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Determining Crispness Level of Dry Food through Its Compressive Strain Energy

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ABSTRACT

Crispness is the most appealing characteristic of dry food products. However, the term crispness has different subjective meaning among consumers. This study aims to quantitatively measure the crispness of potato crisp by performing compression test on a single specimen, and analyzing the compressive behavior, i.e., compressive strain energy. The crispness of the specimens were differentiated by changing the moisture exposure durations, which are 0, 1, 2, 3, 6 hours, in a room and ambient condition. The measured load and displacement data were transformed into stress and strain curves. The strain energy for every 1% strain increment was calculated and investigated to determine the crispness. The crispness difference among specimens of 0, 3, and 6 hours groups was significantly perceived at 8% of strain. It was revealed that the 3 and 6 hours of room air exposure could decrease the crispness by 17% and 45%, respectively. This suggests the compressive strain energy at a certain strain can be an indicator of crispness. This experimental study is expected to evolve food engineering by proposing a simple yet precise crispness measurement method for dry food.

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1. INTRODUCTION

Crisp, especially potato crisps, has been a very popular snack around the world (Kleekayai & Suntornsuk, 2011). Yearly, over 12% from 300 million tons of world potato production are being processed into crisps (Miranda & Aguilera, 2006). Before it is served in the form of crisps, there are many treatments applied to the potatoes. The treatments include specific slicing, frying, drying, and seasoning to enhance the quality of potato crisps such as taste, aroma, crispness, and visual appearance (Pedreschi, 2012).

In accordance with its name, crisp has its prevailing property, which is crispness (Zampini & Spence, 2004). Crispness is widely described as the quality of being pleasingly crackly and producing satisfying sound emission when the crisp is bitten (Saeleaw & Schleining, 2011). Crispness also shows the customer about the quality of the crisp, including the use of fresh ingredients, fine cooking process, and proper storing method (Taniwaki & Kohyama, 2012).

Although it is a vastly known as enjoyable property of crisp, the judgement of crispness is still subjective among people. The word crispness itself is defined differently among consumers, dictionaries, and researchers (Tunick et al., 2013). In general, crispness is defined as brittle and firm characteristics of dry food. The definition of crispness from the dictionaries includes: "the quality of being firm, dry, and brittle, especially in a way considered pleasing" (Oxford Dictionary); "the quality of being fresh, firm, and pleasant to eat" (Cambridge Dictionary); and "the quality of being easily crumbled" (Merriam-Webster Dictionary). From the researchers' perspectives, the description of crispness includes: "a complex failure mechanism in continuous deformation during the chewing process" (Barrett & Peleg, 1992), "the ease of fracture or brittleness of food structure when it is forced until it breaks into pieces" (Tunick et al., 2013), and "firm and brittle, snaps easily, emitting a typical sound upon deformation," (Szczesniak, 1988).

Those different definitions of crispness makes the meaning of crispness very qualitative and subjective. This distinctive interpretation of crispness drives researchers from many branches of science to study the characteristics of crisps that is potential to be the parameter to quantify crispness. In the branch of food engineering, the observation includes the crisps cracks during mastication (Taniwaki & Kohyama, 2012). In the branch of rheology, the study includes the fracturability of crisps and how human mastication perceives the crushing process of it (Nishinari, 2004) (Kayader & Singh, 1999). In the branch of material texture study, the investigation includes the crisps breakdown stages in the mastication process. In addition, it also studies the correlation between structure and mechanical behavior of crisps (Chanvrier, Jakubczyk, Gondek, & Gumy, 2014).

In the scope of material science and engineering, every material has its own mechanical properties, including the properties that are obtained from the stress and strain curve, such as the stiffness, tensile and compressive strengths, and toughness (Triawan, Nandiyanto, Suryani, Fiandini, & Budiman, 2021) (Nandiyanto et al., 2021). Like other solid materials, dry foods, such as potato crisp, also has its own mechanical properties and behavior. Thus, analyzing its stress and strain curve obtained from compression test is often used to effectively understand its mechanical properties and behavior, including its crispness characteristics (Varela, Salvador, & Fiszman, 2008) (Aprilia, Triawan, & Saville, 2021).

