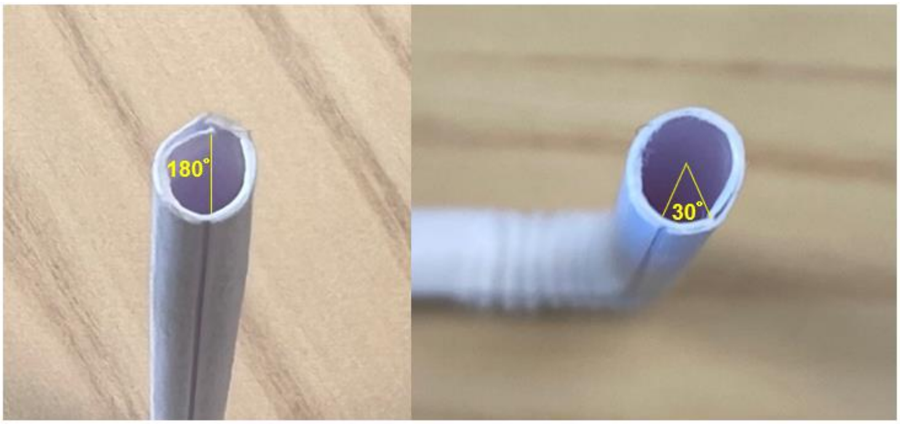

Figure 12 The differences in seaming orientation of Tetra Pak paper straws

3.2 Instrumental Measurements

To objectively evaluate the mechanical and chemical properties of paper straws, the study utilized instrumental measurements. The mouth feeling could be determined by measuring several parameters or properties of paper straws from different testing methods. From internal scouting and screening previously by the team, several parameters/properties of paper straw are believed to be correlated with the subjective methods.

This study selected five properties/parameters related to the mouthfeel of paper straws from the previous internal study. The testing methods that are hypothesized to be correlated to the mouthfeel perceptions are listed in Table 2. Cobb test, surface roughness test, dry compression test, and wet compression test have the testing methods that were already discovered by Tetra Pak. This means that those experiments will be performed in compliance with the company’s pre-defined testing methods.

However, the friction property of paper straws did not have a standardized testing method available in the company since it was a new area of investigation. As such, a preliminary testing method and testing parameters will be defined in this research in order to be able to replicate the test in further study with the same or other samples. Promising resulting data from the selected testing method and parameters will be used to find correlations with other properties/parameters of the paper straws.

Table 2 Parameters/properties of paper straws and their testing method

Parameter/ properties	***Testing method***
Water Absorption	Cobb Test
Surface Roughness	Surface Roughness Test (Surftest SJ-210)
Friction	Tactile Friction Test (ForceBoard^{TM})
Dry Compressive strength	Dry Compression Test
Wet Compressive strength	Wet Compression Test

3.2.1 Water absorption

Cobb Test was performed, with some modification in the method, to measure water absorption of the finished straws. The dry straw sample was weighted (noted as 'before weight') using the scale (Mettler Toledo AE 200, United states). Attach one end of the straw to the silicone hose and immerse the straw sample into the water at the specified height for a specified time, as seen in Figure 13. Ensure that another end of the straw and silicone hose is above water level and not letting water enter the tube. Then, remove the straw from the water after soaking, detach the silicone hose and wipe off excess water on the paper straw with tissue paper. Finally, weigh the soaked straw sample (noted as 'after weight'). Before and after weights were used to calculate the amount of water per area of straw (g/m^2) using the following equation.

$$Amount\ of\ water\ per\ area\ \left(g/_{m^2}\right) = \frac{(After\ weight - Before\ weight)}{\pi r^2 h}$$

Eighteen different samples of each type of straw were tested in the controlled environment at standard conditions of 23 ± 2 °C, 50 ± 5% RH. Results from the sample with water leaking inside the tube need to be excluded, as the measurement will be invalid.

Figure 13 Cobb Test

3.2.2 Surface roughness

Surface roughness was measured using a stylus profilometer, Surftest SJ-210 (Mitutoyo, Japan). The stylus tip was moving parallel to the longitudinal direction of the paper straw at a specified speed. The test was performed in three locations around the straw's circumference on each 6 samples, given 18 measurements in total for each type of straw. To set up the equipment, the straw sample was mounted on the table using the straw's wrap and sticky tape to hold the sample to prevent the movement of the straw during measurement (Figure 14). The R_a, R_q, and R_z values were calculated to measure the arithmetical roughness average, root mean square roughness, and average maximum height of surface profile, respectively. R_a will be used to compare with the subjective result in the following step. All measurements were tested in the controlled environment at standard conditions of 23 ± 2 °C, 50 ± 5% RH.

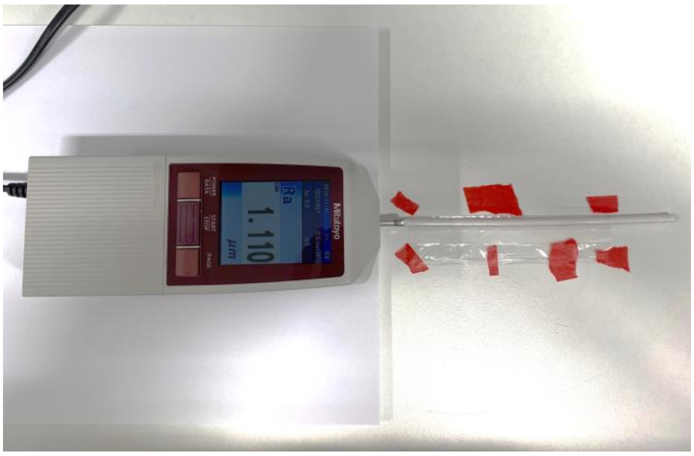

Figure 14 Surface Roughness Test

3.2.3 Dry and wet compression test

3.2.3.1 Preparation of samples

Paper straw samples need to be stored in the controlled climate room at 23 ± 2 °C, 50 ± 5% RH for 24 h before performing a dry compression test to ensure that the moisture content of the paper straw sample reaches the intended equilibrium condition. For the wet compression test, straw samples were presoaked for a specified time in the water at room temperature (23 °C) prior to the test. Remove the samples from the water after soaking, and then gently shake the straws to remove excess water. Store the samples in the non-absorbing container and cover them with the lid while awaiting testing. All straws should be tested within 30 min after removing them from the water.

3.2.3.2 Execution of the test

Compressive strength was measured using a universal tensile/compression tester (Zwick Roell Z005, Germany) equipped with the test probe and flat bottom plate particularly set up for measuring paper straws (Figure 15). Paper straw samples were measured in 2 testing conditions, dry and wet, in a controlled testing climate at 23 ± 2 °C, 50 ± 5% RH. The sample size was set to 15 straws per sample per testing condition.

The paper straw sample was placed straightly on the bottom plate, aligned to the center of the test probe. Because tube-formed straws from Tetra Pak have a visible outer seam, measurements were conducted with the outer seam oriented perpendicular to the probe. However, as the commercial straws were made as winded straw, no seam positioning criteria is needed. After placing the straw sample on the plate, the compressive test was then initiated in the universal test equipment. The $Force_{50\%\ actual}$ as a function of displacement was recorded using TestXpert Software ($Force_{50\%\ actual}$ is the force needed to compress the straw to half of its outer diameter, beyond preload).

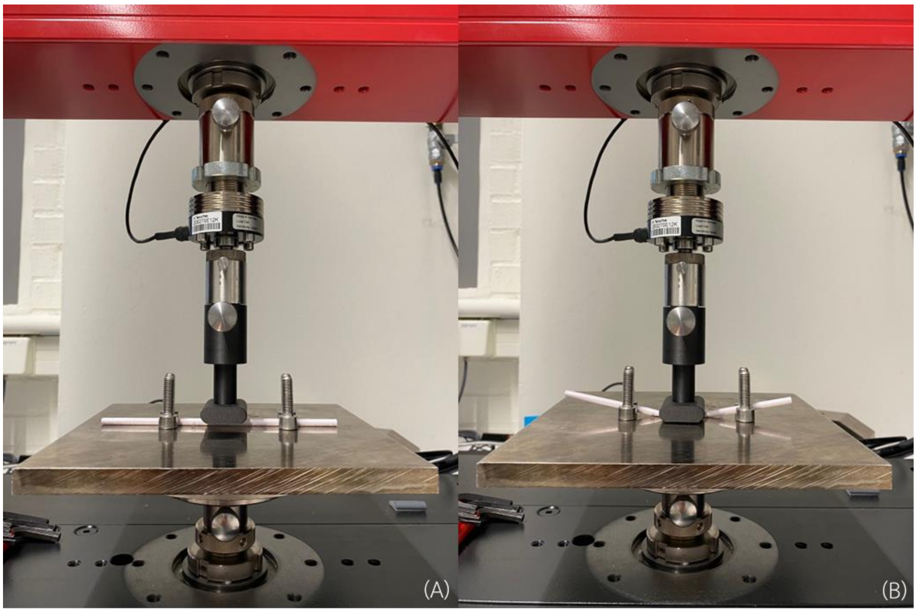

Figure 15 Compression Test, before compressing (A) and while compressing (B)

3.2.4 Tactile friction

3.2.4.1 Identifying the standard testing method and parameters

Since measuring tactile friction on drinking straws is a relatively new area of study, there is currently no standard method for measuring friction, specifically on paper straws available in the company. Therefore, this study will perform preliminary tests in order to develop the testing method and determine appropriate testing parameters that will yield accurate and useful results. In addition, the goal is to establish an approach that is as straightforward and as user-friendly as possible for operators when performing the tests.

ForceBoard™ (Industrial Dynamics AB, Sweden), a universal friction and force tester equipped with one horizontal and one tangential load cell, was used to measure the tactile friction of the paper straw. When the mechanical load cell is applied, it is converted to voltage signals that are proportional to the applied load. DAQFactory Software will then record friction force (the force that occurs when stroking the finger over the sample) as horizontal force and normal force (in this case is the force that is applied by finger so called 'applied load') as vertical force at a frequency of sampling rate of 40 Hz. The weight of the straw samples did not impact the applied load as paper straws have very lightweight; however, both forces were tare to be zero in the machine before starting the measurement. The results recorded in this software are shown in Figure 16.

The tactile friction measurements were examined by a single female operator (26-year-old) using a technique adapted from the literature study (Arvidsson et al., 2017; Harris et al., 2021; Skedung et al., 2020). Straw samples were firmly attached to the ForceBoard™ plate using sticky tape, as shown in Figure 17. The operator used her dominant index finger stroking regularly, with a finger incline at a specified angle, forward and backwards at specified reciprocating cycles over the sample. Multiple test parameters, for example speed and applied load, were used in preliminary test to select which parameter is the most suitable for straw. Table 3 shows the testing parameters that were used in this experiment. An applied load was maintained to the best ability of the operator.

