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Texture Modification of 3D-Printed Maltitol Candy by Changing Internal Design

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Abstract: The purpose of this study is to show more diverse texture modifications by changing the material of a food 3D-printed structure conducted only with soft materials (in this case, potatoes and chocolate) to a hard material (in this case, maltitol here). However, unlike previous 3D-printed food materials, sweetener materials such as sucrose and maltitol are sensitively caramelized at a high melting temperature. As such, there is no commercialized printing equipment. Therefore, a printing process experiment was conducted first in this case. To do this, a high-temperature syringe pump-based extrusion device was designed, and process tests according to the temperature and environment were conducted. An assessment of the internal structural changes according to the infill patterns and infill percentages was conducted based on the acquired process conditions. The texture strength increased as the infill percentage increased. Depending on the infill patterns, the texture strength increased in the order of the Hilbert curve, honeycomb, and rectilinear samples here. As a result, a change in the texture strength was determined through a change in the internal structure of a hard food material using 3D printing, which showed a wider range of change than in conventional soft food materials.

Keywords: food 3D printing; maltitol 3D printing; 3D-printed candy; internal design; texture modification

1. Introduction

3D printing technology is widely used in the production of various prototypes and special-purpose parts because it has the advantage of being able to manufacture parts with complex structures into three-dimensional shapes simply by designing them [1–3]. Accordingly, application areas of 3D printing technology are gradually expanding, and its importance is increasing in various industries such as mechanics, architecture, electronics, medical care, and food [4–7]. As such, as the scope of applications of 3D printing technology is gradually increasing; attempts are actively being made to manufacture structures that can actually be used based on various materials beyond simple shape production. These attempts have had a significant impact on the food industry in recent years. Therefore, food 3D printing that actually creates edible food is being studied in various ways. 3D printing in the food industry is not only used for colorful shapes and decorations but also has a very high functional value because it can provide various textures and appropriate nutrients to the underprivileged in society who have restrictions on their food intake [8,9]. Among the various 3D printing types, the methods mainly used for food printing can be divided into two types: powder-based methods and high-viscosity-gel-based extrusion methods. Given that many types of food materials such as vegetables and fruits, as well as sugar and flour, can easily be produced in powder form, there may be a method by which to form a shape by applying powders of these ingredients individually and thinly and then locally melting the powders with a high-power laser.
or a high-temperature heat source [10]. Alternatively, a food printer that can realize full-color 3D structures using various food powders and edible liquid adhesives was also introduced [11]. However, these powder-based printers have limitations in terms of materials and equipment. Accordingly, numerous attempts to realize food printing using an easy-to-use extrusion-based method have been made.

Extrusion-based food printing requires a simple equipment structure and has almost no material restrictions. Therefore, printing examples for various foods such as chocolate, burritos, pasta, cheese, and pizza have been introduced [12–15]. In addition, recent studies have attempted to observe changes in strength and texture levels by changing the internal design rather than merely making simple shapes. With regard to the existing 3D printing methods using metals or polymers, many studies have concentrated on making various mechanical strength changes through internal structural designs considering the material properties [16–18]. These designs for additive manufacturing (DfAM) studies are emerging as very important in the 3D printing field. Recently, there have been various attempts to study changes in mechanical strength and texture outcomes according to changes in internal design in food printing as well. First, one study investigated various textural and strength changes using mashed potatoes by changing the internal design [19]. By modifying the infill percentage (10%, 40%, 70%, and 100%) with different infill patterns (rectilinear, honeycomb, and Hilbert curve) and variations in the shell perimeter (3, 5, and 7 shells), printed foods of the same size and material could be manufactured, but with different textures. As a result, various firmness values from 25.15 g to 144.81 g were obtained, depending on the manufactured structure. Another study assessed textural changes using a slightly harder material: chocolate [20]. These researchers measured the breaking force in each case by varying the type of chocolate, the infill percentage, and the infill pattern. As a result, it was shown that it is possible to change the texture of chocolate using various break forces ranging from 1.9 N to 114 N, depending on the material and shape.