Table 1. Mechanical tests to measure crispness

No.	Technique	Conditions	Measurement	References
1	Spherical probe test	¼ in diameter spherical probe, constant speed 1mm/s	Number of peaks in force-displacement curve	(Salvador, Varela, Sanz, & Fiszman, 2009)
2	Three-point bending test	Constant speed 2mm/min	Fracture work, ratio of total force drops and total length of fracture path	(Vincent, 2004)
3	Three-point bending test	Jig span 15mm, constant speed 1mm/min	Yield strength, Weibull modulus	(Rojo & Vincent, 2009)
4	Puncture test	2mm diameter puncture probe, constant speed 40mm/s	Average puncturing force, the ratio between sum of force drops to the number of peaks	(Van Hecke, Allaf, & Bouvier, 1998)
5	Puncture test	5mm diameter puncture probe, constant speed 60mm/min	Length of force-displacement curvature	(Arimi, Duggan, O'Sullivan, Lyng, & O'Riordan, 2010)
6	Tensile tests	Specimen dimension: 5mm wide and 15mm long, glued to two tension plates	Fracture toughness, Weibull modulus	(Rojo & Vincent, 2009)
7	Compression test	Flat plate, constant speed 60mm/min	Force magnitude at the first breakdown	(Varela et al., 2008)

From the previous studies, there are many existing techniques to identify mechanical properties of dry food. Due to its random and variety in shapes, identifying the mechanical properties of dry foods becomes a challenge to many researchers. There are several mechanical tests that have been reported in the previous works in order to quantify the crispness of dry foods as sumarized in **Table 1**.

In **Table 1,** crispness quantification carries certain complexities to perform, whether on the instrument, specimen setup, method conditioning, or the measurement parameter. For example, a study by (Varela et al., 2008) demonstrated a case of crispness measurement of roasted almonds by means of compression test. In this study, the load and displacement curve is analyzed to understand the fracture mechanism during mastication process in human mouth. Some mechanical parameters such as the area under the force-discplacement curve (which is translated as the total of work during mastication) and the number of force peaks (which indicates the fracture event in mouth) are investigated. As the result, the human perception of crispness shows a strong correlation with the area under the curve. However, the process of analyzing the data of those mechanical properties is considered as rather complicated and less precise. Hence, the previous study of crispness quantification is arduous, especially when it comes to a large number of samples. In addition to time consuming and expensive, the complexity of mechanical analysis to measure crispness by existing methods may lead to higher probability of committing miscalculation (Andreani et al., 2020).

Considering the above issues, therefore the objective of this study is to develop a simple alternative method of quantifying crispness of curved potato crisps using a single specimen compression testing. The potato crisps specimens with similar shape were prepared with various duration of moisture exposure contained in the ambient air. From the compression test result, the compression strain energy is calculated and deeply analyzed in order to precisely quantify the level of crispness.

The proposed method is expected to support local crisps manufacturers in measuring the crispness of their crisp products. Furthermore, the result of this method is expected to bring positive contribution to the field of food engineering and technology.

2. RESEARCH METHODOLOGY

2.1. Specimen Preparation

Potato crisps are served in many kinds of shape and size. In this study, a uniform shape of potato crisps is used to avoid the influence of geometry on the crispness. Therefore the Pringles® potato crisp product was chosen as the specimen because it has uniform shape. The dimension of major diameter, minor diameter, and height of all samples in this study are 54.20 ± 1.00 mm, 41.40 ± 0.70 mm, and 12.16 ± 0.60 mm, respectively (see **Figure 1**). The major and minor diameters of the crisp were measured by a caliper with 0.05 mm accuracy, both from the centerline of the crisp. The height of crisps was measured by placing the crisp between two flat plates and measuring the distance between plates using a caliper, as shown in **Figure 2**. In addition, the weight of the crisps was measured to be 1.51 ± 0.05 grams. This weight measurement was taken by using a balance with 0.01 g accuracy. The thickness of the crisp was not determined as a part of the dimensions measurements because thin specimen generally is delicate and difficult to be handled (Saptaji & Subbiah, 2013).