Table 3 Testing parameters of preliminary tactile friction test

Experiment	*Speed (mm/s)*	*Applied load (N)*
Experiment 1	40	1
Experiment 2	40	2
Experiment 3	60	1
Experiment 4	60	2

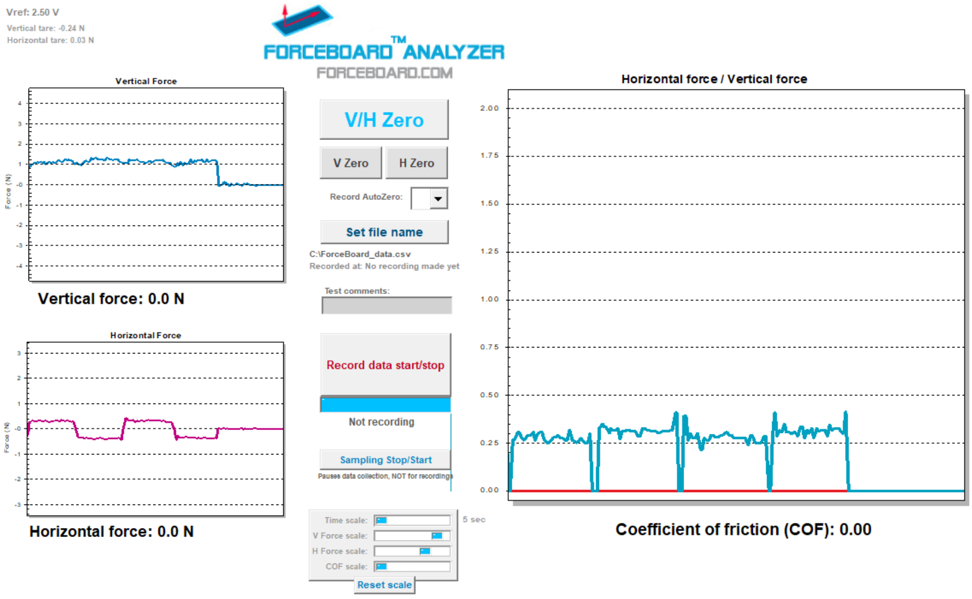

Figure 16 The result recorded from DAQ Factory Software. (Top Left) Vertical force shows the applied load. (Down Left) Horizontal force shows friction force when stroking the finger forward (negative) and backward (positive) direction. (Right) The result of coefficient of friction (COF).

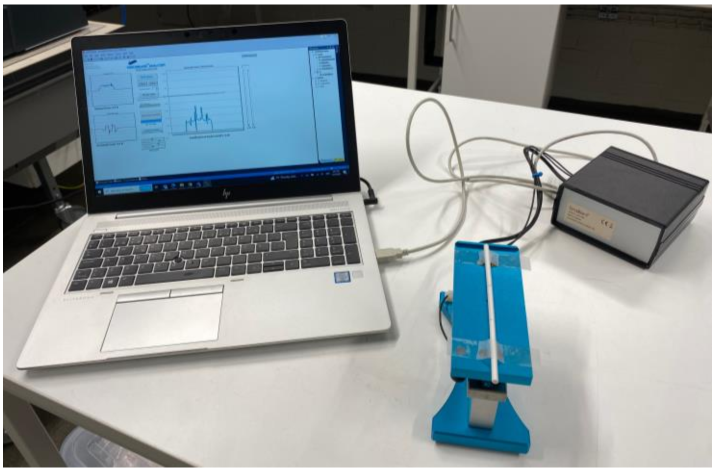

Figure 17 Tactile Friction Test using ForceBoard™

Eighteen measurements were conducted for each type of straw sample, using a new straw sample in every three measurements. The coefficient of friction (COF) was calculated as a ratio of friction force to the applied load in each data point. All calculated COF will be presented as absolute values, even though the friction force in the forward stroke direction (moving away from the operator) is recorded as negative. The output data were then used to calculate the average dynamic COF of each measurement using custom code in EXCEL. Two ways of calculating average dynamic COF were employed to observe which calculation gives the best result. The way of calculations includes (1) using all data that was not given COF value as zero (COF all data) and (2) using the data in the middle 80% of each stroke, with the exclusion of data associated with changing direction (COF 80% data). The changes in the sliding direction of the finger (turning point) in each stroke are defined by the data between the 0 N lateral load.

3.2.4.2 Selection of the testing parameter

During the preliminary tests, it was found that maintaining a constant speed of 60 mm/s for every stroking cycle when sliding a finger on the straw was challenging for operators due to the small diameter of the tube-shaped straw sample. Consequently, the experiment with the speed of 60 mm/s is excluded and was only performed at the speed of 40 mm/s. The calculated average COF results that will be used to identify the correlation were selected based on the consistency of the applied load and the quality of the results, as well as the operator's comfort level during the measurement as it involves human in the operation.

3.3 Subjective Measurements

Sensory evaluation is a subjective way to identify key parameters and comprehend the subjective perception of mouthfeel on paper straws. In this study, the process of sensory evaluation comprises two steps: firstly, setting up the questionnaire and secondly, conducting the final sensory analysis.

3.3.1 Setup the questionnaire

Defining the mouthfeel perception of paper straws is a new area of research. Moreover, formulating a questionnaire using in the sensory test is a delicate thing that needs to be precise with the instructions and descriptions of the mouthfeel parameters to direct the participants in the same direction and not confuse them. Thus, it required several preliminary sensory tests. These tests aimed to refine the questionnaire and identify key attributes that would be used in the final sensory analysis to get the best insights from the user, get the results that are best coherent with physical results and make the test session runs smoothly.

In this study, two preliminary sensory tests were conducted with a small group of colleagues at Tetra Pak (approximately 6 to 7 people) to observe their behavior and collect feedback on the questionnaire, which describes in Table 4. The same variants of straw samples as in the final test were used during these sessions. Changes were made to the testing process in each sensory session, and key parameters were selected along with a clearer given definition of the attributes to ensure a better understanding when performing the final test and to obtain a more accurate result. This is the iterative process meaning that the questionnaire will be reformulated over and over again until obtaining a unanimous questionnaire that can be used in the final sensory evaluation. The key attributes describing the mouthfeel and their definitions used in the final questionnaire are listed in Table 5, and the final questionnaire is shown in Appendix A.

Table 4 Comments and observed actions obtained from two sessions of preliminary sensory test

Sensory test	***Comments and Observed Actions***
First sensory test	Too many questions
	It is easier to do the test if providing reference straw to compare
	Testing time is too long
	Selecting the attributes that is only related to mouthfeel
Second sensory test	Panelists evaluated attributes in the different ways
	Panelists confused about the definition of given mouthfeel attributes

Table 5 Definitions of mouthfeel attributes used in the final version of the questionnaire

Mouthfeel Attribute	***Definition***
Roughness	The extent of irregularities surface of the paper straw that makes you irritate when rubbed between your lips
Dryness	The feeling that your lips are dry when using paper straw as it absorbs water from your lips
Stickiness	The feeling that paper straw sticks to your lips or has jerking motion when sliding it between your lips
Sturdiness	The quality of being physically strong or well-made and not easily damaged when compress with lips
Sogginess	The feeling of unpleasantly wet after it absorbs water for some period of time which makes paper straw soft and lost its shape easily when compress

3.3.2 Sensory analysis

A total of 50 untrained Tetra Pak employees, mixed in age and gender, participated in the test with no repetitions. Six variants of paper straw were evaluated for their subjective mouthfeel attributes, including roughness, stickiness, dryness, sturdiness, sogginess, and overall liking, using a final version of the questionnaire with developed definitions from the previous section. Panelists were instructed to rate the intensity of each attribute and overall liking on the 11-point intensity scale (0-10). To simplify the evaluation, a straw variant (W9C) was used as a reference to compare with other samples, having an intensity score of 5 in every attribute. Reference straw was coded as 'ref' and served as the first in order. Other straw samples labeled with the three digits number code were respectively presented in the randomized order for each panelist, following the Latin Square Design. Tissue paper was provided to each panelist to wipe their mouth before testing in case some of them used lipstick or lip balm before participating in the test. The evaluation took place in a quiet meeting room with a calm environment. All attributes were evaluated in a dry condition, except for sogginess, which was evaluated by using the straw sample to drink water during the test to evaluate the straw in a wet condition. The details of the serving format can be found in Figure 18.

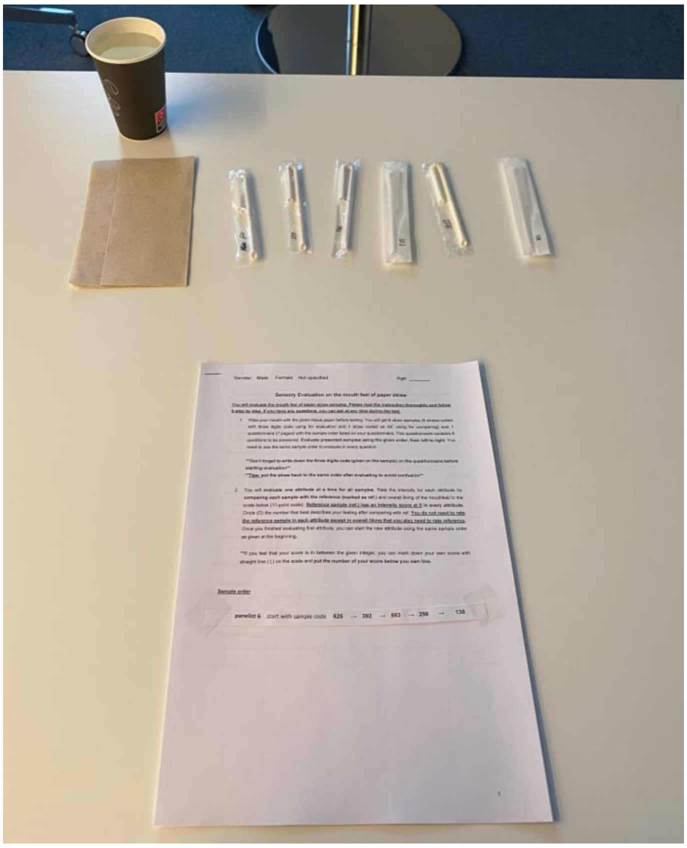

Figure 18 Samples that were served to each panelist during the sensory test

3.4 Data Analysis

The results of the instrumental and sensory measurements of the mouthfeel on paper straw were analyzed using the MINITAB Statistical Software. To determine the significant differences between the means of each measurement in each sample, One-Way Analysis of variance (ANOVA) and Tukey's HSD Pairwise Comparison were conducted at a significance level of 0.05. The raw data obtained from sensory analysis was normalized to eliminate the effect from the operators before analyzing with ANOVA, Tukey's HSD Pairwise Comparison, and identifying the correlations.

Pearson's correlation approach was used to model the relationships between sensory - sensory comparison, sensory - instrumental comparison, and instrument - instrument comparison at a 0.05 and 0.1 significance level. Pearson's correlation coefficient (r) was calculated between normalized raw data of each attribute from sensory analysis for sensory - sensory comparison. On the other hand, Pearson's correlation coefficient (r) was calculated between the mean values of the five instrumental tests and six sensory attributes for sensory - instrumental comparison and between the six mean values of the five instrumental tests for instrument - instrument comparison. The 11-point intensity scale used in the sensory analysis was approximated as an interval scale, which is a prerequisite for these analysis methods.

4 Results and Discussions

This section illustrates the results and discussions of the collected data from the experiments, including the mechanical and chemical properties of paper straws, sensory evaluation, and the relationship between these measurements.

4.1 Mechanical and Chemical Analysis

4.1.1 Water absorption

Water absorption property was measured on the six variants of paper straw applied with the different coating materials. The results of the amount of water per area presented in Table 6 show that the water absorption capacity of paper straw significantly varied depending on the type of coating material applied. Figure 19 clearly shows the trend of water absorption results for each sample in descending order. The ability of paper straws to resist water penetration is a crucial factor in determining the perceived mouthfeel during consumption. As the paper straw comes in contact with the lips, it can absorb water and affect the overall mouthfeel. Additionally, the paper straw can absorb moisture from the beverage, which can cause the straw to become soggy and lose its integrity, resulting in a negative mouthfeel perception.

Table 6 Water absorption for six variants of paper straws

Sample	*Amount of water/area (g/m^2)*
R	23.175 ± 1.696^a
CC	22.582 ± 0.858^a
SC	20.558 ± 0.625^b
W9C	9.644 ± 0.693^c
CM	7.390 ± 2.740^d
W12C	2.742 ± 0.186^e

Note: The results presented in the number of Means ± SD *(n=18). Means that do not share a letter are significantly different at 95% confidence (p-value < 0.05).*

The results suggest that coating the paper straw can effectively reduce its water absorption, as the highest water absorption was observed in the uncoated sample (R), accounting for 23.175 g/m^2. In contrast, the lowest water absorption was observed in W12C, the newest version of Tetra Pak's coated paper straw, at 2.742 g/m^2. It also has a higher ability to resist water penetration than the commercial straw, which displays a water absorption rate of 7.390 g/m^2.

