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Analysis of Compression and Cushioning Behavior for Specific Molded Pulp Cushion

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Abstract Molded pulp products has become more attractive than traditional materials such as expanded polystyrene foam (EPS) owing to low-priced recycled paper, environmental benefits such as biodegradability, and low production cost. In this study, various design factors regarding compression and cushioning characteristics of the molded pulp cushion with truncated pyramid-shaped structural units were analyzed using a test specimen with multiple structural units. The adopted structural factors were the geometric shape, wall thickness, and depth of the structural unit. The relative humidity was set at two levels. We derived the cushion curve model of the target molded pulp cushion using the stress-energy methodology. The coefficient of determination was approximately 0.8, which was lower than that for EPS (0.98). The cushioning performance of the molded pulp cushion was affected more by the structural factors of the structural unit than by the material characteristics. Repeated impacts, higher static stress, and drop height decreased the cushioning performance. Its compression behavior was investigated in four stages: elastic, first buckling, sub-buckling, and densification. It had greater rigidity during initial deformation stages; then, during plastic deformation, the rigidity was greatly reduced. The compression behavior was influenced by structural factors such as the geometric shape and depth of the structural unit and environmental conditions, rather than material properties. The biggest difference in the compression and cushioning characteristics of molded pulp cushion compared to EPS is that it is greatly affected by structural factors, and in addition, strength and resilience are expected to decrease due to humidity and repetitive loads, so future research is needed.

Keywords Molded pulp cushion, Cushion curve, Stress-strain curve, Yield strength

Introduction

Molded pulp products are manufactured by molding molten pulp at a certain pressure using a mold. They have a high bulk, high basic weight, and the advantage of ensuring the structural diversity of products, as well as environmental benefits such as biodegradability, and are used for various purposes such as, as containers and cushioning packaging cushions. In particular, as a molded pulp product is a structure with airspace, the reaction to external forces and the cushioning mechanism are notably different from those of expanded polystyrene foam (EPS), a cushioning material with less airspace. In other words, in an EPS cushion, the material itself has cushioning properties. However, in the case of a molded pulp cushion, the structure manufactured by molding one material exhibits cushioning properties.

Molded pulp products are generally manufactured through the process of forming, dehydrating, and drying by vacuum-adsorbing a pulp solution made by solidifying 5~0.5% of the weight of water using wood pulp and recycling waste papers (Fig. 1). Molded pulp products can be divided into wet and press-drying molded pulp depending on the drying method after molding. In the former method, mass drying is performed using a hot-air drying conveyor, whereas, in the latter method, pressure-type compression drying of each product is performed using an intermittent method. Therefore, owing to the differences in drying methods, each molded pulp product shows distinct characteristics of quality.[1)]

The question of how to measure the cushioning perfor-

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Fig. 1. Example of the manufacturing process of a typical molded pulp product.

mance of molded pulp cushions has always been a hot research topic, and research on the manufacturing process of molded pulp cushions and quality changes due to the application of additives has been steadily conducted. Noguchi et al.[2] studied a novel material by mixing expanded plastic microspheres with pulp composites to improve the cushioning properties of molded pulp cushions for electronic equipment. Wang et al.[3–5] studied the effect of strain rate, humidity, and other factors on the cushioning capacity and energy absorption of molded pulp products. Sorense and Hoffmann[6] explored the moisture absorbency of molded-fiber trays under different humidities, and Hongwei et al.[7] investigated the effect of different loading, temperature, and humidity conditions on the mechanical properties of molded pulp materials. Xiao and Shao[8] analyzed the effect of temperature change on the moisture content and compression characteristics of molded pulp products. They reported that the compression performance of molded pulp products increases with an increase in temperature as an increase in temperature reduces the moisture content of the molded pulp product and increases the binding force between fibers.