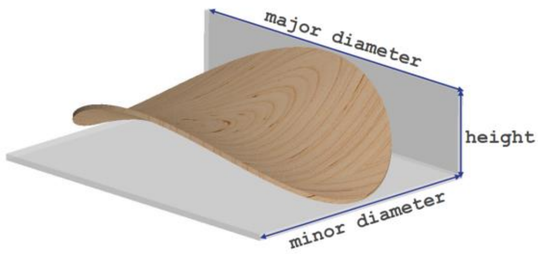


Figure 1. Typical shape of Pringles® crisp

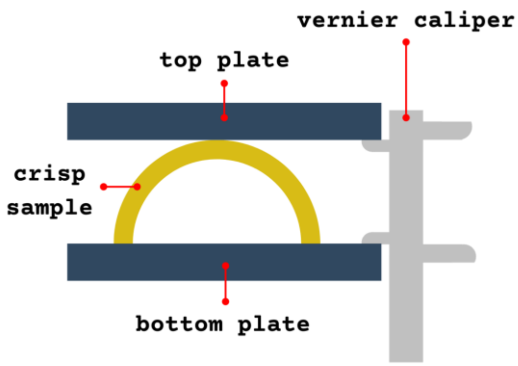


Figure 2. Measuring crisp height by using two flat plates

The samples were grouped and placed in a room for moisture exposure under variation of exposure duration. These settings are selected to mimic the major cause of crisps sogginess in daily practice (Hirte, Primo-Martín, Meinders, & Hamer, 2012)(Peleg, 2015). Initially, 9 samples were used to observe the compression behavior of crisps, with 3 crisps on 0 hour air exposure, 3 crisps in 1 hour air exposure, and 3 crisps in 2 hours air exposure. However, the data taken from this method could not show a significant crispness difference among the groups. Therefore, the air exposure duration was increased from 1 hour to 3 hours. In addition, for this purpose, the number of the sample was also added into 60 crisps for a more reliable data. Those 60 samples were equally divided into three groups, 20 in 0 hour air exposure (including 3 crisps that had been tested in a 1 hour increment sample cluster), 20 in a 3 hour air exposure, and the remaining in a 6 hour air exposure. The air condition was in 50% relative humidity and temperature of 18oC. The increment was set to be 3 hours to observe the key variable to indicate the crispness level of crisps.

2.2. Compression Test

The compression test was performed using the Test Resources 313 Universal Testing Machine with flat plates as the jig and crosshead (**Figure 3**). Compression test is generally performed to determine resistance of materials / structure to a crushing load. It can be used to optimize honeycomb structure by observing deformation behavior under compressive load (Octarina, Saptaji, & Kurniawan, 2021). The universal testing machine has a load cell with accuracy of 0.1 N. Prior placing the crisp, the surfaces of the compression plate are greased to minimize the effect of friction force on the compression result (Triawan et al., 2012). The machine's crosshead was set to move at a constant speed of 10 mm/s. The local overload value was set to 50 N to stop the machine when it compresses at 50 N. The 50 N load setting was used because the machine compresses the jigs beyond 50 N of force.