Furthermore, the results show that the choice of coating material also influences the water absorption rate, where coating materials with a high hydrophobicity tend to be more effective in reducing water absorption. It can be assumed that the W12C sample, for instance, was coated with a highly hydrophobic material, which explains its lower water absorption capacity compared to other samples.

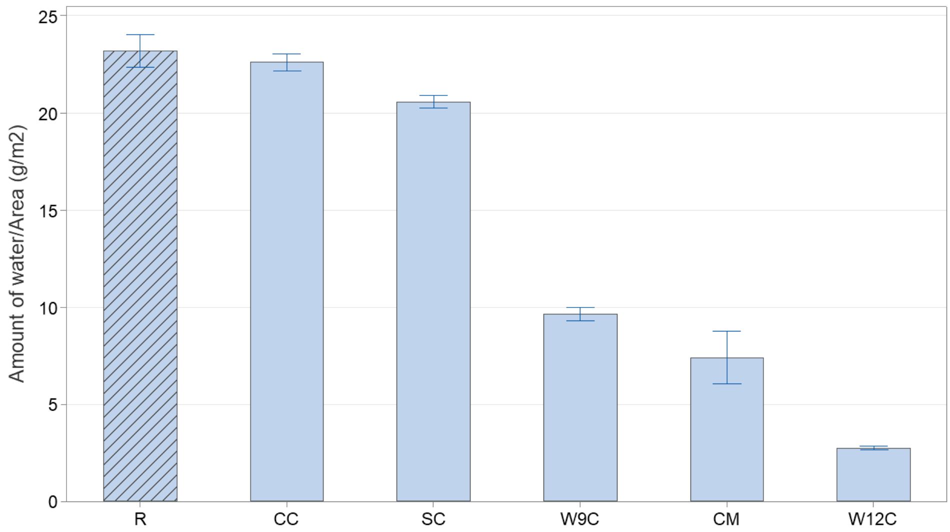

Figure 19 The average amount of water per area for the six variants of paper straws, sorted in descending order (n=18). Striped bar displays the uncoated paper straw and blue bars display the coated paper straws.

4.1.2 Surface roughness

Surface roughness is another critical factor that is believed to have a major impact on the mouthfeel, as well as the first impression that consumers will have when holding the straw in their hand. This impression can influence a consumer's judgement of that paper straw even before using it, which can ultimately affect their satisfaction with the overall mouthfeel. A rough paper straw may lead consumers to believe that consuming their beverage with this straw could result in an unpleasant feeling on their lips. Conversely, a smoother surface possibly feels more promising for consumers since it closely resembles the conventional plastic straws that they are used to.

Table 7 Surface roughness for six variants of paper straws

Sample	***R_a (μm)***	***R_q (μm)***	***R_z (μm)***
R	2.575 ± 0.231^a	3.278 ± 0.269^a	16.763 ± 1.225^a
SC	2.269 ± 0.187^b	2.893 ± 0.229^b	15.220 ± 1.268^b
W9C	2.167 ± 0.165^b	2.758 ± 0.214^b	14.541 ± 1.212^b
W12C	1.931 ± 0.181^c	2.446 ± 0.225^c	12.773 ± 1.400^c
CC	1.286 ± 0.148^d	1.657 ± 0.189^d	8.788 ± 0.938^d
CM	0.770 ± 0.150^e	0.963 ± 0.184^e	4.224 ± 0.979^e

Note: The results presented in the number of Means ± SD *(n=18). Means that do not share a letter in the same column are significantly different at 95% confidence (p-value < 0.05).*

The results presented in Table 7 show the surface roughness output data of R_a (μm), R_q (μm) and R_z (μm) of different paper straws (6 variants). This study primarily focused on the R_a parameter, as it provides an average value of all the roughness profiles. Nonetheless, the results obtained from R_q and R_z also exhibit a similar pattern to that of R_a, with the samples ranking in the same order. Figure 20 clearly shows the trend of R_a results for each specimen in descending order. The study found that uncoated paper straws (specimen R) exhibited the highest surface roughness (R_a = 2.575 μm), while the commercial straw (specimen CM) had the lowest surface roughness (R_a = 0.770 μm). All samples are significantly different from each other (p-value < 0.05) except the sample SC and W9C, which cannot conclude that they are significantly different. As expected, uncoated paper straws are rougher than coated paper straws. The surface roughness values obtained in this study are also consistence with those values reported by previous studies (Skedung et al., 2010, 2011), where they measured the surface roughness of coated and uncoated printing paper.

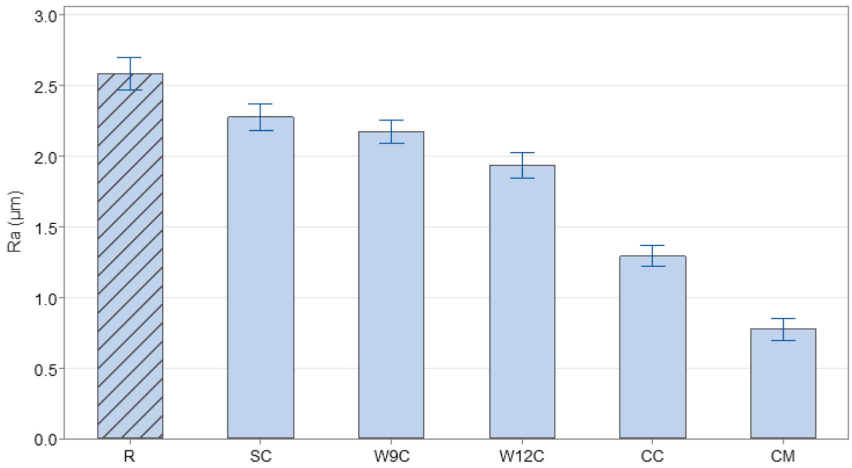

Figure 20 The roughness average for the six variants of paper straws, sorted in descending order (n=18). Striped bar displays the uncoated paper straw and blue bars display the coated paper straws.

4.1.3 Compressive strength

Compressive strength is another important mechanical property that ensures the good functionality of drinking straws. This is because the straw can be exposed to compressive forces during transportation and handling, which can affect its performance. Additionally, the compressive strength can also affect the overall mouthfeel of the straw, as it determines the ability to remain sturdy and maintain its shape when in contact with drinks. Therefore, a straw with sufficient compressive strength can better satisfy the user experience.

The results of the compressive strength measurement show that different types of paper straws have varying degrees of strength when subjected to compression forces, both in dry and wet conditions. Focusing on dry compressive strength, the highest value was observed for CM, commercial paper straw and the lowest value was observed for W9C paper straw. This means that commercial paper straw has more potential to withstand the compression force than other samples. On the other hand, the highest value of wet compressive strength was observed for W12C specimens, and the lowest value was observed for CM paper straw. It is clearly seen that there is no significant difference in the wet strength between coated paper straw (SC, CC and CM) and uncoated paper straw (R); however, the strength was significantly improved when using another coating material, such as W9C and W12C.

When comparing the dry and wet compressive strength, the study found that the wet compressive strength values were significantly lower than the dry compressive strength values for all types of paper straws (Figure 21), indicating that moisture content has a significant impact on their strength. This is probably because moisture weakens the structure of the cellulose fibers, making them more vulnerable to compressive forces. Among the six different types of paper straw tested, the difference between the two strengths is most notable in the commercial straw (CM), as it had the highest strength when testing in dry condition; however, in wet condition, the strength showed the lowest value.

According to the result, it is suggested that the wet strength of paper straws may be influenced by the application of coating materials as well as the type of coating. The coating material might potentially enhance paper straws' durability by acting as a hydrophobic layer so that water will not be able to penetrate the paper straws and compromise their structural integrity. It is also worth noting that the differences in seaming orientation (Figure 12) or structural design (tube-formed or winded) (Figure 11) of paper straws might affect their strength as well.

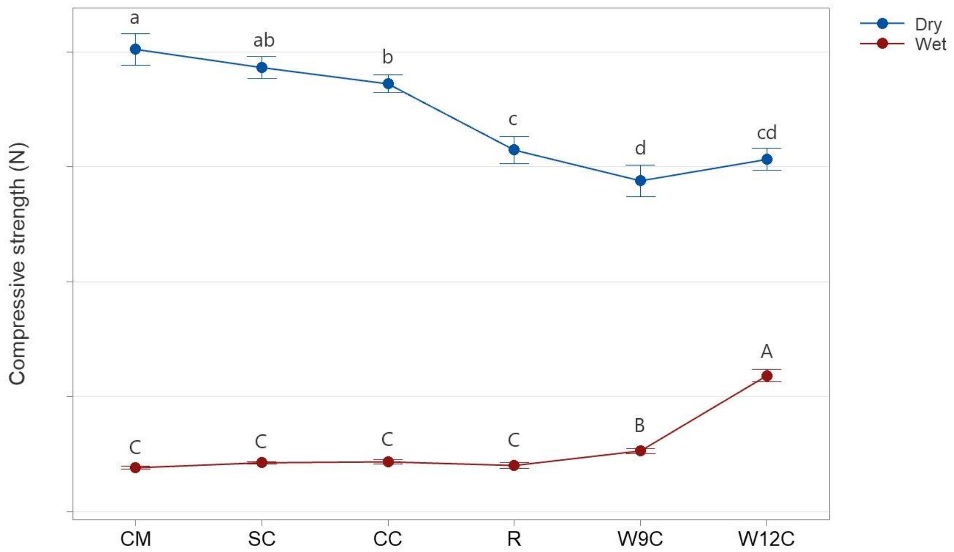

Figure 21 The results of dry (blue line) and wet (red line) compressive strength of six variants of paper straws. The specimen that does not share an uppercase or lowercase letter are significantly different at 95% confidence (p-value < 0.05).

4.1.4 Tactile friction

Tactile friction is believed to be an interesting parameter for the mouthfeel experience. The friction caused by the paper straw can create varying degrees of resistance and roughness, which can affect the perceived texture of users. The friction property of paper straws has been measured between an index finger and six variants of coated and uncoated paper straws. The measurements were taken for both 1N and 2N applied loads at the speed of 40 mm/s. The average dynamic COF was calculated in 2 different ways, using a different selection of the obtained data for each specimen. The results from all calculations are indicated in Table 8 for both 1N and 2N applied loads.

For the 1N applied load, the COF values range from 0.297 to 0.800 and from 0.287 to 0.682 when using the applied load at 2N. Uncoated paper straw (specimen R) displays the lowest COF in both applied loads and both calculations when compared to the coated paper straws, which exhibited a higher COF. However, the results within the coated paper straw also differed between the type of the applied coating material. The reason could be that the chemical composition and the amount of the applied coating, paper filler and chemicals in the pulp may contribute to specific molecular interactions such as adhesion, which in the end, influence the friction property of paper straw (Skedung et al., 2011).

Table 8 Average Coefficient of Friction (COF) at 1N and 2N applied load using 2 different methods of calculation

Sample	*1N*		*2N*	
	COF all data	*COF 80% data*	*COF all data*	*COF 80% data*
R	0.304 ± 0.018[d]	0.297 ± 0.017[d]	0.291 ± 0.012[c]	0.287 ± 0.011[c]
SC	0.312 ± 0.027[d]	0.302 ± 0.024[d]	0.309 ± 0.035[c]	0.304 ± 0.035[c]
CC	0.332 ± 0.034[d]	0.322 ± 0.030[d]	0.294 ± 0.016[c]	0.291 ± 0.015[c]
W9C	0.490 ± 0.090[c]	0.479 ± 0.101[c]	0.466 ± 0.138[b]	0.467 ± 0.143[b]
W12C	0.587 ± 0.047[b]	0.570 ± 0.056[b]	0.537 ± 0.071[b]	0.527 ± 0.081[b]
CM	0.790 ± 0.156[a]	0.800 ± 0.183[a]	0.657 ± 0.104[a]	0.682 ± 0.108[a]

Note: The results presented in the number of Means ± SD (n=18). Means that do not share a letter in the same column are significantly different at 95% confidence (p-value < 0.05). No statistically different between both calculations for all samples in each applied loads at 95% confidence (p-value < 0.05).