As mentioned above, there have been several studies on the texture change of 3D-printed structures, but most have been limited to soft materials that can be easily chewed with teeth. Therefore, this study intends to examine changes in textures based on a sweetener material, which is a favorite food of many people, but also is one used as a main ingredient in very strong and hard candy. These sweetener-based materials are hard materials with excellent aesthetics because they are generally excellent in terms of transparency and can easily realize a range of colors when they are melted and then solidified properly. Although general candy is hard enough to cause tooth damage, cotton candy made of the same material but with a very high internal porosity is soft enough for anyone to chew. Therefore, if 3D-printed candy with various internal designs is manufactured based on the hardness properties of these sweetener-based materials, a much wider range of strength changes can be expected compared to soft materials. However, sweetener-based materials generally have a high melting point and are easily caramelized at high temperatures, meaning that it is very difficult to 3D print them into precise shapes with complex internal structures while ensuring that the taste and transparency match those of general candy.

Recently, many 3D-printing studies and applications using these sweetener-based materials have been introduced. When sucrose, a typical sweetener material, is melted alone, it is very difficult to control the printing due to problems such as a volume reduction caused by voids, temperature imbalances due to the low thermal conductivity, and rapid caramelization and carbonization. Therefore, most studies have relied on a sugar glass material made by mixing sucrose, liquid glucose (corn syrup), and water to lower the melting point of sucrose, making it easier to manufacture. However, although the melting point is reduced as water is added, it is almost impossible to control the extrusion because it boils easily as the water vaporizes at a temperature that allows extrusion. Accordingly, Leung attempted to print while continuously evaporating the water vapor generated through an open heating vat [21]. Through this, 3D printing was possible while continuously supplying and melting a large amount of material, but due to the lack of a forced extrusion
device stemming from the use of the open vat, it was impossible to control the extrusion amount, meaning that the line width approached 10 mm and precise shape control was impossible. Therefore, in most other studies, 3D printing was performed by sufficiently heating in advance to evaporate most of the water in the sugar glass, with the material then injected into a syringe-type extruder [22–24]. Through this, it was possible to manufacture a relatively precise micro-shape with a minimum line width of about 0.7 mm; however, caramelization occurred due to excessive heating to remove water vapor, which resulted in deterioration of the transparency and color changes. Therefore, due to the change in color and taste caused by caramelization, most previous studies used this 3D printing technology for the production of stents or microfluidic mixers rather than using them to create food. Therefore, thus far, there have been few studies of sweetener 3D printing premised on edible food, and there has also been no study on textures according to the printing structures of hard materials such as sweeteners.

Therefore, this study aims to manufacture 3D-printed candy based on sweetener materials that are edible while also ensuring excellent transparency and aesthetics. To this end, the entire process from selecting a material suitable for printing with excellent transparency to developing equipment and processes for precision printing will be carried out. In addition, through the proposed process, we seek to observe the change in the texture of the 3D-printed candy due to the change in the internal design.

2. Materials and Experimental Setup

2.1. Materials

Sugar generally means sucrose, which is a disaccharide composed of fructose and glucose. Sucrose melts at about 186 °C; before that, it decomposes into fructose and glucose, which is easily oxidized and caramelized [7]. When oxidized caramelization of sucrose occurs, as shown in Table 1, it turns dark brown and has a bitter taste and is thus not suitable as a food. Therefore, in order to manufacture candy while maintaining the taste and transparency of sugar, water and corn syrup are added to sucrose to lower the glass transition temperature (Tg) and crystallization temperature (Tc) of the sucrose mixture [25,26]. However, in order to harden like candy, it must be boiled at a high temperature and then cooled. At this time, as the sucrose mixture exceeds the boiling point of water (100 °C), expansion occurs at the point of boiling. Therefore, in previous studies, a method such as putting a pre-melted sucrose mixture into an open vat and extruding it by its own weight was mainly used [21]. However, in this case, it was impossible to manufacture a precise structure because it was difficult to control the extrusion amount through a small diameter. In addition, for rapid crystallization after extrusion, the mixture should be boiled at a high temperature of about 150 °C. At this time, some caramelization occurred, resulting in a light brown color. Therefore, maltose and maltitol are food substances that can be used as substitutes for sucrose with relatively low levels of oxidized caramelization.