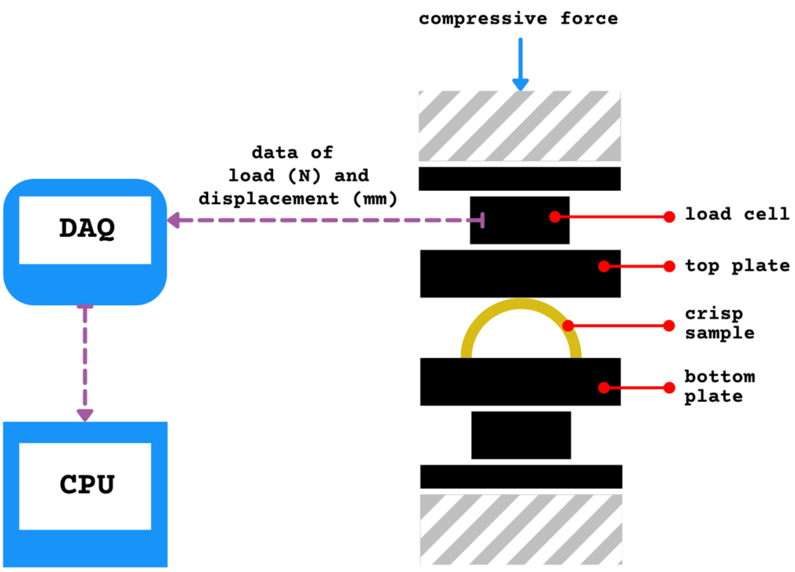


Figure 3. Schematic diagram of the compression test on crisp

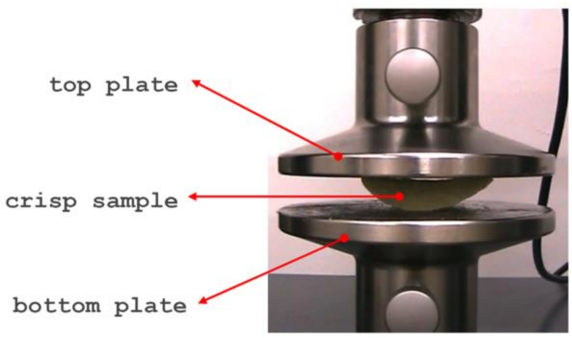


Figure 4. Positioning of crisp on compression plate (Aprilia et al., 2021)

After setting the machine and greasing the plates, a single crisp specimen was placed on the jig as shown in **Figure 4**. The position of crisp must be facing down, to let the crisp stand in balance by itself. Then, the compression test can be executed. The data in the form of load and displacement curve was directly collected from the machine's data acquisition system. Moreover, the number of crisp fragments after being completely compressed was also examined.

2.3. Data Analysis

The data analysis process started by converting the force-displacement data into stress-strain data. In dealing with this case, the principal formula of engineering-stress was applied. The cross-section area of the object was assumed to be in an elliptical shape, which has major and minor diameters (**Figure 1**). This approach was taken due to the homogeneity of the shape of samples (Triawan et al., 2021)(Nandiyanto et al., 2021). Therefore, the engineering stress formula can be written as:

$$\sigma = \frac{P}{A} = \frac{P}{\pi \frac{Dd}{4}} \quad (1)$$

where:

σ = stress, Pa

P = force, N

A = cross-section area, m^2

D = major diameter, m

d = minor diameter, m

Engineering strain formula was also applied to convert the displacement data into strain values. The height of the crisp was marked as the initial length of the specimen. Hence, the strain formula becomes:

$$\varepsilon = \frac{s}{h} \quad (2)$$

where:

ε = strain

s = displacement, mm

h = height of the sample, mm

In order to quantify the crispness precisely, the compressive strain energy was carefully investigated. First, integration of the stress-strain curve was performed to calculate the area under the curve, which represents the strain energy of a crisp or the work done to the crisp in mastication process. The integration process was conducted by calculating the area of trapezoidal space under the curve. Referring to **Figure 5**, the formula to gain the strain energy is:

$$U = \frac{\Sigma(\sigma_f + \sigma_i)(\varepsilon_f - \varepsilon_i)}{2} \quad (3)$$

where:

σ_i = initial stress, Pa

σ_f = final stress, Pa

ε_i = initial strain, Pa

ε_f = initial strain, Pa

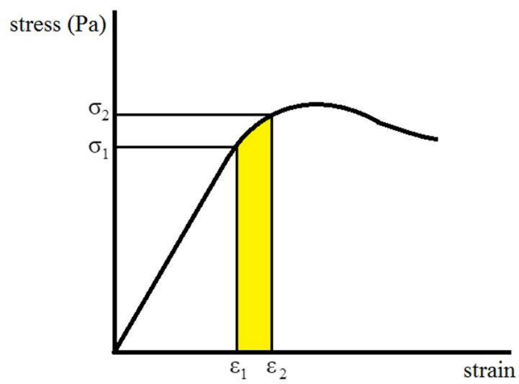
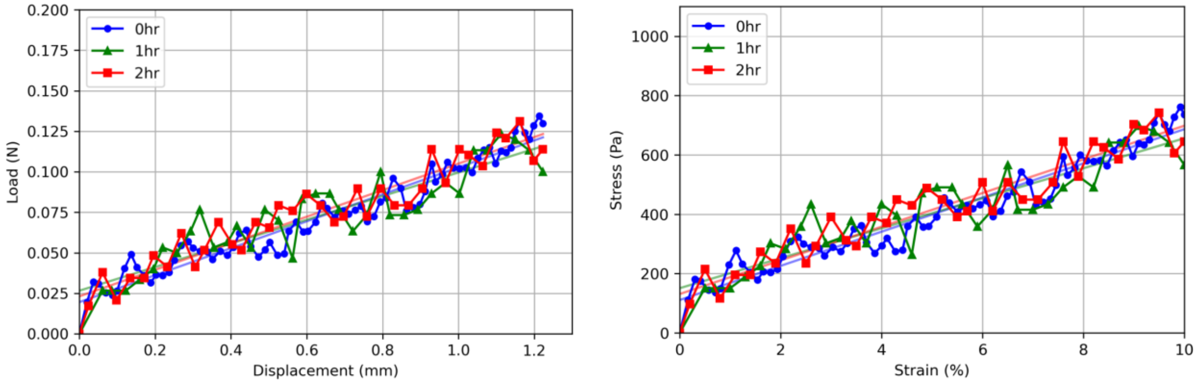