Despite using the different selections of obtained data in the calculation, no significant difference is observed between both ways. Moreover, when considering each calculation method individually, all specimens were consistently ranked in the same order within the same applied load. Specimen R, the only uncoated paper straw, showed the lowest COF values among all the samples tested in both 1N and 2N, followed by SC, CC, W9C, and W12C. The CM-coated paper straw displayed the highest COF value in both applied loads. Previously, Skedung et al. (2010, 2011) studied the friction property on a series of printing papers, which their results are consistent with the result obtained in this study.

To select the calculation methods, the lowest pooled standard deviation value was used as a criterion. The results showed that the calculated average COF using all obtained data that was not given as zero (COF all data) marked the lowest pooled standard deviation value in both 1N and 2N when compared to the calculation that used 80% of the data (COF 80% data). Hence, this calculation method will be used in the following study.

The COF values were also found to be affected by the load applied during the measurements; in this case were 1N and 2N. Several relationships between the coefficient of friction and applied load were investigated in the previous study. Derler et al. (2009) have found that the coefficient of friction for skin can vary with load; increasing applied load could result in a decrease of COF. The same trend was observed in the study of Seo & Armstrong (2009) when increasing the applied load from 1 to 10 N. However, a linear relation – friction force is proportional to the load (aligned with Amontons' law) – can be found in some research. The difference between these behaviors could be because the type of countersurface materials used in those studies was different (van Kuilenburg et al., 2015). In this experiment, a lower applied load at 1N displayed a higher COF value in every specimen, as seen in Figure 22, in which a significant difference was found in CM, W12C, CC and R paper straws at a significance level of 0.05. The differences in COF were observed more in the smooth surface of coated paper straw.

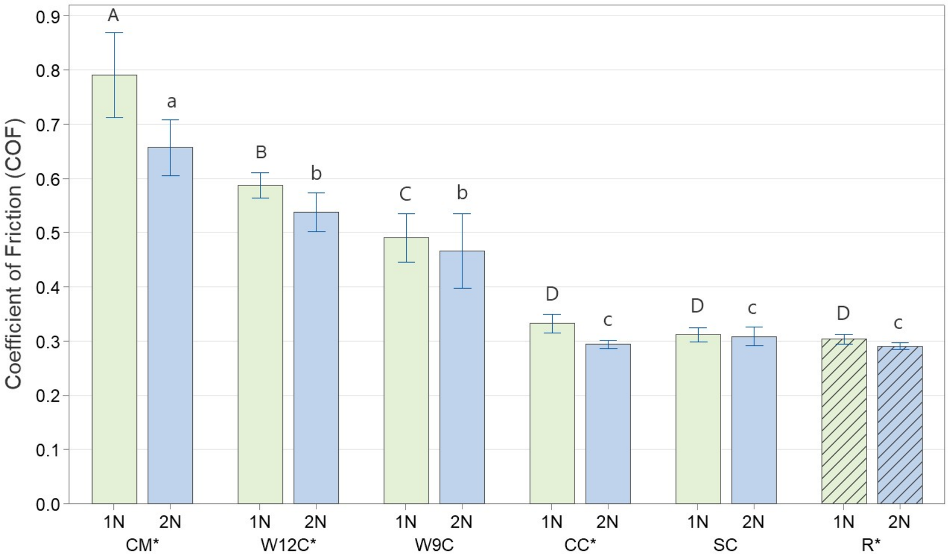

Figure 22 The average COF results calculated with the obtained data that was not given as zero (COF all data) for the six variants of paper straws (n=18). Striped bar displays the uncoated paper straw and unstriped bars display the coated paper straws. Green bars and blue bars show the average COF when using 1N and 2N applied load, respectively. The specimen that does not share an uppercase or lowercase letter are significantly different at 95% confidence (p-value < 0.05). The sample with an asterisk (*) indicates that the COF from the applied load of 1N and 2N are significantly different at 95% confidence (p-value < 0.05).

It was discovered that maintaining the constant applied load at 1N was easier than 2N, proven by the final calculated vertical load at 1 ± 0.1 N and 2 ± 0.2 N, respectively. Additionally, some researchers have previously discovered that the optimal applied load to detect a stimulus through touch is approximately 1N (Soneda & Nakano, 2010). Considering the difference between the group of specimens, 1N provide a higher order of significantly different group (4 groups instead of 3 groups in 2N), which was calculated by Tukey's HSD pairwise comparison. Therefore, the data obtained from 1N applied load measurement will be used with the calculation of 'COF all data' for studying correlation in the next section.

During the experiment, the COF was recorded in 2 stroking directions: forward (away from the body), given a negative horizontal force, and backward (toward the body), given a positive horizontal force. The friction hysteresis between the forward and backward strokes can be noted in this study (see Figure 23), with the COF being greater in the forward stroke than in the backward stroke among all specimens. However, this happens in the opposite way when compared to the previous studies where the friction in the backward direction gave a higher value, i.e., noted in the study of Skedung et al. (2018). This could be explained by a larger real contact area (from a lower sliding angle) in that direction with more skin in contact, making a higher COF. The difference in results between this study and previous studies may be explained by differences in the way of measurement within different operators and specimens. For instance, differences in the sliding angle of the operator's finger when stroking in both directions could contribute to the different contact areas. Also, this study performed the measurement on paper straws with a small diameter. Thus, the finger might lower down and contact more on the straw' surface when stroking away from the body as it was harder to maintain stability on the straw in that direction. In addition to real contact area that is a large contributor to tactile friction, this study observed a greater difference in the two stroking directions on smoother surfaces (coated paper straws), with more stick-slip phenomenon observed in the forward direction, aligning with other studies.

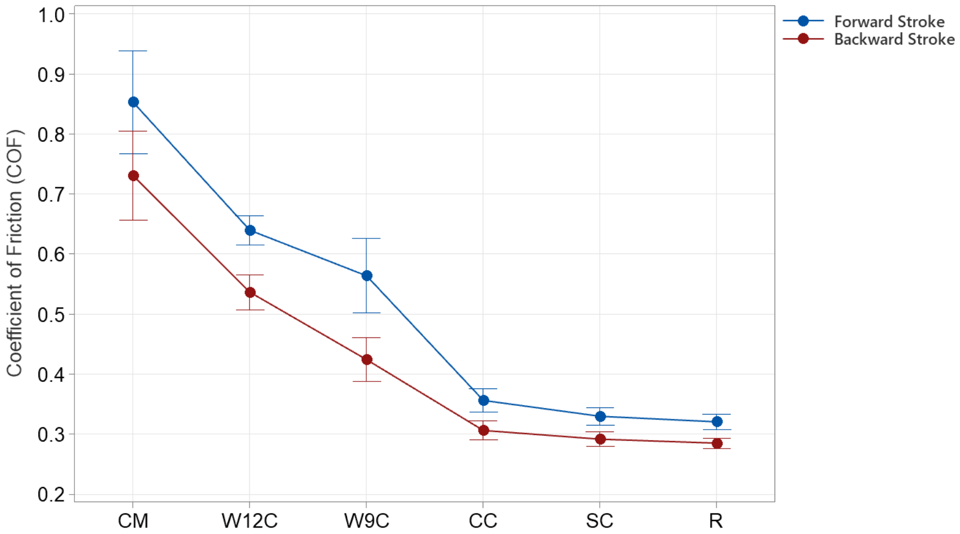

Figure 23 The average COF results of six variants of paper straws using all data obtained in forward (blue line) and backward (red line) strokes, with the applied load of 1N. The COF values of the forward stroke are significantly higher than backward stroke at 95% confidence (p-value < 0.05) in all samples.

4.2 Sensory Analysis

A sensory evaluation was performed with 50 untrained Tetra Pak employees, where each participant individually evaluated all six variants of paper straws without repeating any sample. Evaluators were asked to give the intensity scores, from 0 to 10, where the W9C specimen was used as a reference to compare with other specimens, having an intensity score of 5. The objective of the evaluation was to assess the mouthfeel attributes of paper straws, including roughness, dryness, stickiness, sturdiness and sogginess, and in the end rate their overall liking. The information of panelists regarding age and gender are presented in Figure 24 and Figure 25, respectively.

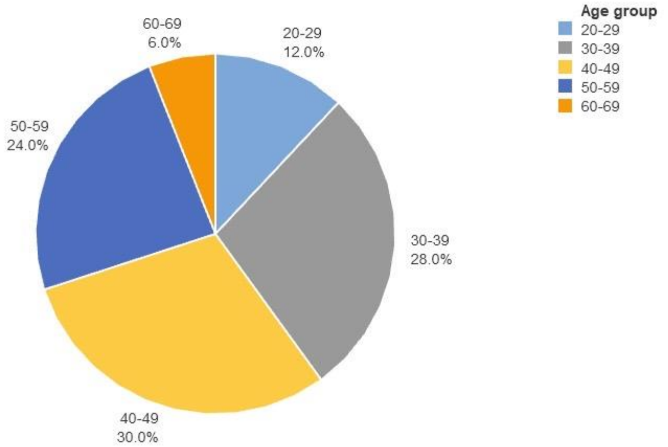

Figure 24 Summary of panelists age group

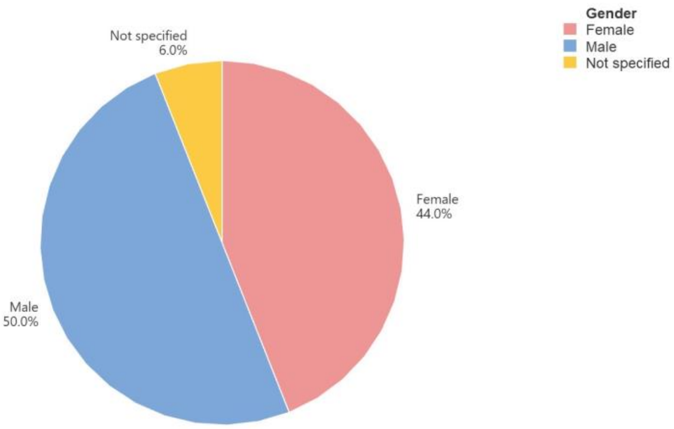

Figure 25 Summary of panelists gender

Table 9 Summary of the sensory evaluation results for all mouthfeel attributes and overall liking of paper straw

Sample	*Mouthfeel Attribute*					*Overall liking*
	Roughness	*Dryness*	*Stickiness*	*Sturdiness*	*Sogginess*	
R	5.90 ± 1.43^{ab}	6.15 ± 1.60^{a}	6.20 ± 1.35^{a}	4.69 ± 1.15^{b}	5.81 ± 0.94^{a}	3.92 ± 1.47^{c}
SC	6.17 ± 1.35^{a}	6.45 ± 1.47^{a}	5.97 ± 1.51^{a}	5.00 ± 1.22^{ab}	5.47 ± 1.07^{ab}	3.91 ± 1.47^{c}
W9C	5.48 ± 0.97^{ab}	4.95 ± 0.93^{b}	5.28 ± 0.90^{a}	4.73 ± 0.89^{b}	5.09 ± 0.92^{b}	5.01 ± 1.15^{b}
W12C	4.00 ± 1.52^{c}	3.54 ± 1.89^{c}	3.63 ± 2.02^{b}	5.22 ± 0.99^{ab}	4.09 ± 1.35^{c}	6.68 ± 1.41^{a}
CC	5.11 ± 1.53^{b}	5.69 ± 1.57^{ab}	5.70 ± 1.66^{a}	4.75 ± 1.08^{b}	5.31 ± 1.35^{ab}	4.03 ± 1.28^{c}
CM	3.36 ± 1.76^{c}	3.21 ± 1.92^{c}	3.24 ± 1.99^{b}	5.61 ± 1.21^{a}	4.23 ± 1.50^{c}	6.43 ± 1.75^{a}

Note: The results presented in the number of Means ± SD *(n=50). Means that do not share a letter in the same column are significantly different at 95% confidence (p-value < 0.05).*

The results presented in Table 9 indicate that paper straw variants differ significantly in terms of their mouthfeel attributes and overall liking. It is also important to point out that the range of scores among the specimens in sturdiness perception was relatively narrow, with a difference of only 0.92. Moreover, panelists mostly rated the sturdiness score closely to 5, which this behavior was also observed the same in sogginess perception. This could be because the panelists found that it was difficult for them to detect the differences between the specimens and reference in sturdiness and sogginess perception by using only their lips. As a result, they provided scores that closely matched the reference score of 5.