Table 1. Characteristics of various sweeteners.

| Raw materials | Sugar Glass | Maltose | Maltitol |
|---------------|-------------|---------|----------|
| Color after melting | Sucrose Brown | Sucrose + Water + Syrup Transparent | Maltose White | Maltitol Transparent |

Maltose has a relatively low melting point and is a very stable material for oxidation, but it has the disadvantage of being expensive and not being transparent when melted. On the other hand, in the case of maltitol, as shown in Table 1, when melting, it can maintain a very transparent state and, at the same time, is relatively inexpensive. Therefore, it
was judged to be suitable as a candy material instead of sucrose. In addition, maltitol is a substance widely used as a substitute for sucrose in many foods because it offers the advantage of blood sugar management due to its low absorption rate by the body. Therefore, in this study, D-maltitol (D-maltitol, MC-Towa International Sweeteners Co., Ltd., Rayong, Thailand) powder was used as a raw material for the 3D-printed candy.

2.2. Material Extruder

For smooth melting and extrusion of maltitol, it is essential to use an extruder capable of withstanding high temperatures/high pressures. Because the melting point of maltitol is 148 to 151 degrees Celsius, there should be no structural deformation at temperatures that exceed these levels, and the extruder should be made of a material that does not generate harmful substances at high temperatures to be used for food printing. Accordingly, all parts of the extruder that come in direct contact with maltitol consisted of only materials widely used in food equipment. Therefore, as shown in Figure 1, a stainless steel syringe (Stainless Steel Syringe 100 mL, Fhis Dispensing Store, Yuhuan, China) and a piston head with a capacity of 100 mL were used for the precise extrusion of the materials. In addition, a double O-ring structure was adopted to prevent leakages when extruding the maltitol material. The O-ring (NPS, Misumi, Tokyo, Japan) used was made of a silicon rubber material for food; it was safe and could be used up to 200 °C, enabling stable extrusion. In the front part of the syringe, a medical stainless steel nozzle with an inner diameter of 0.61 mm (20 G, Needle Store, Bucheon, Korea), as shown in Figure 1c, was machined and mounted.

![Figure 1](image-url)

**Figure 1.** Photographs of (a) the material extruder, (b) the piston head, and (c) the nozzle.

Given that maltitol is a material with a high melting point and that its properties change greatly with the temperature, it is very important to maintain an appropriate temperature during the printing process. Therefore, in this study, a heating block was manufactured using aluminum 6061, which has excellent thermal conductivity and is easy to process, to keep the temperature of the entire extruder part constant and to effectively heat it. It was then mounted in close contact with the syringe pump and nozzle part. Six ceramic cartridge heaters (12 V/40 W, Nasspop, Incheon, Korea) and two K-type thermocouples were installed at the Al heating block for quick and uniform temperature control. A PID controller (CNT-P500, Conotec Co., Busan, Korea) was used to control the configured heating block at a precise temperature. In addition, a ceramic fiber insulating material was attached to the outside of the heating block to maintain the temperature during extrusion and to minimize the external heat loss. Polyurethane paint, suitable for high temperatures, was additionally applied to the surface to improve the durability of the ceramic fiber insulator.