Figure 5. Trapezoidal space under the stress-strain curve

Along with data processing, statistical analysis is also conducted. In this study, one-way ANOVA F-Test and T-Test with a 95% significance level were performed to compare data from each group of samples.



(a) (b)

Figure 6. Typical compression test results of samples in 0, 1, and 2 hours air exposure, within 10% of strain. (a) the load-displacement curve, (b) the stress-strain curve.

3. RESULTS AND DISCUSSION

As the first step of calculating stress, the cross-section area of every crisp was calculated using the formula of elliptical area. By taking a total of 69 samples into account, it was found that the cross-section area is 1763.64 ± 7.00 mm^2.

Subsequently after completed all of the experiments, it was found that the crisps tend to break when the strain value exceeded 10%. It indicates that after 10% of strain, the crisp may experience complete fracture (brittle fracture). Due to the uncertainty of the ultimate strength, hence, the data in the 0-10% strain value was used to judge and compare the crispness of all samples from the compression test.

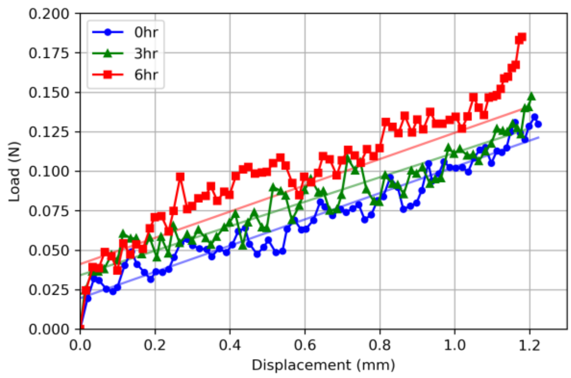
3.1. One-hour Increment of Air Exposure Duration

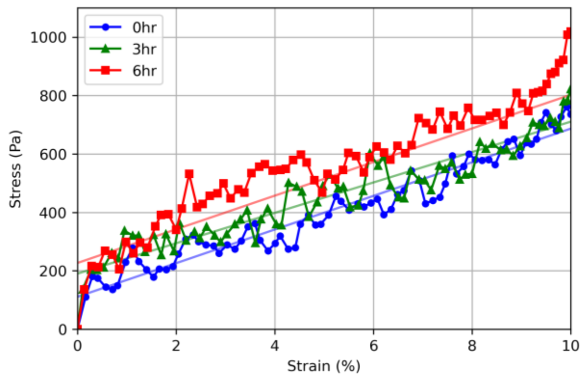
There are three groups of samples In a one-hour increment of air exposure duration. The stress and strain values of each group were presented by applying stress and strain formula to the load and displacement data. **Figure 6** shows the typical load and discplcement and stress-strain curves of each group of samples. The information in **Table 2** is extracted from the stress-strain curve in **Figure 6**. In the 1-hour increment of air exposure, it can be seen that no pattern can be observed in the peak force and peak stress as the air exposure duration is increased. Nevertheless, the slight increase in strain energy is observed when the air exposure duration is raised. This indicates that as the strain energy value increases, the crispness might have changed.

After performing F-Test to the strain energy values, the result shows that the difference between the sample groups of 0, 1, 2 hours is insignificant ($p = 0.061$). Therefore air exposure duration was increased along with the increase in the number of samples in order to see more significant differences of crispness between sample groups.