Based on these results, it is obvious that the sensory profile of paper straws is clearly divided into two groups, as evidenced by the two distinct hexagons in Figure 26. The CM and W12C specimens were grouped together, while the other four were clustered separately from these two specimens. It is important to highlight that the SC and R specimens were not perceived any significant differences by the panelists in any attribute, and both specimens performed worse than the others, receiving the lowest overall liking scores. They had the highest roughness, dryness, stickiness, and sogginess scores but the lowest sturdiness scores.

In the other hexagon, both the CM and W12C specimens exhibited similar good performance across all attributes, with no significant differences observed between them. They performed better in terms of mouthfeel attributes, scoring lowest in roughness, dryness, and stickiness but highest in sturdiness. This suggests that they might be less likely to irritate or stick to the mouth or lips when used and is more durable compared to other specimens. On the other hand, they scored the lowest in sogginess, suggesting that they may last longer when exposed to drinks.

In regard to the overall performance, the W12C paper straw outperformed all other paper straws developed by Tetra Pak and was comparable to the commercial straw variant, as expected. This was demonstrated by its high overall liking score, indicating that it was the most preferred option among all specimens. However, as the results of this study were obtained from a small group of untrained evaluators, they may not reflect the preferences of all consumers. Lastly, it also needs to keep in mind that those sensory attributes can be influenced not only by the age and gender of participants, but their emotions, knowledge, and the lips conditions (dry or wet lips) might also play a crucial role in evaluating paper straws.

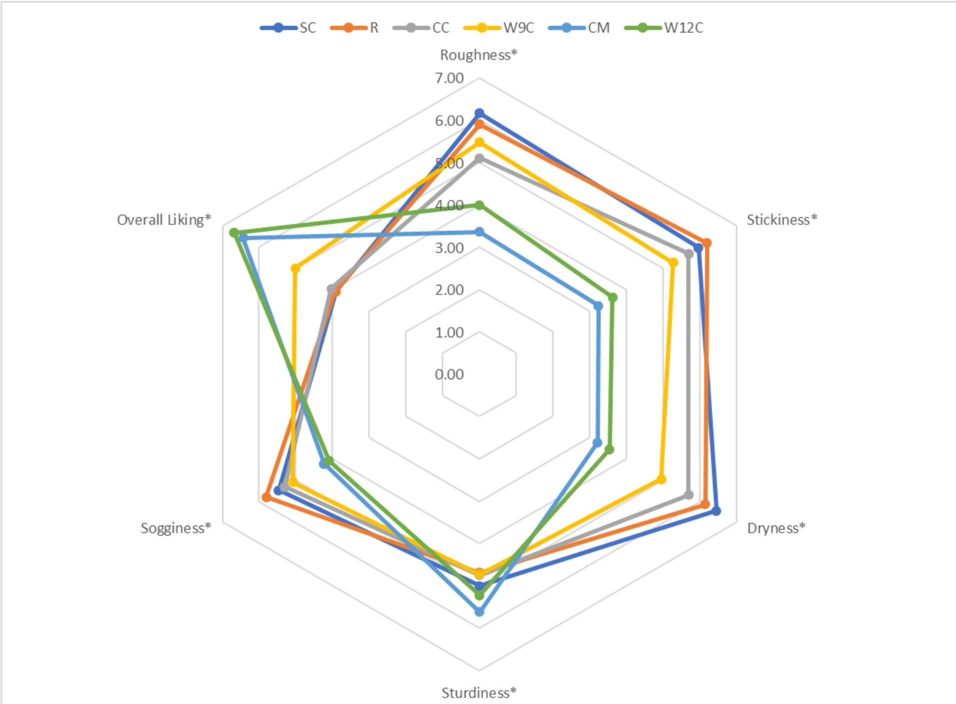

Figure 26 Spider plot showing the sensory profile of mouthfeel on paper straws; SC (blue line), R (orange line), CC (grey line), W9C (yellow line), CM (light blue line) and W12C (green line). Asterisks (*) indicate a significant difference between each variant in that attribute (p-value < 0.05)

4.3 Analysis of Correlations

The correlation analysis between subjective and objective measurements is a crucial step in understanding the relationship between sensory evaluation and instrumental testing when developing a new product. In the study of mouthfeel analysis for paper straw products, subjective measurements are based on sensory evaluation by human testers, while objective measurements are obtained through instrumental testing of the mechanical and chemical properties of the paper straw. By comparing these two types of measurements, researchers could gain valuable insights into the quality and mouthfeel characteristics of the products. Moreover, they can potentially develop more accurate and reliable instrumental measurements to evaluate mouthfeel attributes. This, in turn, could lead to the development of cost and time-efficient substitute methods for the sensory panel test, which is currently the standard method for evaluating consumer perception.

Although the main objective is to identify the correlation between subjective and objective measurements (sensory - instrumental comparison), this study also evaluated the correlation between subjective measurements themselves (sensory - sensory comparison), as well as objective measurements themselves (instrumental - instrumental comparison). This comprehensive approach aims to thoroughly describe the relationship between subjective and objective measurements. The sensory - sensory comparison will be discussed in a separate section, while instrumental - instrumental comparison will be simultaneously described in the sensory - instrumental comparison section.

4.3.1 Sensory - sensory comparisons

The study highlights the importance of texture in determining the overall sensory quality, which can be used to develop the new version of paper straw. By understanding the relationship between various mouthfeel attributes, developers can create paper straws with desirable combinations of these attributes to enhance consumer acceptance and satisfaction.

Table 10 Pearson's correlation coefficient (r) values between mouthfeel sensory attribute of six variants of paper straws

	Roughness	***Stickiness***	***Dryness***	***Sturdiness***	***Sogginess***
Stickiness	0.594				
Dryness	0.511	0.541			
Sturdiness	-0.166	-0.196	-0.178		
Sogginess	0.335	0.360	0.434	-0.315	
Overall liking	-0.451	-0.531	-0.551	0.217	-0.381

Note: The results presented in the number of Pearson's correlation coefficient (r) values (n=50). All results are significantly correlated at 95% confidence (p-value < 0.05).

The results of Pearson's correlation coefficient (r) presented in Table 10 were used to indicate the relationship between different mouthfeel sensory attributes of paper straws. All results are significantly correlated at 95% confidence; however, the differences in the result were observed in the degree and direction of correlation. The results reveal that roughness has a strong positive correlation with stickiness (r = 0.594) and dryness (r = 0.511), and dryness has a strong positive correlation with stickiness (r = 0.541). These findings suggest that paper straws that feel rougher may also feel stickier and dryer for panelists.

It is worth considering that the sensation of dryness and stickiness were concurrently perceived by the participants in the experiment, as it was difficult for them to distinguish the difference between these two sensations. Most panelists said that they often combine them together and use the same context to evaluate the samples. This could be because panelists interpreted the dryness of paper straw as it is absorbing moisture from their lips and consequently turning to the sticky feeling, suggesting that dryness could influence stickiness perception. As a result, it may be possible to use only one of them in the correlation analysis with the instrumental measurement.

Furthermore, the study found that sturdiness was not observed any strong correlations with other attributes. It was found only a moderate negative correlation with sogginess (r = -0.315). Likewise, sogginess perception was found to have only moderate positive correlations with roughness, stickiness, and dryness, presented with the r value of 0.335, 0.360 and 0.434, respectively. This might align with the discussion in the previous section regarding the difficulties in differentiating the strength of paper straws when using their lips, which results in a lower degree of correlation.

Lastly, overall liking is negatively correlated with all attributes except for sturdiness. This means that panelists generally preferred straw that has a lower level of roughness, stickiness, dryness, and sogginess but higher sturdiness.

4.3.2 Sensory - instrumental comparisons

The main objective of the study is to investigate the relationship between subjective mouthfeel perception of paper straws and their instrumental quality measurements, with the goal of finding how well the instrument could predict those sensory scores. Performing instrumental measurement is preferable in the developing process as having consumers or trained panelists to test the product generally has more complications and is time-consuming.

Table 11 Pearson's correlation coefficient (r) values between mouthfeel sensory attribute and instrumental measurement of mechanical and chemical properties of six variants of paper straws

	Mouthfeel Attributes					***Overall liking***
	Roughness	***Stickiness***	***Dryness***	***Sturdiness***	***Sogginess***	
Water absorption	0.756*	0.886**	0.908**	-0.648	0.919**	-0.954**
R_a	0.781*	0.648	0.620	-0.663	0.595	-0.485
COF all data (1N)	-0.916**	-0.956**	-0.956**	0.861**	-0.896**	0.920**
Dry compressive strength	-0.222	-0.137	0.002	0.516	-0.066	-0.073
Wet compressive strength	-0.385	-0.491	-0.500	0.210	-0.617	0.622

*Note: The results presented in the number of Pearson's correlation coefficient (r) values (n=6). The asterisks * and ** indicate the r values that are significantly correlated at 90% confidence (p-value < 0.1) and 95% confidence (p-value < 0.05), respectively.*

Table 11 demonstrates the result of the Person's correlation coefficient between mouthfeel sensory attributes of six variants of paper straws and their mechanical and chemical properties. It can be indicated that tactile friction and water absorption properties appear to be the most promising instrumental measurements for predicting mouthfeel perceptions of paper straws. This is evident from their significant correlations with the majority of the mouthfeel attributes and overall liking. The COF values were significantly correlated with all mouthfeel sensory attributes of paper straws, including perceived roughness, stickiness, dryness, sogginess, and sturdiness at 95% confidence. Further analysis revealed that water absorption property was significantly correlated with perceived stickiness, dryness, and sogginess at a confidence level of 95% while significantly correlated with perceived roughness at a confidence level of only 90%.

Rating of overall liking of the paper straws was also influenced by variations in their mechanical and chemical properties. It was found that overall liking was significantly related to tactile friction (COF) ($r = 0.920$) and water absorption ($r = -0.954$) at a confidence level of 95%, suggesting that paper straws with higher COF or lower water absorption might be more preferred.

More thorough explanations of the correlation between each mouthfeel perception and the mechanical-chemical properties of paper straws are given in the following section.

4.3.2.1 Perceived roughness

When focusing on these perceptions in more detail, a correlation analysis between roughness perception and surface roughness measurement has also been carried out in an earlier study. The researchers found a strong positive correlation between perceived smooth/rough feelings and measured R_a (Liu et al., 2008). The surfaces that have a higher R_a were perceived to be rougher. Skedung et al. (2011) also noticed the same behavior when measuring a series of printing papers, in which the correlation coefficient accounted for 0.85. Moreover, the correlation between perceived roughness and R_a was also found in this study ($r = 0.781$, p-value < 0.1), indicating that rougher uncoated paper straw was perceived to be rougher than coated paper straw (Figure 27).

Even though this study found a correlation between perceived roughness and R_a, some studies suggested that R_z (average maximum height of surface profile) and R_p (maximum peak height of surface profile) are more suitable for assessing roughness perception in some rough surfaces. Moreover, roughness perception is very subjective as it can be defined differently in different people (Bergmann Tiest & Kappers, 2007; van Kuilenburg et al., 2015). Although this study provided the definition of perceived roughness to create the same direction in the sensory session, it might be some other dimensions that influence the roughness perception, or panelist might define roughness in their own ways.