The load-bearing capacity and cushioning performance of the molded pulp cushion are due to structural units. Therefore, many researchers have tried to analyze the compression and cushioning characteristics based on the geometric shapes and dimensions of each structural unit and then analyze the performance of the entire molded pulp product using the results. Eagleton and Markonds[9] compared the cushion curves of molded pulp products and EPS. They suggested that the cushioning properties of the molded pulp product are caused by the destruction of a large number of "dimples" molded into the pulp sheet against external force. Therefore, it has excellent cushioning properties against low static stress, low drop height, and single impact. However, the cushioning performance is inferior to that of the EPS cushion with the same thickness against a static stress greater than 5 kPa, higher drop height, or multiple impacts. No difference was observed in cushioning properties based on the geometric shape of the "dimple" after one impact. Gurav et al.[10] analyzed the compression characteristics of the molded pulp product for cushioning of one rib of video recorder through an experiment and FEA and qualitatively analyzed the mechanical behavior according to the geometric shape of the rib through FEA. Dongwei and Wencal[11] also showed good agreement between the drop height-maximum acceleration curves analyzed through experiment and FEA for the conical type rib, which is a key element of the molded pulp product. Wang et al.[12] announced that, in one structural unit of a molded pulp product, an increase in the material thickness increases its bearing capacity though decreases the cushioning performance; therefore, the material thickness should be determined through a compromise between load-bearing capacity and cushioning performance when designing a molded pulp-based cushioning packaging material. Hoffmann[13] suggested that under the same conditions (density and dimensions), the compressive strength of the circular truncated cone-type molded pulp product is approximately 20% greater than that of the truncated square pyramid-type molded pulp product, and the lowest point on the cushion curve is wider, which increases the design application area. Ma et al.[14] analyzed the effect of structural factors on the load-bearing capacity through numerical simulations of structural units of molded pulp products.

Recently, in relation to environmental problems, the use of more eco-friendly molded pulp-based cushioning packaging materials has increased remarkably. To substitute this material for EPS-based cushioning packaging materials, quality standardization and design data construction for cushioning packaging are essential. However, in the case

of molded pulp-based cushioning packaging materials, establishing comprehensive design data is complicated as the material is molded in various forms depending on the shape of the product.

In this study, various design factors in terms of compression and cushioning characteristics for the molded pulp cushion with truncated pyramid-shaped structural units were analyzed using a test specimen with multiple structural units. The specific research objectives are as follows:

1. Analyze the compression behavior of molded pulp cushion based on geometric shape, dimension and density of the structural unit, and relative humidity (rh)
2. Model and analyze the cushioning behavior of molded pulp cushions based on geometric shape, dimension and density of the structural unit, and relative humidity.

Experimental Design and Methods

1. Experimental material

In this study, the raw material of the target molded

(a) Before the test (upper surface) (b) After the test (lower surface)

Fig. 2. Photographs of samples before and after the test.

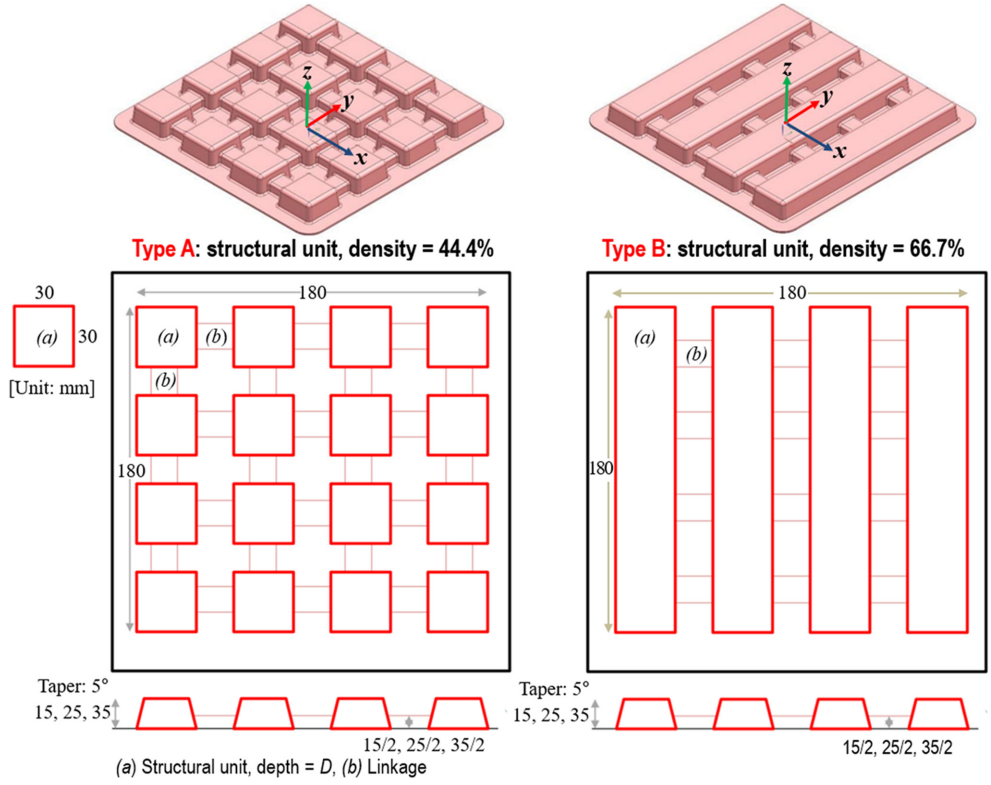


Fig. 3. Structure of the target molded pulp cushion.

pulp cushion was 100% corrugated waste paper, which was manufactured of hot pressing molded pulp product (drying temperature of the mold surface was 270°C) under the manufacturing conditions, that is, a stock concentration of 0.5%, the vacuum pressure of 0.06 MPa, and vacuum dehydration time (including times for suction forming) of 8 s.