In order to extrude the melting maltitol precisely, given its viscoelasticity, instead of the pneumatic extrusion method, which is sensitive to the temperature and pressure, a method in which a syringe piston head was directly pushed with a motor to control the extrusion amount through position control was used. To provide sufficient extrusion torque, a 0.8 Nm two-phase hybrid stepper motor (17HS2310-P4120, GKTOOLS, Shenzhen,
China) was used, and a microstep driver (A4988, Sparkfun, Boulder, CO, USA) was used for current supply and position control. In addition, a 2:1 spur gear reducer was used to increase the extrusion torque. Then, for linear motion, a lead screw with a diameter of 8 mm, a pitch of 2 mm, and a lead of 8 mm/rev was attached to each output gear to make a linear feed, and a linear motion (LM) guide was additionally installed for precise linear motion.

2.3. Experimental Equipment

The manufactured extruder was composed of a heating block and an insulating material for uniform temperature maintenance and precise control. Accordingly, it was much heavier than the extruder part of a general 3D printer. Therefore, as shown in Figure 2a, biaxial x-y movement was implemented based on the H-bot structure, which is advantageous for vibration and the load distribution. In addition, in order to minimize the moment due to the weight of the extruder, a double LM rail structure was used, as shown in Figure 2b. To drive each axis, an easy-to-control two-phase stepper motor (Nema17 5.0, Aplus, China) was used, with current supplied with a sixteen-microstep resolution driver (A4988, Aplus, China). The Z axis, which corresponds to the printing bed, was manufactured to be vertically moved under the X and Y axes. The maximum printable area of the manufactured equipment is 70 × 70 × 100 mm in size.

![Figure 2](image_url)

**Figure 2.** Candy 3D printer: (a) front view, (b) top view.

The sensor and motor of the printer were controlled through a connection to MKS integrated board based on the Arduino Mega 2560 board (MKS GEN V1.4, Lankeda, Shenzhen, China). As the operating software, Marlin firmware, an open-source software widely used in fused deposition modeling (FDM) printers, was partially modified and used.

2.4. 3D-Printed Candy

Based on the fabricated candy 3D printer, standard specimens for the texture test were manufactured under the conditions obtained after performing a basic process test. The standard specimen for the texture test was manufactured in the form of a square with a cross-sectional shape of 40 mm in width, a length of 40 mm, and a height of 10 mm. For the infill pattern, among the options provided by Slic3r, three commonly used structures were used, as shown in Figure 3: a rectilinear structure, a honeycomb, and a Hilbert curve. The infill percentage for printing was changed to 10%, 35%, and 60%. Also, for a valid comparison with general candy, completely melted maltitol was poured into a mold of the same size as the 3D-printed specimen and hardened to produce a casting candy specimen.
Figure 3. 3D design in the form of a square with a side length of 40 mm, with various internal designs.

2.5. Textural Testing Method

The measuring instrument was manufactured as shown in Figure 4, with reference to the analysis equipment (Model TA-XT plus, Stable Micro Systems, Godalming, UK) mainly used in previous texture research. However, because maltitol is a brittle material, instead of the TA-42 knife blade type widely used in studies of soft materials such as chocolate, a round bar blade with a diameter of 5 mm was manufactured, referring to Shimadzu’s cookie strength measuring instrument [27]. The printed candy specimens were placed horizontally on two round-bar support structures with a diameter of 10 mm and distance of 30 mm. To measure the texture, the flexural force was measured based on a three-point bending test. To do this, a load cell (SBA-25L & SBA-100L, CAS, Yangjoo, Korea) with a measurement resolution of 1/3000 or less was mounted on the upper blade. All experiments were conducted at the same room temperature of 25 degrees Celsius regardless of the shape of the specimen, and the test was conducted at a constant feed rate of 0.8 mm/s. All specimens were measured at a similar position by placing the blade in the center of the specimen as much as possible, and the flexural force according to the blade feed was measured.