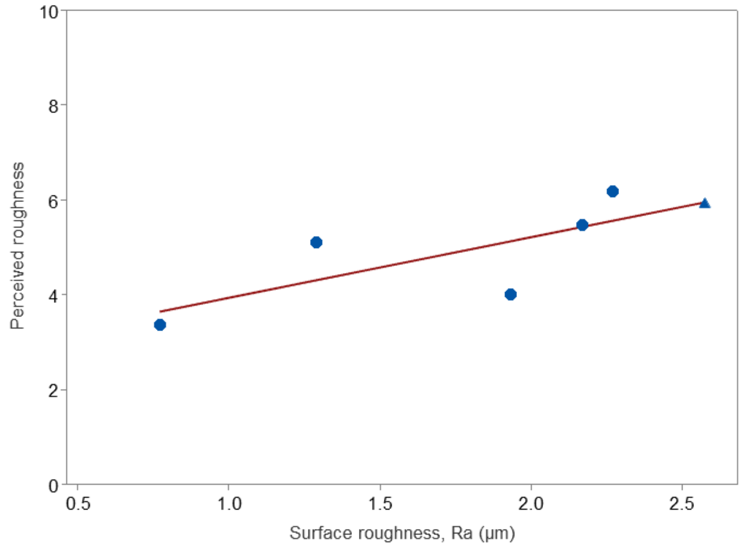

Figure 27 The relationship between perceived roughness and surface roughness. The red line indicates a fit linear regression (r = 0.781, R^2 = 61.1%). The coated paper straws are shown as circles and uncoated paper straw as triangle.

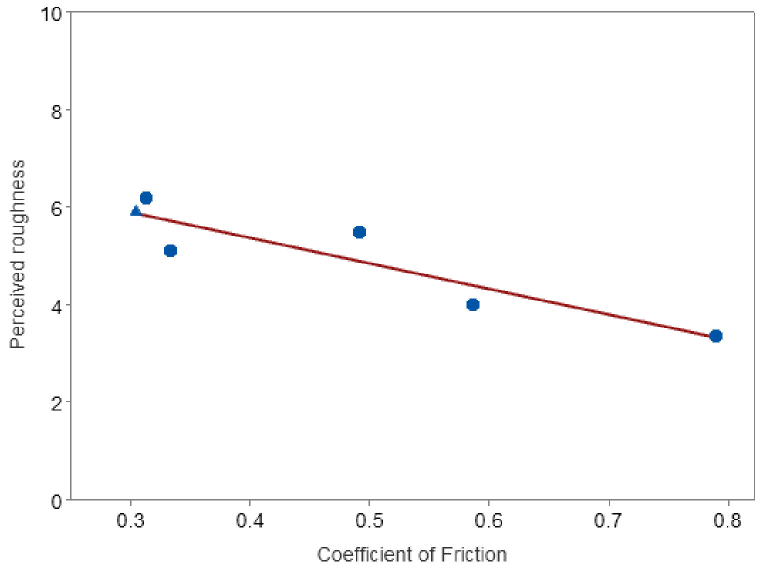

Figure 28 The relationship between perceived roughness and COF. The red line indicates a fit linear regression (r = -0.916, R^2 = 83.8%). The coated paper straws are shown as circles and uncoated paper straw as triangle.

Roughness perception is also associated with more than one physical property. The study found a strong negative correlation between perceived roughness and COF ($r = -0.916$, p-value < 0.05), as seen in Figure 28. The uncoated paper straw with the lowest COF was perceived as rougher than coated paper straws. The result is synonymous with the research of Skedung et al. (2011).

The results seem to be logical as the study found a trend of a negative relationship between instrumental measurements – surface roughness (R_a) and coefficient of friction ($r = -0.669$). Figure 29 demonstrates the trend in which smoother paper straws have a greater COF when compared to rougher paper straws. Likewise, this finding is also aligned with the research of Skedung et al. (2010, 2011). They explained this observation as smoother surfaces provide a larger true contact area with the finger, resulting in higher levels of friction.

However, when considering the degree of correlation, the measured friction showed a stronger correlation with perceived roughness compared to the measured R_a, contradicting the initial hypothesis that R_a would have a higher correlation. This might lead to the theory that the perception of roughness is multidimensional, consists of surface roughness and friction components (Bergmann Tiest & Kappers, 2006), which in this case, panelists evaluated the roughness of paper straw based on the detection of friction between lips and straw rather than roughness topography profile.

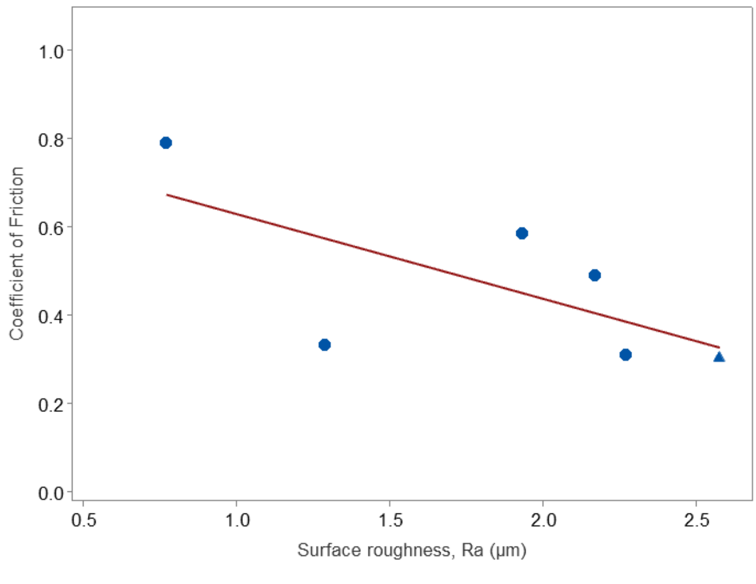

Figure 29 The relationship between COF and surface roughness. The red line indicates a fit linear regression ($r = -0.669$, $R^2 = 44.7\%$). The coated paper straws are shown as circles and uncoated paper straw as triangle.

4.3.2.2 Perceived stickiness & perceived dryness

Stickiness perception can be perceived differently by individuals in various contexts. Additionally, perceived dryness can also influence stickiness perception, as described in the sensory – sensory comparison section. The correlation between these perceptions and instrumental measurements showed consistent behavior, with a significant positive correlation observed between water absorption and a significant negative correlation with COF. This supports the argument that these attributes are interrelated and directly proportional to each other. Therefore, this section will focus mainly on stickiness perception. The study also observed a greater degree of correlation between perceived stickiness/dryness and COF, associated with the conclusion of Okamoto et al. (2013). They concluded that these two attributes, stickiness and dryness, derived from the same single dimension, which is mainly related to friction force or the coefficient of friction.

As mentioned, this study revealed a significant positive relationship between water absorption and stickiness perception ($r = 0.886$) (Figure 30). This might be because the sensory analysis was conducted under dry condition, where the only liquid that was absorbed in this context was panelists' saliva. The presence of saliva can act as a lubricant between the lips and the surface of paper straws, thereby reducing the perception of stickiness. However, if the paper straw has the ability to absorb more water, in uncoated paper straw for example, this lubricating saliva is effectively removed, leaving no lubricant between the straw surface and the lips. Consequently, the perception of stickiness increases. Not only perceived stickiness but water absorption also contributes to the sensation of dryness as it removes moisture from the lips.

Conversely, the coating material on coated paper straws can act as a barrier, preventing paper straws from absorbing saliva from the lips. This barrier effectively preserves the presence of saliva as a lubricant, creating a smoother interface between the lips and the surface of paper straws which can decrease the sticky feeling.

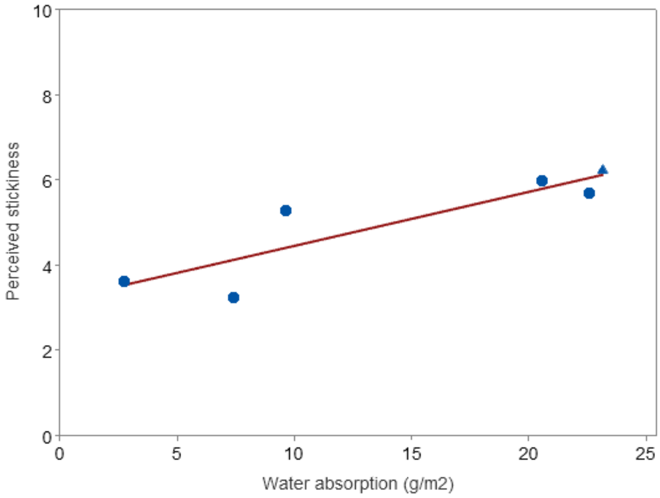

Figure 30 The relationship between perceived stickiness and water absorption. The red line indicates a fit linear regression (r = 0.886, R^2 = 78.5%). The coated paper straws are shown as circles and uncoated paper straw as triangle.

To explain the observed inverse correlation between COF and perceived stickiness in this study (Figure 31), it is true that saliva allows for easier movement when evaluating in sensory test, leading to a more reduction in friction force in coated paper straws and ultimately contributing to a decreased perception of stickiness. However, the context of friction and its interpretation is not the same in instrumental measurement. The higher physical COF of coated paper straws was attributed to their smoother surface with a larger contact area. This, combined with their lower water absorption properties as described earlier, explains why coated paper straws with a higher COF were perceived as less sticky.

This study also found a strong negative correlation between instrumental measurements of water absorption and COF ($r = -0.848$, p-value < 0.05), presented in Figure 32. The result suggested that paper straws with lower water absorption exhibit higher COF, which can be observed in the coated ones. The strong correlation between these two measurements could be partly due to the fact that all samples in this study, except the commercial, are based on the same paper substrate with different coatings applications, thus having similar material structures. Nevertheless, since this study involved only 6 variants of paper straw, it may be necessary to incorporate a broader range of sample variants in the further study to ensure the accuracy and significance of these obtained results.

From the results, it is obvious that stickiness/dryness perception strongly depends on the coefficient of friction and water absorption properties. However, additional properties such as adhesiveness, elasticity and surface roughness can also be considered to comprehensively determine the stickiness/dryness perception (Okamoto et al., 2013). This study already found a trend of correlation between these perceptions with R_a, but it was not statistically significant. It is also worth noting that the physical and chemical properties can vary depending on the composition, texture, and adhesion properties of the paper and coating, as well as the lubricating effects of saliva, which therefore alters the result in the overall perception of stickiness/dryness.

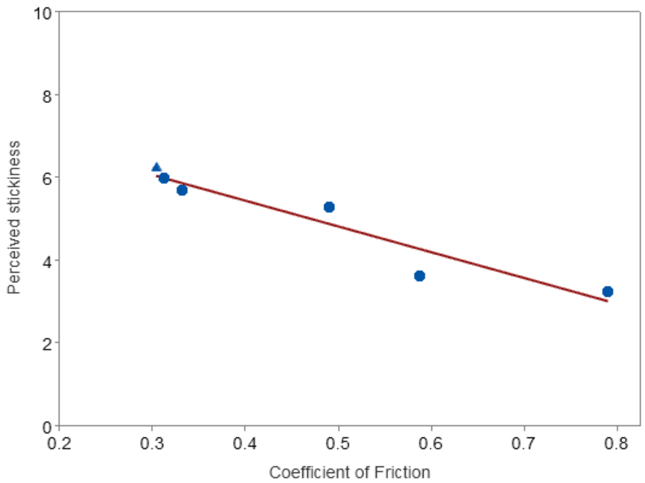

Figure 31 The relationship between perceived stickiness and COF. The red line indicates a fit linear regression (r = -0.956, R^2 = 91.4%). The coated paper straws are shown as circles and uncoated paper straw as triangle.