The function of the molded pulp cushion is to secure and protect the product. The structure of a molded pulp cushion can be largely divided into structural units that provide the functions of positioning and protection and the linkages that connect the structural units to form a whole piece of cushioning packaging.[14] The geometric shape of the structural unit of the target molded pulp cushion was the truncated pyramid, as shown in Fig. 2 and 3. The major structural parameters were two types based on the cross-section of the structural unit: Type A, a square (30×30 mm), and Type B, a long rectangle (30×180 mm)]. The structural unit had three levels of depth (15, 25, and 35 mm) and two levels of wall thickness (material thickness) (1.3 mm_ 1.3T and 1.6 mm_1.6T). The slope of the side wall of the structural unit, that is, the angle between the side wall of the structural unit and the mold-moving direction during the molding process, was 5°. Meanwhile, the sample conditions were treated with two levels of 50% and 90% of relative humidity (rh) at 23ºC.

In the analysis, the cross-sectional area of the test specimen was defined as the apparent area surrounding a certain number of structural units, and the area densities of Types A and B were 44.4% and 66.7%, respectively, based on the top surface of the 180×180 mm specimen.

2. Experimental apparatus and methods

When the methodology specified in ASTM D1596[15] is applied to the derivation of the cushion curve of the target molded pulp cushion, even for a specific material thickness, geometry, and environmental conditions, a large number of drops should be performed for several combinations of different parameters, that is drop height, static stress (drop body weight/specimen area), and depth of the structural unit. Therefore, this method is time consuming and cost intensive. In this study, a method of modeling the cushion curve with a drastic reduction in the number of drop tests was applied. That is, a stress-energy methodology was applied for modeling the cushion curve using the relationship between the energy density and dynamic stress combined with these parameters.[16-18,20]

$$DE = \frac{\sigma_{st} \times h}{D} \quad (1)$$

$$DS = G_p \times \sigma_{st} \quad (2)$$

where DE is the energy density (J/m^3), σ_{st} is the static stress (loading) (Pa), h is the drop height (m), D is the depth of structural unit (m), DS is the dynamic stress (Pa), and G_p is the peak acceleration (G's).

To derive the cushion curve using the stress-energy methodology, after comprehensively considering the specifications of the drop tester to be applied, the characteristics of the sample, and the securing of the sample, the range of energy density that can be implemented through sufficient preliminary tests should be determined. The free-fall drop tester used in this study is shown in Fig. 4 (Dawha Testing Machine in Korea, 2000 g one-

Table 1. Test plan established by the stress-energy methodology

Drop no.	Drop height (cm)	Weight (N)	Specimen, L×W×D[1] (cm)	Static stress (kPa)	Energy density (kJ/m^3)
1	20	29	18×18×2.5	0.8951	7
2	30	59	18×18×3.5	1.8210	16
3	40	49	18×18×2.5	1.5123	24
4	45	39	18×18×1.5	1.2037	36
5	45	108	18×18×3.5	3.3333	43
6	55	49	18×18×1.5	1.5123	55
7	85	88	18×18×3.5	2.7160	66
8	65	98	18×18×2.5	3.0247	79
9	100	78	18×18×2.5	2.4074	96

Note: 1) D=depth of structural unit

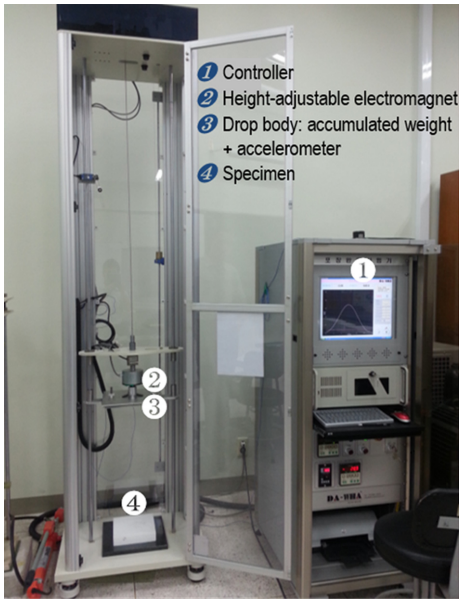


Fig. 4. Experimental apparatus for cushioning test.

dimensional piezoelectric accelerometer).