Figure 4. Compression tester.
3. Extrusion Process

3.1. Extruder Temperature

In 3D printing, the extrusion temperature and the viscosity of the material are inversely proportional such that the temperature has a strong effect on the printability of a material extrusion (ME) type of 3D printer. In order to determine the optimal printing temperature of the maltitol material, experiments were conducted at various extrusion temperatures. The melting point of maltitol as reported by the manufacturer is 148–151 °C, but the glass transition temperature is 43 °C, which is clearly lower [28]. In general filament-based 3D printing, extrusion is performed without completely melting the material to increase the precision of the laminated structure. Therefore, in this experiment, the extrusion test was performed while increasing the extruder temperature by 10 °C from 130 °C, lower than the melting point. The thermal conductivity of maltitol in the liquid phase is as low as 0.36 to 0.46 W/m-K and is even lower in the solid powder state. Therefore, in order to maintain all of the material at a uniform temperature, the extruder part was sufficiently maintained at the test temperature for 5 h or more in a convection oven (Thermo Stable OF-105, Daihan Scientific, Wonju, Korea).

As shown in Figure 5, at a temperature of 140 °C or less, maltitol melting was incomplete despite heating for a sufficient time such that the extrusion was not uniform and was irregular, in the form of small lumps. On the other hand, at 160 °C, higher than the melting temperature, very stable extrusion was achieved, but slight caramelization was observed. For foods such as candy, very important aspects are not only the taste but also the aesthetic quality to the extent that there is the expression “Eat with your eyes” [29]. Therefore, caramelization, which is inevitably generated during the heating process of a sweetener, is a fatal defect not only in terms of taste but also in terms of aesthetics. However, at 150 °C, close to the melting point of maltitol, it was possible to manufacture a stable printed structure while maintaining relatively high transparency, even after a long-term experiment. Therefore, in this study, the optimal extrusion temperature was set to 150 °C, and the experiment was carried out.

Figure 5. Printed specimens according to the extrusion temperature: (a) 130 °C, (b) 140 °C, (c) 150 °C, (d) 160 °C.

3.2. Chamber Condition

When printing a structure by solidifying a high-temperature material, the environment inside the chamber changes the cooling rate during the process, thereby affecting the precision of the structure. In particular, maltitol as used in this study has high solubility in water and is thus affected not only by the temperature but also by the humidity. In order to determine the appropriate environmental conditions for maltitol 3D printing, an experiment was conducted while changing the temperature and humidity of the chamber.

3.2.1. Chamber Temperature

The experiment to determine the proper chamber temperature during printing was carried out by increasing the maltitol in 10 °C steps to the temperature at which glass transition occurs based on a room temperature of 26 °C. At this time, the relative humidity was maintained at 20% to minimize the effect of humidity. As a result of the experiment,
as shown in Figure 6, although the internal temperature was raised to 46 °C, which is higher than the glass transition temperature, there was little effect on the printed result. That is, the chamber temperature did not have a significant effect on the experiment in the general temperature range. Accordingly, the other experiments were carried out at a room temperature of 26 °C.

![Figure 6](image_url)

**Figure 6.** Printed specimens according to the chamber temperature: (a) 26 °C, (b) 36 °C, (c) 46 °C.

3.2.2. Chamber Humidity

Maltitol, an edible material, has very high solubility in water, similar to common sweeteners. Therefore, the experiment was conducted while increasing the humidity by two times from 20%, which was the lowest humidity that could be reached using a dehumidifier at a room temperature of 26 °C. As shown in Figure 7, it was confirmed that the printed structure maintained its shape well when the chamber humidity was 20%. At a chamber humidity of 40%, the overall shape was printed well, but the thin outer wall of the printed structure was slightly melted and the appearance was uneven. In addition, when the humidity of the chamber was forcibly increased to 80% using a humidifier, the outer wall of the printed structure reacted with the surrounding moisture and melted, making it impossible to print in the desired shape. Therefore, in this study, the experiment was conducted by maintaining the chamber humidity at 20% for stable printing.