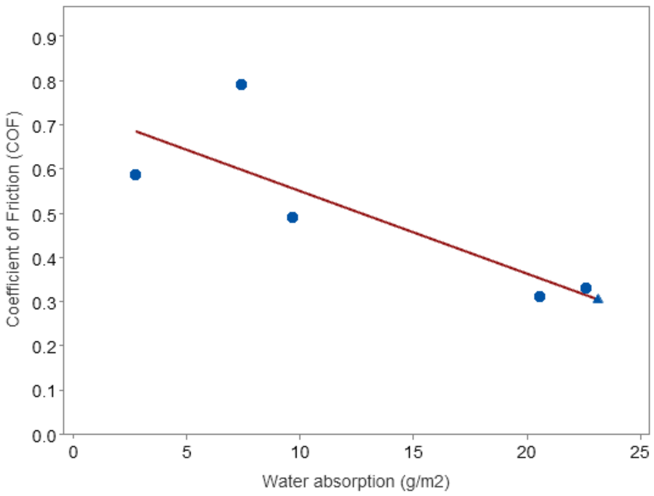

Figure 32 The relationship between COF and water absorption. The red line indicates a fit linear regression (r = -0.848, R^2 = 72.0%). The coated paper straws are shown as circles and uncoated paper straw as triangle.

4.3.2.3 Perceived sturdiness & perceived sogginess

The results of correlation analysis revealed a significant relationship between perceived sturdiness and COF (r = 0.861), as shown in Figure 33. However, perceived sogginess exhibited significant correlations with both COF (r = -0.896) and water absorption (r = 0.919), which can be seen in Figure 34 and Figure 35, respectively. When assessing the strength of correlation between these two properties with sogginess, it is evident that the water absorption property provides a better description of sogginess perception compared to the friction property, as it demonstrates a higher r value with perceived sogginess. The correlation between water absorption and perceived sogginess can be attributed to the application of the coating material. Coated paper straws with lower water absorption rates were perceived as less soggy, while uncoated paper straw with higher water absorption rates was perceived as soggier. The explanation regarding this would be the same as in the previous section. Coated paper straws exhibited higher hydrophobicity on their surfaces, preventing water from penetrating the paper fibers. This results in less swelling of the paper straws with less sogginess perception.

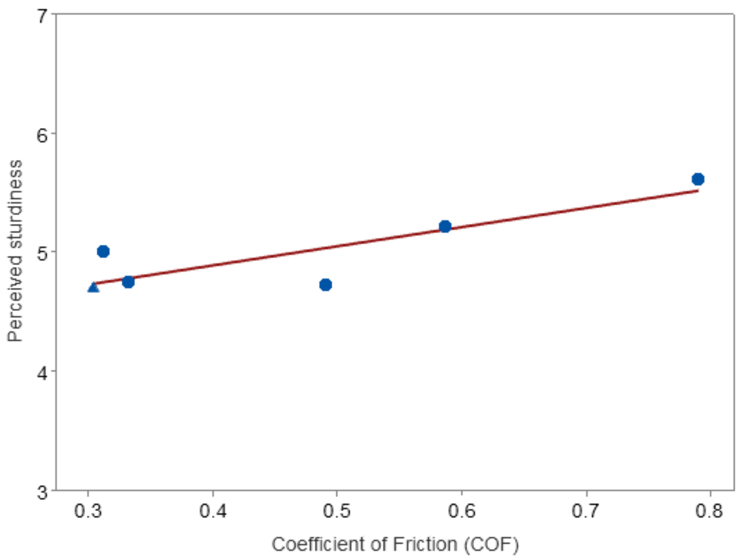

Figure 33 The relationship between perceived sturdiness and COF. The red line indicates a fit linear regression (r = 0.861, R^2 = 74.1%). The coated paper straws are shown as circles and uncoated paper straw as triangle.

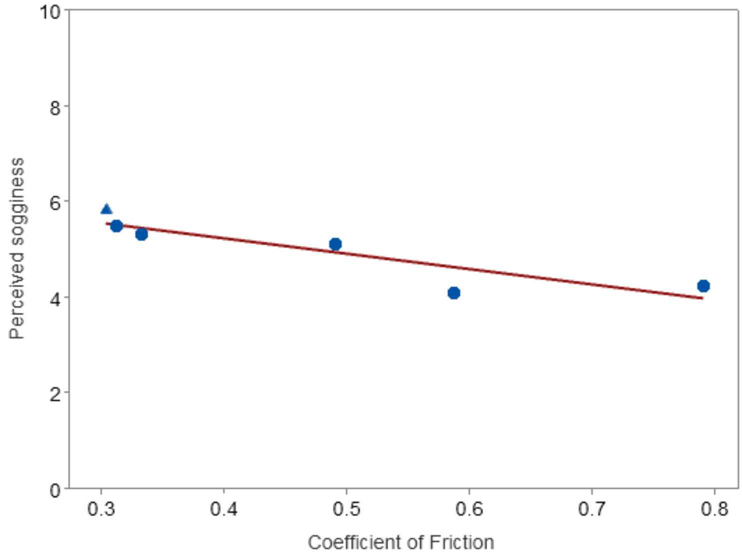

Figure 34 The relationship between perceived sogginess and COF. The red line indicates a fit linear regression (r = -0.896, R^2 = 80.4%). The coated paper straws are shown as circles and uncoated paper straw as triangle.

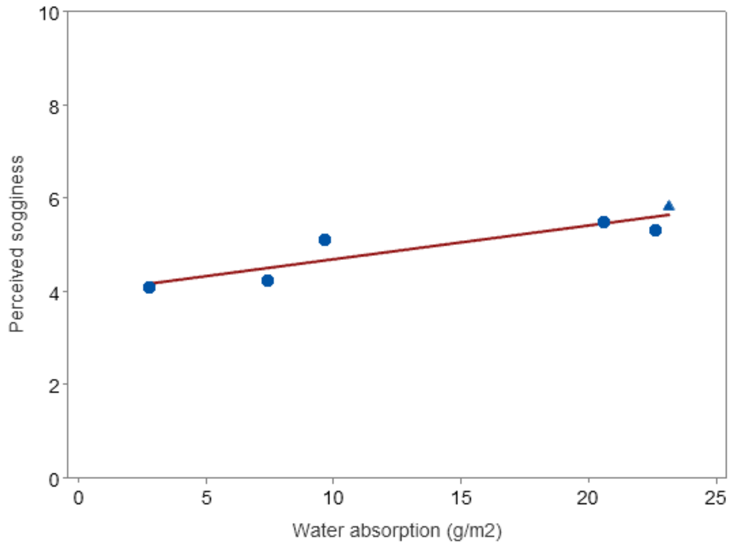

Figure 35 The relationship between perceived sogginess and water absorption. The red line indicates a fit linear regression (r = 0.919, R^2 = 84.5%). The coated paper straws are shown as circles and uncoated paper straw as triangle.

It is also important to highlight that the sturdiness and sogginess perceptions of paper straws may not be predictably determined solely by COF and/or water absorption in this case, despite their significant correlations to those perceptions. Other objective testing methods, such as dry and wet compressive strength, were initially hypothesized to have strong and significant correlations with sturdiness and sogginess, respectively. However, in this study, only trends of correlation were observed, without statistical significance (see Figure 36 for the sturdiness – dry compressive strength relationship and Figure 37 for the sogginess – wet compressive strength relationship). This could be because there are several control variables that impact the strength of paper straws, which need to be considered when selecting testing specimens for further study. Due to limitations, it was not possible to completely control these variables in the study. The samples used for measurement were limited to those available in the company. Factors such as the type and amount of coating material, as well as variations in seaming orientation and their structural designs, could potentially affect the results related to the strength of paper straws.

Moreover, consistency in the experimental procedure, both in subjective and objective tests, is also important. In this study, panelists judged straw sturdiness and sogginess at the tip, while the instrument measured dry and wet compressive strength at the middle of the straw. Additionally, differences in soaking methods of paper straws were employed during the measurements in this study. The water absorption test allowed water to come into contact only with the outer surface of the paper straw, while the wet compression test submerged the entire straw in water. On the other hand, during the subjective test for sogginess perception, half of the straw was submerged in the cup containing water, while another half of the straw contacted water only inside the straw's tube when sucked. In addition, panelists were not provided with specific instructions regarding the duration of straw soaking. Consequently, the soaking duration differed depending on the people. These differences in soaking techniques and durations could have influenced the results obtained in the correlation assessment of sogginess perception.

It can also be argued that panelists may not be able to detect small differences in sturdiness and sogginess between different paper straw specimens using their lips. Further investigation is, therefore, necessary to comprehensively understand and predict paper straw's strength characteristics.

All these reasons mentioned above may have influenced the statistical power of analyses, resulting in the observed results being only a trend of correlation. By expanding the number of variants with a broader range of properties and assigning the same control variables, a more comprehensive and accurate assessment of the significant relationship could be achieved.

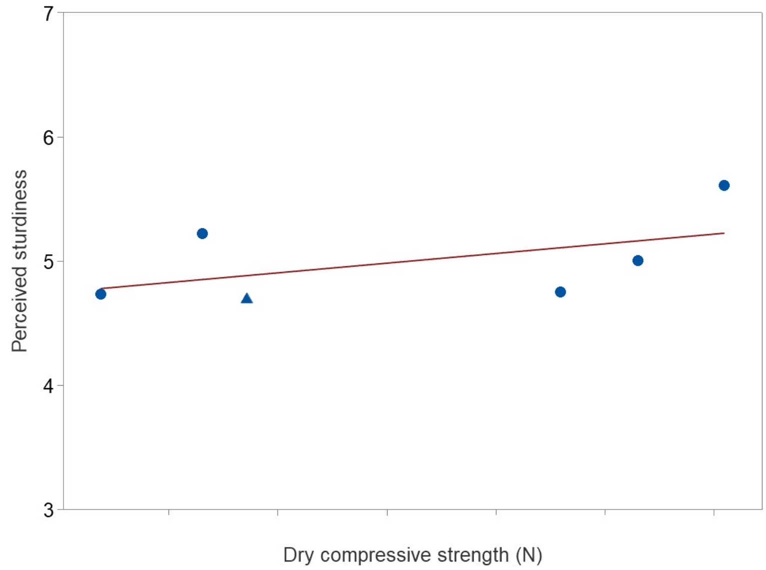

Figure 36 The relationship between perceived sturdiness and dry compressive strength. The red line indicates a fit linear regression (r = 0.516, R^2 = 26.6%). The coated paper straws are shown as circles and uncoated paper straw as triangle.

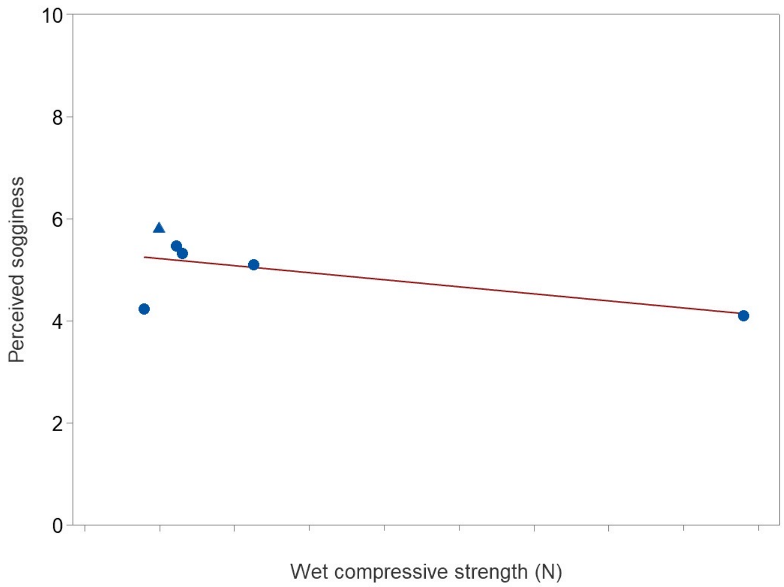

Figure 37 The relationship between perceived sogginess and wet compressive strength. The red line indicates a fit linear regression (r = -0.617, R^2 = 38.1%). The coated paper straws are shown as circles and uncoated paper straw as triangle.

5 Conclusions

Summary of the key findings from the results are described in this section.