Table 1 shows the test plan established by the stress-energy methodology based on the determined energy density range. Prior to the main tests, sufficient pre-tests were conducted in accordance with the test plan to ensure data generation and reproducibility of equipment operation. The number of repetitive drop tests for each test piece was limited to the first drop, with reference to the plastic properties of the sample and literature.[9] Before the test, the specimens were equilibrated for more than 72 h under the planned temperature and relative humidity conditions.[19]

A universal testing machine (KST Co. in Korea) equipped with a 1-ton load cell was used for the compression test of the target molded pulp cushion. In the compression test, the loading rate was 10 mm/min,[18] and the start of the compression displacement was set when a preload of 2 N was applied. The specimens were equilibrated for more than 72 h under each environmental condition before testing.[19]

Results and Discussion

1. Cushioning behavior and modeling

The drop test for the target molded pulp cushion was conducted according to the test plan shown in Table 1. Fig. 5 shows the energy density-dynamic stress curves calculated based on the acquired data. When the relationship was expressed as an exponential function, the coefficient of determination was approximately 0.8 on average. This is low compared to the average of approximately 0.98 for EPS and multi-layered corrugated structures (MLCS),[16-18,20] which are cushioning materials with less airspace. This result is due to the effect of the shape irregularity of the target molded pulp cushions

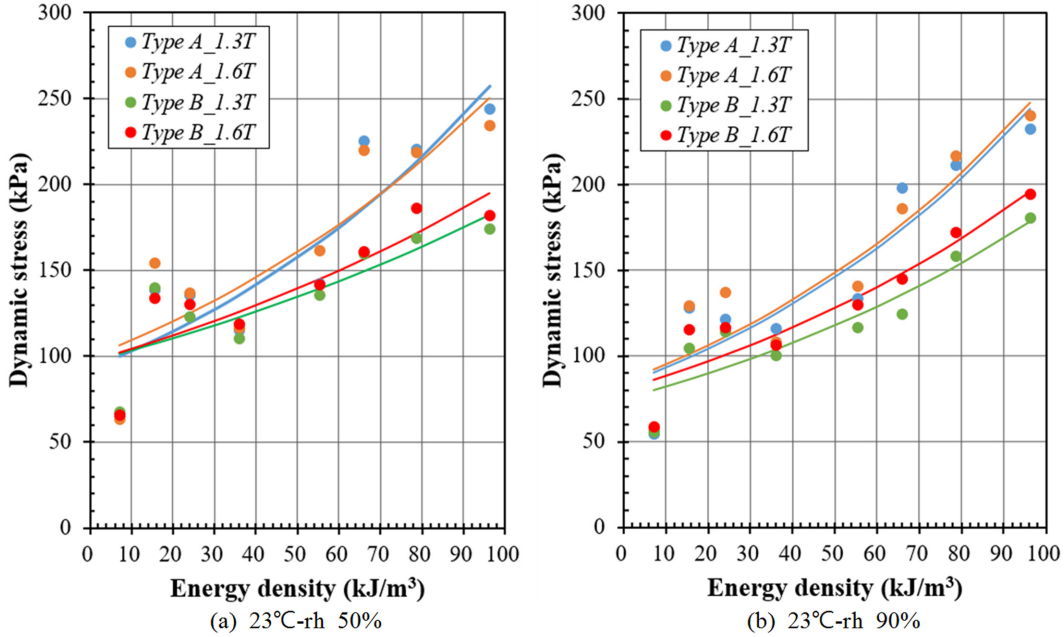


Fig. 5. Energy density-dynamic stress curves of target molded pulp cushions.

and the linkages connecting each structural unit in all directions at medium depth. In particular, the energy density in the range of 40~50 kJ/m^3 is the moment at which the linkages collapse, and at this time, the dynamic stress is very large. If these data are included in the modeling, it may lead to the distortion of other ranges of data; therefore, it was excluded from the modeling.