![Figure 7](image_url)

**Figure 7.** Printed specimens according to the relative humidity of the chamber: (a) 20%, (b) 40%, (c) 80%.

3.3. Syringe Piston Feed Rate

It is very important to control the extrusion amount properly in order to create a stable structure. If the extrusion amount is insufficient at a general ME-type 3D printer, the line width is thinner than the nozzle diameter, meaning that the extrusion amount becomes non-uniform. Due to this, the bonding force between the extruded lines is insufficient during 3D printing, making it difficult to maintain the 3D shape. On the other hand, if the extrusion amount is excessive, the material is extruded in a spread form, resulting in poor shape precision and a large motor load during the extrusion process.

In 3D printing, the extruded line width is affected by the nozzle diameter, layer height, printing speed, and syringe piston feed rate. Based on the nozzle diameter used in this study and the Slic3r manual, the layer height and theoretical extrusion width were set to be 0.2 mm and 0.67 mm, respectively [30]. However, the actual extruded shape is formed when the material is pressed by the nozzle, as shown in Figure 8. Therefore, if the
theoretical extrusion line width (b) of 0.67 mm is changed to the actual observed extrusion line width ($b_T$) using the formula shown in Equations (1)–(3), it should be 0.71 mm [31]. The printing speed used in previous chocolate printing studies was 300–700 mm/min, but in this study, the extruder part became quite heavy due to the weight of the insulating material. Therefore, the printing speed was determined to be 300 mm/min [32]. The extruded line width was observed while increasing the feed rate by 0.01 mm/min from the calculated syringe piston feed rate of 0.07 mm/min. As a result, as shown in Table 2, it was observed that the line width increased according to the piston feed rate. Given these findings, the piston feed rate was determined to be 0.08 mm/min to achieve an actual observed extrusion line width ($b_T$) of 0.71 mm.

\[
bh = b_c h + b \left( \frac{h}{2} \right)^2. \tag{1}
\]

\[
b_c = \frac{bh - \left( \frac{\pi h^2}{4} \right)}{h} = b - \left( \frac{\pi}{4} \right) h \tag{2}
\]

\[
b_T = b + \left( 1 - \frac{\pi}{4} \right) h \tag{3}
\]

**Figure 8.** Photograph of the extrusion width for (a) the software and (b) the real 3D printing for a single wall.

| Piston Feed Rate (mm/min) | Microscope Image | Line Width (mm) |
|---------------------------|------------------|-----------------|
| 0.07                      | ![Image](image1.png) | 0.67            |
| 0.08                      | ![Image](image2.png) | 0.71            |
| 0.09                      | ![Image](image3.png) | 0.74            |

**Table 2.** Extruded line width according to piston feed rate.

4. Texture Test of 3D-Printed Candy

4.1. Printing Stability of the Selected Process

Specimens with different infill patterns (rectilinear, honeycomb, and Hilbert curve) and infill percentages (10%, 35%, and 60%) were manufactured using the process conditions in Table 3 obtained through the experiment, as shown in Figure 9. In addition, a cast
sample was produced as a comparison group. The manufactured specimens did not show any particular problems when visually observed, except for an unintentionally extruded diagonal line. This unintentionally extruded diagonal line was observed in most of the specimens. This is inevitably generated due to the nature of the movement path generation of the extruder part according to the infill pattern during printing. However, because the unintentionally generated diagonal line was very thin and there was concern about damage to the manufactured internal structure when it was removed after printing, an additional post-processing step was not performed.

Table 3. Experimental parameters.

| Parameter            | Unit | Value |
|----------------------|------|-------|
| Nozzle diameter      | mm   | 0.61  |
| Layer height         | mm   | 0.2   |
| Printing speed       | mm/min | 300   |
| Extruder temperature | °C   | 150   |
| Chamber temperature  | °C   | 26    |
| Chamber humidity     | %    | 20    |
| Piston feed rate     | mm/min | 0.08  |

Table 4. Void fraction of different infill patterns.

| Infill percentage | Rectilinear | Honeycomb | Hilbert curve |
|-------------------|-------------|-----------|---------------|
| 10%               | ![Image](image1) | ![Image](image2) | ![Image](image3) |
| 35%               | ![Image](image4) | ![Image](image5) | ![Image](image6) |
| 60%               | ![Image](image7) | ![Image](image8) | ![Image](image9) |
| Cast sample       | ![Image](image10) | ![Image](image11) | ![Image](image12) |

Figure 9. 3D-printed candy samples.