Instrumental measurements

The instrumental measurements were used to analyze the mechanical and chemical properties of paper straws. The result revealed that applying coating material on paper straws proved to be effective in reducing water absorption and their surface roughness (R_a). The coated paper straw, such as W12C and CM specimens, demonstrated a significantly lower water absorption and surface roughness. In contrast, the COF in coated paper straw was found to be higher when compared to the uncoated one (R specimen). In terms of compressive strength, the highest value was observed for CM when measuring in dry conditions, while there was no significant difference in the wet strength between coated paper straw (SC, CC and CM) and uncoated paper straw (R). However, the wet strength was found to be significantly improved in the two remaining paper straw variants (W12C and W9C) which had different types of coating. The study also noticed a significant difference when compared the dry and wet strength. Wet compressive strength was considerably lower than dry compressive strength in all specimens, emphasizing that water greatly affects the integrity regarding the mechanical strength of paper straws.

Subjective measurement

Subjective measurement of paper straws was carried out using sensory evaluation involving untrained employees of Tetra Pak. The result found significant differences among the samples in every attribute. Coated paper straws marked a lower score in perceived roughness, stickiness, dryness, and sogginess but a higher score in perceived sturdiness when compared to uncoated paper straws. The CM and W12C were the most preferred coated samples that exhibited similar good performance across all attributes, with the W12C sample receiving the highest overall liking score among the other Tetra Pak paper straws.

Correlation analysis

The results from the sensory - sensory comparison found that perceived roughness, stickiness, and dryness had direct proportion to each other, where panelists often evaluate perceived stickiness concurrently with perceived dryness. Conversely, perceived sturdiness showed a negative correlation with perceived sogginess. Regarding the overall liking rating, panelists preferred paper straws that were less rough, less dry, less sticky, and less soggy, but high in sturdiness.

The results from correlation analysis between instrumental - sensory comparison indicated that tactile friction and water absorption properties emerged as the most promising instrumental measurements for predicting mouthfeel perceptions of paper straws, as they have significant correlations to most of the mouthfeel attributes and overall liking. In addition, a strong trend of correlations between surface roughness, dry compressive strength, or wet compressive strength and some mouthfeel attribute of paper straws were also observed, although their significance may need to be confirmed with larger and more diverse variants. The current study used a limited variant – using only the samples that were available in the company. This may have an impact on the statistical power of analyses. By expanding the number of variants with a broader range of properties and assigning the same control variables, a more accurate and comprehensive assessment of the significant relationship could be provided.

6 Recommendations for Future Research

This section presents the recommendations acquired from this study that might be useful in the future.

Recommendations for enhancing the accuracy and reliability of the results

1. It is important to maintain control variables consistently across all specimens in the experiment to ensure that they do not impact the results. It is also recommended to employ the same method, context, technique, and interpretation for both sensory and instrumental measurements to accurately assess the correlation between subjective and objective measurements. This will enable more confidence to conclude that instrumental measurement can use to predict sensory perceptions.
2. In order to perform the sensory test for correlation analysis between objective and subjective properties, participating panelists should be carefully selected and well-trained prior to the sensory session. They do not need to be experts, and only a small group of evaluators is adequate, approximately 8-12 participants. Small highly-trained panelists will enhance more reliability of the results than large untrained panelists, as they will be more capable to discriminate the differences and evaluate among all specimens with the same context and understanding.
3. To enhance the statistical power and discover more potential correlations, it is recommended to increase the number of distinct variants in the measurements. Each selected paper straw should exhibit apparent differences within each property, resulting in a broader range of outcomes. The samples could be prepared by manually producing them using coating materials that provide the desired properties for the straws. By doing this, the results might be less likely to cluster only on one side of the range. It might also facilitate panelists in detecting distinctions in mouthfeel perception among the paper straws.

Recommendations for the experiments that could be done in future studies

1. The tactile friction measurement was only a preliminary test in this study. The testing method should be verified in the future, for example, using different operators to perform the test, replicate the same testing method to ensure the consistency of the results or adjust some of the testing techniques or parameters to obtain a better output.

2. Conducting measurements with wet straws could provide insights into how the properties of paper straws change over time, as exposure to liquids may affect their texture.

3. R_a was used to identify the correlation in this study: however, some studies suggested that other roughness parameters, such as R_z and R_p, are more suitable for assessing roughness sensation. It would be interesting to include these additional parameters in future studies when analyzing the correlation. Additionally, it could be beneficial to perform a contact angle measurement as well as utilize a saliva simulant instead of water to measure the absorbing property of paper straws, as the wetting properties of saliva differ from water.

4. As age and gender might influence the results of sensory evaluation. It would be interesting to analyze the impact of age and gender on mouthfeel perceptions, especially in the overall liking score. Moreover, using the panelist with age nearly the target group who usually use straws for drinking from the package might give more insights and interesting results.

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Appendix A Final questionnaire

The following figure is a final questionnaire that was used in the final sensory evaluation. It consists of 6 questions to be answered within 7 pages, including the instruction on the first page.

Gender: Male Female Not specified Age: _______

Sensory Evaluation on the mouth feel of paper straw

You will evaluate the mouth feel of paper straw samples. Please read the instruction thoroughly and follow it step by step. If you have any questions, you can ask at any time during the test.

1. Wipe your mouth with the given tissue paper before testing. You will get 6 straw samples (5 straws coded with three digits code using for evaluation and 1 straw coded as ref. using for comparing) and 1 questionnaire (7 pages) with the sample order listed on your questionnaire. This questionnaire contains 6 questions to be answered. **Evaluate presented samples using the given order, from left to right**. You need to use the same sample order to evaluate in every question.

   ****Don't forget to write down the three digits code (given on the sample) on the questionnaire before starting evaluation****
   ****Tips: put the straw back to the same order after evaluating to avoid confusion****

2. You will **evaluate one attribute at a time for all samples**. Rate the intensity for each attribute by **comparing each sample with the reference (marked as ref.)** and overall liking of the mouthfeel in the scale below (11-point scale). **Reference sample (ref.) has an intensity score at 5 in every attribute.** Circle (O) the number that best describes your feeling after comparing with ref. **You do not need to rate the reference sample in each attribute except in overall liking that you also need to rate reference.** Once you finished evaluating first attribute, you can start the new attribute using the same sample order as given at the beginning.

   If you feel that your score is in between the given integer, you can mark down your own score with straight line (|) on the scale and **put the number of your score below you own line.

Sample order

Now you can start your test. First, you will test all samples in the **dry condition** (do not put it in the water yet). **Test the sample by putting it into your mouth and sliding it forward and backward between your lips.** You can try to slide the straw between your lips several times to evaluate the mouthfeel. Answer the following questions.

1. How intense of the **roughness** do you feel on this paper straw at a time you **slide it between your lips**?

   *(**Roughness:** the extent of **irregularities surface of the paper straw that makes you irritate** when rubbed between your lips)*

Sample code: ______

0 1 2 3 4 5 6 7 8 9 10

(very smooth) (similar to ref.) (very rough)

Sample code: ______

0 1 2 3 4 5 6 7 8 9 10

(very smooth) (similar to ref.) (very rough)

Sample code: ______

0 1 2 3 4 5 6 7 8 9 10

(very smooth) (similar to ref.) (very rough)

Sample code: ______

0 1 2 3 4 5 6 7 8 9 10

(very smooth) (similar to ref.) (very rough)

Sample code: ______

0 1 2 3 4 5 6 7 8 9 10

(very smooth) (similar to ref.) (very rough)

2. How intense of the **stickiness** do you feel on this paper straw at a time you **slide it between your lips**? *(**Stickiness:** the **feeling that paper straw sticks to your lips or has jerking motion** when sliding it between your lips)*

Sample code: ______

0 1 2 3 4 5 6 7 8 9 10

(very slippery) (similar to ref.) (very sticky)

Sample code: ______

0 1 2 3 4 5 6 7 8 9 10

(very slippery) (similar to ref.) (very sticky)

Sample code: ______

0 1 2 3 4 5 6 7 8 9 10

(very slippery) (similar to ref.) (very sticky)

Sample code: ______

0 1 2 3 4 5 6 7 8 9 10

(very slippery) (similar to ref.) (very sticky)

Sample code: ______

0 1 2 3 4 5 6 7 8 9 10

(very slippery) (similar to ref.) (very sticky)

3. How intense of the **dryness** do you feel once the straw is touching your lips?

*(**Dryness:** the **feeling that your lips are dry when using paper straw** as it absorbs water from your lips)*

Sample code: ______

0 1 2 3 4 5 6 7 8 9 10

(not dry at all) (similar to ref.) (very dry)

Sample code: ______

0 1 2 3 4 5 6 7 8 9 10

(not dry at all) (similar to ref.) (very dry)

Sample code: ______

0 1 2 3 4 5 6 7 8 9 10

(not dry at all) (similar to ref.) (very dry)

Sample code: ______

0 1 2 3 4 5 6 7 8 9 10

(not dry at all) (similar to ref.) (very dry)

Sample code: ______

0 1 2 3 4 5 6 7 8 9 10

(not dry at all) (similar to ref.) (very dry)

Then, try to compress the paper straw sample by using your lips. Answer the question below.

4. How intense of the **sturdiness** of this paper straw do you feel when you **compress it with your lips**?

   *(**Sturdiness:** the quality of being physically strong or well-made and **not easily damaged when compress** with lips)*

Sample code: ______

0 1 2 3 4 5 6 7 8 9 10

(not strong at all) (similar to ref.) (very strong)

Sample code: ______

0 1 2 3 4 5 6 7 8 9 10

(not strong at all) (similar to ref.) (very strong)

Sample code: ______

0 1 2 3 4 5 6 7 8 9 10

(not strong at all) (similar to ref.) (very strong)

Sample code: ______

0 1 2 3 4 5 6 7 8 9 10

(not strong at all) (similar to ref.) (very strong)

Sample code: ______

0 1 2 3 4 5 6 7 8 9 10

(not strong at all) (similar to ref.) (very strong)

Now use the presented paper straw to drink water from the cup by grabbing it with your lips and sucking water from the cup for some period of time. Answer the questions below.

5. After you drink water from the cup for some period of time, how intense of the **sogginess of the paper straw** do you feel?
*(**Sogginess: the feeling of unpleasantly wet** after it absorb water for some period of time **which makes paper straw soft and lost its shape** easily when compress)*

Sample code: ______

0 1 2 3 4 5 6 7 8 9 10
(not soggy at all) (similar to ref.) (very soggy)

Sample code: ______

0 1 2 3 4 5 6 7 8 9 10
(not soggy at all) (similar to ref.) (very soggy)

Sample code: ______

0 1 2 3 4 5 6 7 8 9 10
(not soggy at all) (similar to ref.) (very soggy)

Sample code: ______

0 1 2 3 4 5 6 7 8 9 10
(not soggy at all) (similar to ref.) (very soggy)

Sample code: ______

0 1 2 3 4 5 6 7 8 9 10
(not soggy at all) (similar to ref.) (very soggy)

6

Now you need to rate the overall liking of mouth feel of the paper straw that you have tested before. **Take only mouth feel into consideration once you evaluate the overall liking.**

6. *How much do you* ***like the <u>mouth feel</u> of this paper straw in overall****?*

Reference (Ref.)

0 1 2 3 4 5 6 7 8 9 10
(extremely dislike) (extremely like)

Sample code: ______

0 1 2 3 4 5 6 7 8 9 10
(extremely dislike) (extremely like)

Sample code: ______

0 1 2 3 4 5 6 7 8 9 10
(extremely dislike) (extremely like)

Sample code: ______

0 1 2 3 4 5 6 7 8 9 10
(extremely dislike) (extremely like)

Sample code: ______

0 1 2 3 4 5 6 7 8 9 10
(extremely dislike) (extremely like)

Sample code: ______

0 1 2 3 4 5 6 7 8 9 10
(extremely dislike) (extremely like)

****Feel free to give the comment!**

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