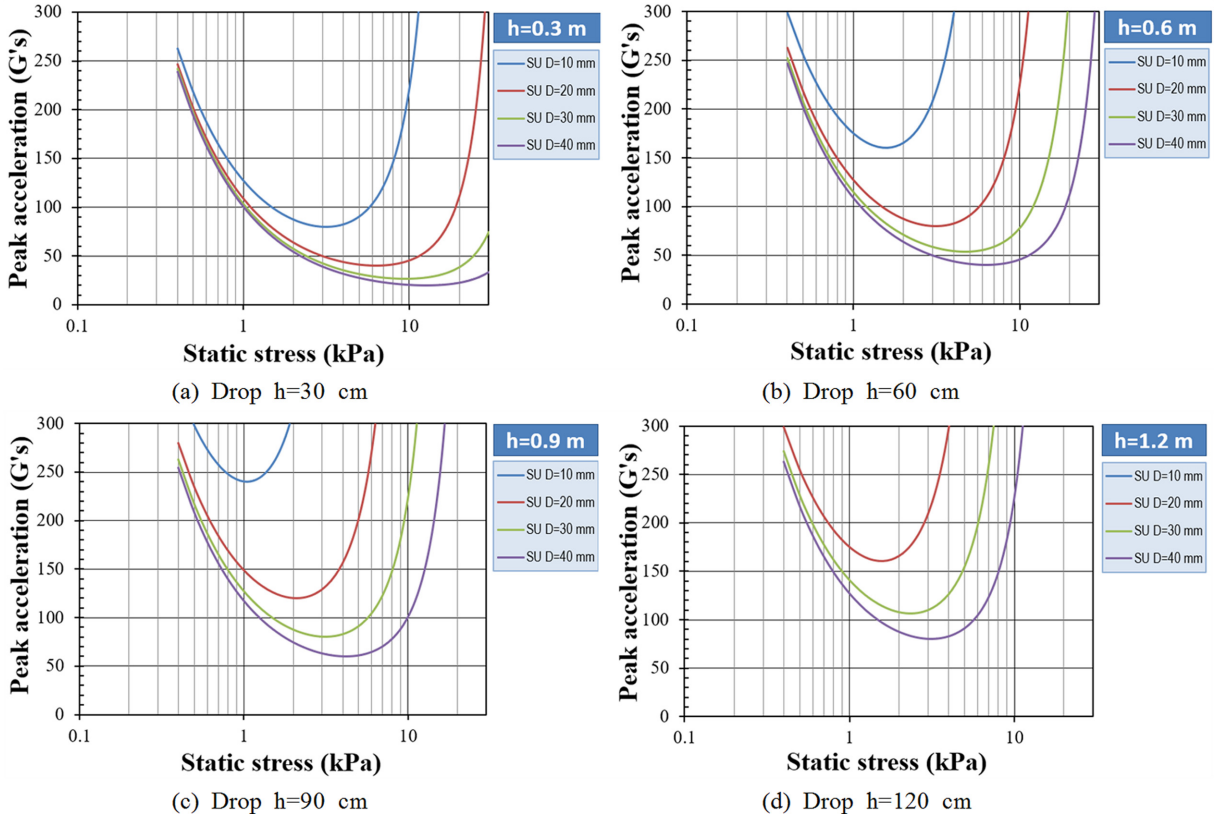
As an example, the energy density-dynamic stress relationship for Type A-1.3T under a condition of 23°C-rh 50% was modeled as an exponential function, as shown in equation (3).

$$DS = 92.5667 \times \exp(1.0617 \times 10^{-2} \times ED),\ r^2 = 0.8152 \quad (3)$$

$$G = \frac{92.5667}{\sigma_{st}} \times \exp\left\{1.0617 \times 10^{-2} \times \sigma_{st}\left(\frac{h}{D}\right)\right\} \quad (2)$$

If the parameters of equations (1) and (2) are replaced in equation (3), the cushion curve model of equation (4) can be derived. Therefore, the cushion curves of the target molded pulp cushion according to the drop height and depth of the structural unit were calculated using equation (4), as shown in Fig. 6. The shapes of the cushion curves of other target molded pulp cushions, other than the example, are all similar; only the characteristics and position of the lowest point on the cushion curve are numerically different.