For a quantitative evaluation of the printed specimens, the size and weight were measured and the void fraction was calculated, as shown in Table 4. All specimens were designed with a rectangular parallelepiped structure of $40 \times 40 \times 10$ mm and then printed. As a result, there was only an error of about 2% between the design dimension and the measured dimension, demonstrating that the fabricated candy 3D printer operated reliably when considering the nozzle diameter. However, with regard to the height, an error of up to 6% was noted because some damage occurred in the lower part during the process of removing the product from the bed after printing.
Table 4. Dimensional accuracy of 3D-printed candy specimens with infill densities of 10%, 35%, and 60%, with various infill patterns.

| Infill Percentage | 10%          | 35%          | 60%          |
|-------------------|--------------|--------------|--------------|
|                   | REL          | HNY          | HC           | REL          | HNY          | HC           | REL          | HNY          | HC           |
| Horizontal (mm)   | 39.96        | 39.63        | 40.32        | 40.02        | 39.4         | 39.71        | 39.13        | 39.88        | 40.32        |
| Vertical (mm)     | 39.49        | 40.38        | 39.72        | 38.99        | 40.0         | 40.26        | 40.49        | 40.36        | 39.81        |
| Height (mm)       | 9.39         | 9.81         | 9.82         | 9.50         | 9.7          | 10.03        | 9.53         | 9.73         | 9.58         |
| Weight (g)        | 5.2          | 6.9          | 4.8          | 12.6         | 14.5         | 11.5         | 19.8         | 20.06        | 20.2         |
| Void fraction (%) | 74.66        | 68.29        | 77.98        | 38.68        | 31.57        | 48.26        | 5.40         | 5.34         | 5.24         |

Regarding the weight of the printed specimen, at the same infill percentage, the Honeycomb specimen was heaviest and the Hilbert curve specimen was lightest. Accordingly, regarding the void fraction calculated based on the volume and weight of the printed specimens, the Honeycomb pattern was lowest and the Hilbert curve pattern was highest at the same infill percentage. This was due to the difference according to the path generation method for each internal pattern structure. However, when the infill percentage was 60%, as shown in Figure 9, the interior was mostly filled, and there was little difference in the void fraction for each infill pattern. Therefore, it was confirmed that it was possible to produce a reliable test specimen for various texture modifications realized through the manufactured equipment and process used.

4.2. Flexural Force of the 3D-Printed Candy

Sweetener-based candy materials such as maltitol are generally brittle and hard after crystallized. Therefore, by measuring the flexural force according to the change in the internal design, the force exerted on the teeth when chewed could be analyzed, and the texture change was inferred through this. As mentioned above, the measurement was carried out based on a three-point bending test of the type mainly used to test the textures of fragile materials, with biscuits being one example. A flexural force graph for each manufactured specimen was measured, as shown in Figure 10. Because maltitol is quite brittle, all specimens except for the cast sample quickly fractured completely within 1 mm of displacement after contact with the blade. This outcome was found to be about 1/10 or less than the breaking distance of soft materials such as potatoes and chocolate, which were mainly used in previous studies [19,20]. In particular, given that there was almost no flexural deformation of the specimen; it can be observed that, unlike previous studies, complete fracturing occurred due to crack propagation immediately after passing the maximum load point, with the force decreasing rapidly. This phenomenon is identical to that observed in the flexural tests of typical brittle materials.