Table 2. Data gathered from 1-hour increment of air exposure duration (with standard deviation)

Air Exposure Duration	Peak Force (N)	Peak Stress (Pa)	Strain Energy (J)
0 hr	1.35 ± 0.50	761.09 ± 288.07	39.74 ± 13.56
1 hr	1.33 ± 0.35	754.87 ± 198.83	40.50 ± 4.46
2 hr	1.40 ± 0.36	881.27 ± 480.72	42.17 ± 13.05





(a) **(b)**

Figure 7. Typical compression test results of samples in 0 hr, 3 hr, and 6 hr air exposure, within 10% of strain. (a) load-displacement curve, (b) stress-strain curve.

3.2. Three-hour Increment of Air Exposure Duration

Figure 7 shows the typical load-displacement and stress-strain curves of each group of samples. Linear curve fitting was applied onto the graph to ease the comparison among each group of the samples. Based on the stress-strain curves, some parameters that can be extracted from the graph are the stress at the first breakdown, peak force, peak stress, and the strain energy. The summary of the compression test result can be seen in **Table 3**.

The graph on **Figure 7** shows that the samples with more air exposure duration have higher resistance towards compression. This is due to the fact that the constant of the linear-fit equation increases following the increase of air exposure duration. The rise of the stress resistance in the longer duration is caused by the thickening of the crisp cellular wall due to moist air insertion to its cell, making the crisp become tougher and difficult to compress (Peleg, 2015).

Next thing to be considered is the stress magnitude at the first breakdown. Curve first breakdown is described as the first stress drop on the stress-strain curve, indicating the appearance of the first microcrack of the crisp. In the case of Pringles® crisps, the first breakdown appears between 0.25% and 0.5% of strain. It can be noticed that stress magnitude at the first breakdown is higher when the air exposure duration increases. Yet, the difference of their value is insignificant. This implies that the data is sensitive and can be easily disturbed by many factors such as the noise from the load cell, machine vibrations, and the data acquisition system of the machine.

Peak force and peak stress are tightly correlated to each other. **Table 3** shows that longer air exposure duration leads to higher peak force and peak stress. Indeed, the result of peak force and peak stress in this 3 hour increment of air exposure duration makes a noticeable pattern. In contrast, the result of peak force and peak stress in 1 hour increment of air exposure duration fails to make a clear pattern. This implies that in the case of crisps with slight crispness different, the method of comparing peak force and peak stress to determine the level of crispness is weak. Therefore another certain parameter also needs to be considered to support the measurement of crispness.

Table 3. Data gathered from 3-hour increment of air exposure duration (with standard deviation)

Air Exposure Duration	Linear-Fit Equation (ax+b)	Stress at the First Breakdown (Pa)	Peak Force (N)	Peak Stress (Pa)	Strain Energy (J)
0 hr	57.6x + 111	180.98 ± 39.82	1.35 ± 0.50	761.09 ± 288.07	39.74 ± 13.56
3 hr	52.7x + 189	203.58 ± 34.61	1.58 ± 0.20	877.86 ± 115.17	45.25 ± 6.61
6 hr	67.2x + 226	216.25 ± 49.74	1.98 ± 0.52	1094.34 ± 286.72	55.51 ± 10.67

Alongside with the previous parameters, strain energy is also an important parameter to consider in quantifying crispness. Both in 1 and 3 hours increment in **Table 2**, the strain energy showed a noticeable change indicates a correlation with the crispness change. As the duration of air exposure increases, the strain energy is also increased. This relation indicates that reduction of crispness level can increase the strain energy amount in a crisp. A higher strain energy implies that the material tends to be more ductile. In this case, crisps are being chewier (soggy) once their crispness is reduced.

In the 3-hour increment of air exposure duration, the calculated strain energy at 10% strain of each group of samples exhibits a significant difference. However, there is still a probability of having a more significant difference in strain energy value at the earlier stage of strain (before 10%). To see whether the strain energy is more effective to be used at the earlier stage, the value is calculated at every strain increment of 1%. The result of breaking down the strain energy at every 1% strain increament is presented in **Table 4**.

The strain energy values from 1% to 3% are fluctuating in each group of samples (**Table 4**). Then, the value of strain energy has an increasing trend starting from 4% of strain. Although the strain energy difference between groups at 4% strain is still minor, that point is considered as the earliest stage where one can utilize the strain energy as the key parameter in measuring the crispness. Nevertheless, this percentage may vary depending on the experimental conditions, such as the compression testing machine (type of load cell, jigs, etc.) and the type of specimen (materials type). Here, the accuracy level of the load cell may also affect the result. Machines with higher accuracy are able to detect the smallest force shift, so the pattern of strain energy value can be seen earlier on the lower strain percentage value.