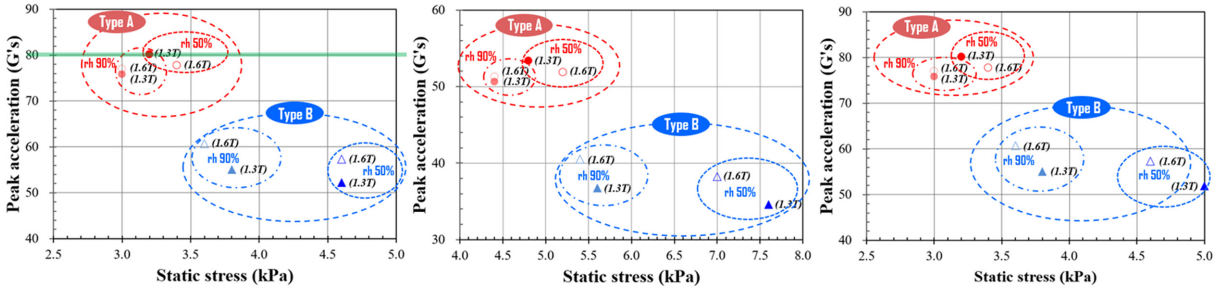
From the structural point of view of the target molded pulp cushion, the position of the lowest point, which represents the optimal cushioning condition on the cushion curve, shifted significantly to the lower right with an increase in the depth of the structural unit under the same conditions (wall thickness and drop height), and the rate of acceleration in the position gradually decreased. In addition, with an increase in the depth of the structural unit or with a decrease in the drop height, the width near the lowest point on the cushion curve, which is the range of allowable static loading (stress) in the cushioning packaging design, increased significantly. When the lowest point on the cushion curve moved to the lower right at the same drop height, the drop impact force decreased. Under these circumstances, the required area for cushioning decreased owing to an increase



(a) Drop h=30 cm (b) Drop h=60 cm

(c) Drop h=90 cm (d) Drop h=120 cm

Fig. 6. Example of cushion curves of a target molded pulp cushion (SU=structural unit): Type A-1.3T (23°C-rh 50%).



(a) SU D=30 mm, drop h=90 cm (b) SU D=30 mm, drop h=60 cm (c) SU D=20 mm, drop h=60 cm

Fig. 7. Example of analyzing the lowest point on the cushion curve of the target molded pulp cushion (SU=structural unit).

in static stress; however, the required thickness for cushioning increased, and the package dimension increased. Therefore, optimization of packaging cost and logistics efficiency is necessary.

For a qualitative comparison of the cushioning properties of the target molded pulp cushions according to the geometric shape of the structural unit, wall thickness (material thickness), and relative humidity, the position of the lowest point on the cushion curve was analyzed for each example of the three cases shown in Fig. 7. Under the same conditions (depth of structural unit and drop height), the lowest point on the cushion curve generally tended to move to the lower right for Type A and to the lower left for Type B with an increase in the wall thickness. In addition, under all example conditions, the lowest point position of Type B was located at the lower right of that of Type A. For both types, the lower the relative humidity, the lower the lowest point located on the right. In general, the difference in position between rh 50% and rh 90% in Type B was found to be approximately three times larger than that in Type A, and the geometric shape of Type B showed a greater effect of relative humidity on the cushioning properties.

The molded pulp cushion is a structural cushioning product structured with a material. As the cushioning mechanism is different from that of the non-specific cushioning material (density and shape uniform), the cushioning properties were observed to depend more on the structural factor, that is the depth and geometric shape of the structural unit, than the characteristics (material thickness and density) of the material itself. This effect was more pronounced in Type B.

As an example of the application of target molded pulp cushion, if the critical acceleration of one product is 80 G and the design drop height (DDH) is 90 cm, the optimal cushioning material applicable is 1.3T for Type A, and 1.6T is a candidate for review [Fig. 7(a)].