The maximum flexural force for each specimen is indicated in Table 5. It can be seen that the flexural force increased as the infill percentage was increased in all specimens. At the same infill percentage, the flexural force increased in the order of the Hilbert curve, honeycomb, and rectilinear structures. In particular, during the previous measurements of the void fraction for each specimen, when the infill percentage was the same, the rectilinear pattern always had the highest maximum flexural force until the point of actual fracture, with the honeycomb pattern showing the lowest porosity. This was identical to the result showing that the rectilinear pattern withstands the best compared to other patterns when a load in the vertical direction is applied to the pattern plane, as demonstrated in existing polymer 3D-printing research [33,34]. On the other hand, for the Hilbert curve, the number of interconnected nodes between the patterns is clearly smaller than those in the other infill patterns. Therefore, it was measured to have the lowest level of flexural force, as in previous food printing studies. Through these changes in infill patterns and infill percentages, it was possible to manufacture 3D candy specimens with various strengths ranging from 1.83% to 50% compared to the strength of cast samples, similar to traditional candy.
Figure 10. Flexural force graph with various infill patterns: (a) IP_10%, (b) IP_35%, (c) IP_60%, (d) Cast.

Table 5. Flexural forces needed to break 3D-printed candy specimens with different patterns and various infill percentages, and cast samples.

| Infill Percentage | Rectilinear (N) | Honeycomb (N) | Hilbert Curve (N) |
|-------------------|----------------|---------------|------------------|
| 10%               | 19.25 ± 2.05   | 14.3 ± 0.4    | 13.55 ± 0.35     |
| 35%               | 137.95 ± 6.15  | 92.3 ± 2      | 37.25 ± 0.85     |
| 60%               | 338.6 ± 7.3    | 292.65 ± 0.55 | 138.3 ± 0.5      |
| Cast sample       | 739.7 ± 1.37   |               |                  |

The flexural force to the break point was measured using the same method used for various commercially available biscuits in order to estimate the force exerted on the teeth and the texture level of the manufactured 3D-printed candy specimens. At this time, in order to judge mainly the maximum force exerted onto the teeth, the flexural force was compared, as shown in Figure 11, without considering the thickness effect of the control biscuit. Specimens with the honeycomb or Hilbert curve structures with an infill percentage of 10% showed flexural force levels similar to those of weak biscuits (Original Biscoff cookies, Lotus, Lembke, Belgium). This was a smaller value than the flexural force of a 6-mm-thick chocolate specimen (Ghana, Lotte, Tokyo, Japan). In addition, measurements showed that the Hilbert curve specimen with an infill percentage of 35% had flexural force similar to that of a sandwich cracker (KID-O butter cracker, Monde Nissin, Makati, Philippines). It was thus proved that 3D-printed candy with various internal designs had flexural force levels similar to those of various sweets ranging from biscuits to crackers and candies. Through this, it was confirmed that the taste of candy can be realized in various textures; furthermore, it was shown that it is possible to manufacture candy that minimizes tooth damage.

Figure 11. Comparison of flexural force levels needed to break commercial snacks.
5. Conclusions

In this study, candies with various infill patterns and percentages were 3D printed using maltitol and a syringe pump of stainless steel, which is harmless to the human body and able to handle high temperatures. Considering material properties sensitive to the process temperature and environment, various process conditions were assessed through an insulation treatment of the extrusion part and with a simple chamber, and the effects of each were investigated. Through this, the optimal extrusion temperature, process environment, and extrusion amount were determined, and various specimens were printed. Moreover, it was confirmed that the fabricated equipment and process were appropriately selected through visual observations and dimension and weight measurements. In addition, specimens with various internal designs were manufactured to realize 3D candy structures with various strengths. As the infill density was increased, the mechanical strength increased. Even at the same infill percentage, the flexural force value that affects the teeth differed by more than 3.7 times depending on the shape of the infill pattern. Through these results, it was shown that it is possible to manufacture candies, which were previously only recognized as hard sweets, into structures with various textures, from biscuits to crackers to traditional candies. By 3D printing with maltitol (a hard material) at various flexural force levels, it is expected that various textures can be created, and that concerns about tooth damage can be greatly reduced. In addition, based on the characteristics of maltitol, which is harmless to the humans, it is possible to present the possibility of a new method feasible for use in bio-related fields that require various precise shapes.

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