Furthermore, based on the ANOVA T-Test with 95% significance level, it is found that in 8% of strain, the strain energy is significantly increased as the rise of air exposure duration. Accordingly, 8% strain is the optimum point to measure crispness through strain energy. Also, in 8% of strain, the level of crispness is found to severely decrease after 3 hours of air exposure.

The percentage of crispness reduction at 8% strain can be calculated by performing percent difference computation on strain energy. The result of calculation shows that crispness level is reduced by 17.6% from 0 to 3 hours of air exposure, and it is further reduced by 45.7% from 3 to 6 hours of air exposure.

Table 4. Strain energy of each group of specimens based on strain percentage

Strain Percentage	Strain Energy (J)		
	0-hr	3-hr	6hr
1%	1.441 ± 0.40	2.206 ± 0.49	2.189 ± 0.56
2%	3.682 ± 0.90	5.167 ± 1.18	4.539 ± 1.26
3%	6.596 ± 1.63	8.428 ± 1.81	8.243 ± 2.54
4%	9.775 ± 2.42	12.049 ± 2.32	12.460 ± 3.92
5%	13.086 ± 3.53	16.582 ± 3.13	16.612 ± 5.20
6%	17.325 ± 4.59	21.335 ± 3.76	21.667 ± 6.24
7%	23.190 ± 6.65	26.460 ± 4.23	26.485 ± 7.61
8%	27.135 ± 8.40	31.916 ± 4.97	39.539 ± 6.62
9%	32.859 ± 10.84	38.109 ± 5.95	46.863 ± 8.67
10%	39.745 ± 13.56	45.247 ± 6.61	55.609 ± 10.67

Accordingly, the strain energy can be judged to be a suitable parameter to determine the level of crispness. At 10% of strain, the strain energy is consistently increasing both in the case of 1 hour and 3 hours increments of air exposure duration. This implies that the method of comparing strain energy at the certain percentage is applicable for any cases, even when the crispness differences between samples are very slight. In addition, the comparison of strain energy among groups of samples can quantitatively measure the crispness drop of the crisps.

Figure 8 shows the pictures of fractured specimens after test. The number of crisp fragments were counted to observe the effect from crispness level. Evidently, crisps with lower air exposure duration have more fragments after being compressed. Here, the 0 hr group has 8.7 ± 3.03 fragments, the 3 hr group has 5.4 ± 0.88 fragments, and the 6 hr group has 3.4 ± 1.09 fragments. This phenomenon is supported by the result of ANOVA F-Test with $p < 0.0001$, indicating the number of fragments is significantly different among the group of samples. Through the number of fragments, it can be said that the crisps of 0 hr group are the most brittle group than crisps on the other group, because brittle material produces more fragments when it breaks.

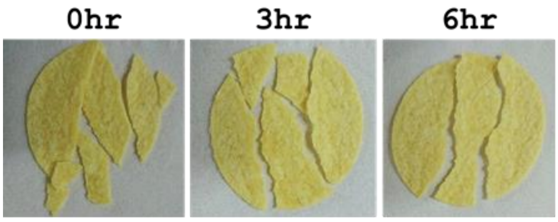


Figure 8. Crisps fragments after being completely compressed

4. CONCLUSION

This study presents a quantitative measurement method of crispness of dry food products by single specimen compression test. The crisps sample was taken from Pringles® potato crisps which has a uniform shape. The proposed method is proven to be effective in precisely measuring crispness of curved potato crisps. The calculated strain energy at a certain stage is able to show the level of crispness and quantify the percentage of crispness drops due to air exposure. To be specific, as the crispness level declines due to moist air exposure, the strain energy of the crisp becomes higher. Along with the employed machine specification and the load cell ability to detect force, the strain energy can be utilized to distinguish the change of crispness starting from 4% of strain, and optimally after 8% of strain. In addition to the strain energy, the number of crisp fragments after being completely crushed is also affected by its crispness level. The crisps with higher crispness level exhibit more fragments after compression test.

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