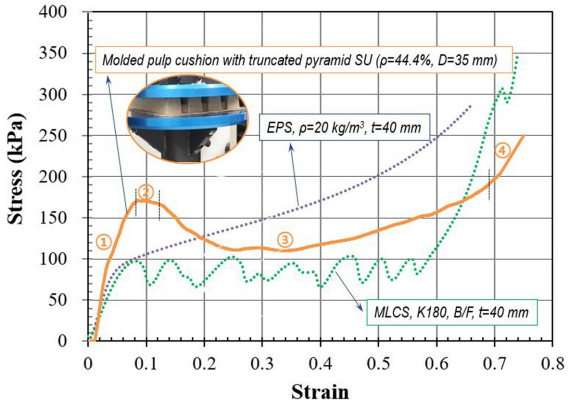
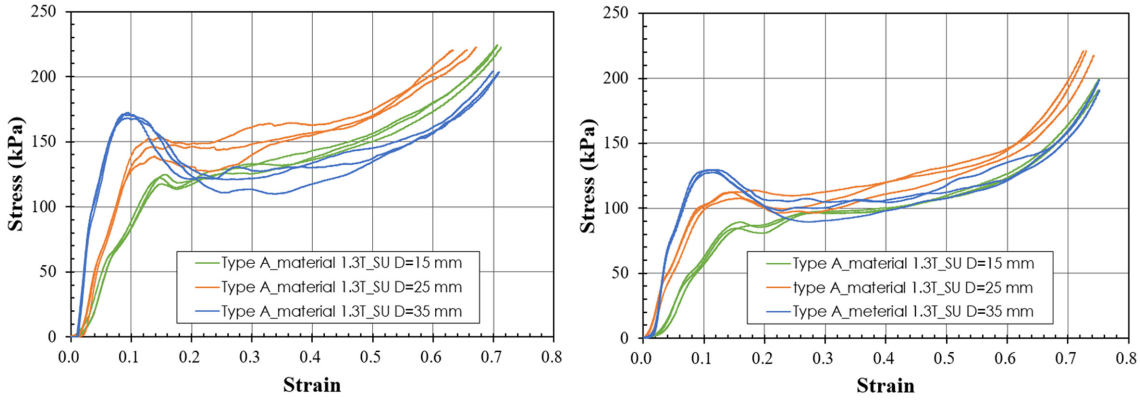


Fig. 8. Typical SS curve of the target molded pulp cushion.[19]

2. Compressive stress-strain behavior

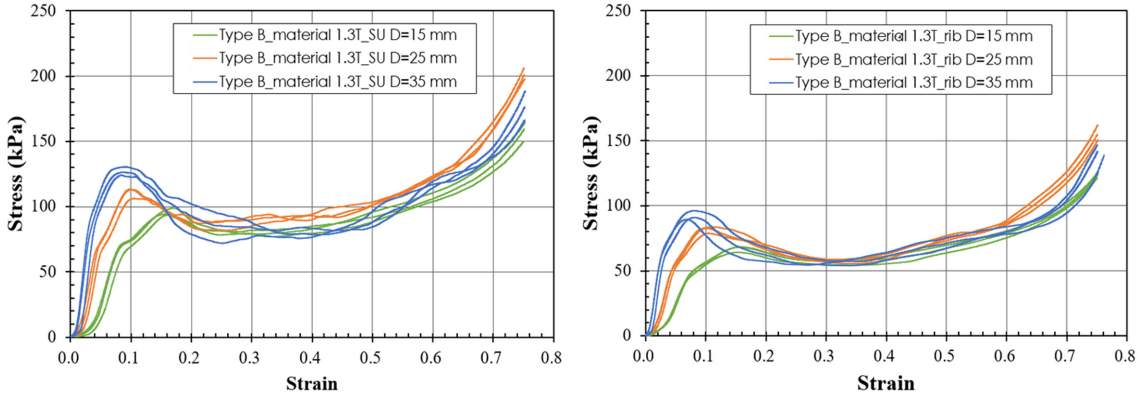
An example of the stress-strain curve (SS curve) of the target molded pulp cushion is shown in Fig. 8 along with the SS curves of other materials. The compression behavior of the target molded pulp cushion is generally divided into four stages: elastic, first buckling, subbuckling, and densification. Following the elastic behavior at the beginning of the deformation, the structural unit end is crushed (first buckling stage), and the structural unit shank is buckled for a considerable amount of time with continuous structural unit crushing (subbuckling). Eventually, with the complete collapse of the space, it enters the densification stage.

As the target molded pulp cushion is a cushioning material with airspace, it has a greater rigidity (yield strength and curve slope) than EPS and MLCS in the early stage of deformation, and this rigidity is notably lost owing to plastic deformation. In addition, the



(a) 23℃-rh 50% (b) 23℃-rh 90%

Fig. 9. Example of the SS curve of the target molded pulp cushion: Type A-1.3T (SU=structural unit).



(a) 23℃-rh 50% (b) 23℃-rh 90%

Fig. 10. Example of the SS curve of the target molded pulp cushion: Type B-1.3T (SU=structural unit).

continuous buckling stage of this cushion is relatively longer than that of the EPS and MLCS, and the stress change at this stage generally decreases and increases, which is clearly distinguished from the MLCS with little stress change.[22] The SS behavior of the target molded pulp cushion shows that this cushion has stronger plastic properties than EPS and MLCS under conditions above the yield point.[22] In addition, the slope and yield strength of the curve are large in the early stages of deformation because the structural unit is approximately 5° tapered, and the increase in contact area along with deformation rapidly increases the resistance.

Fig. 9 and 10 show examples of the SS curves of the target molded pulp cushion, and Fig. 11 shows the yield strength and yield strain analyzed from the SS curve. For the EPS and MLCS cushions, the SS curves did not differ significantly depending on the size (especially thickness) of the specimen.[22] For the target molded pulp cushion, up to approximately 20% of the depth of the structural unit, the slope of the SS curve increased with the depth of the structural unit, and the yield strength was also greater. The yield strain decreased with increasing depth of the structural unit. After compression of more than 30% of the depth of the structural unit, the difference in the SS curve based on the depth of the structural unit was significantly reduced. However, a significant difference was observed between the geometric shape of the structural units, and the relative humidity.

The difference in yield strength between 50% and 90% of the relative humidity was approximately 24~30%, and the difference in the yield strength between 1.3T and 1.5T was approximately 10~29% at 15 mm depth of the structural unit. However, the difference decreased significantly with an increase in the depth of the structural unit.

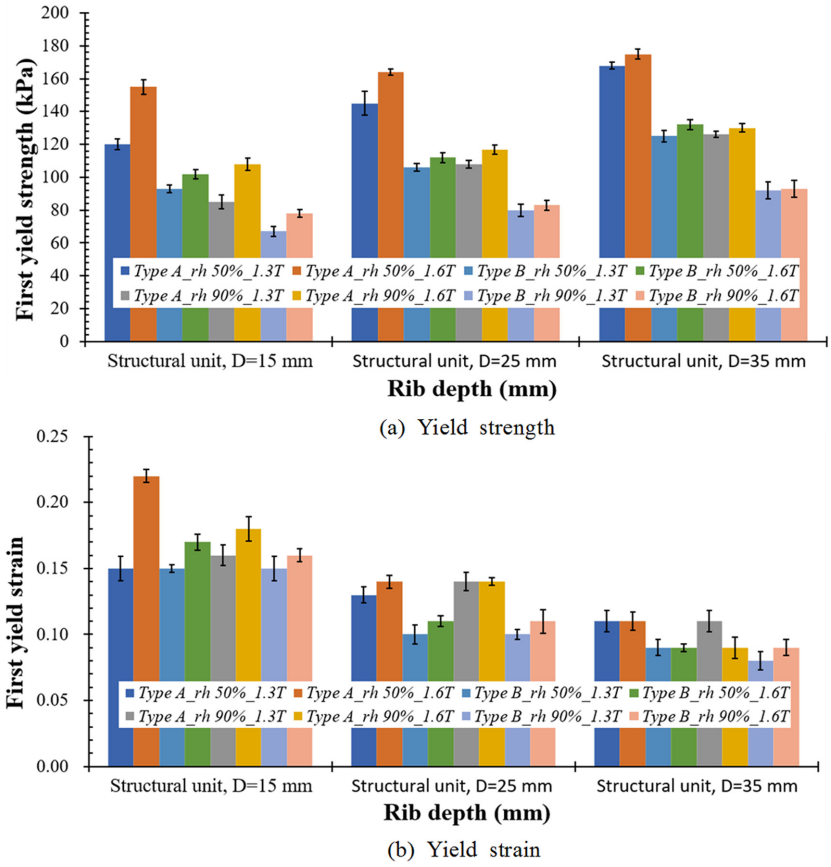


Fig. 11. Yield strength and strain of the target molded pulp cushion.

Conclusions

Molded pulp cushions are three-dimensional, thin-walled structures that confine the packed goods within the packaging and protect them against external loads. The molded pulp cushion is attracting attention as a substitute for the EPS cushion; however several difficulties exist in standardizing its quality and constructing cushioning packaging design data. In this study, various design factors in terms of the compression and cushioning characteristics of the molded pulp cushion with truncated pyramid-shaped structural units were analyzed using a test specimen with multiple structural units. The adopted structural factors in this study were the geometric shape, wall thickness, and depth of the structural unit; the relative humidity was adopted as two levels for indicating the environmental condition. The results of this study can be summarized as follows:

1. When deriving the cushion curve model of the target molded pulp cushion using the stress-energy methodology, the coefficient of determination of the model was approximately 0.8 on average. This value was lower than that of the EPS (0.98) with a uniform shape.

2. The molded pulp cushion is a structural cushioning product molded from a material, and its cushioning performance was affected more by the structural factors of the structural unit than by the characteristics of the material itself, such as thickness and density. In addition, repeated impacts, higher static stress (loading), and higher drop height resulted in a severe decrease in cushioning compared to the EPS cushion.

3. The compression behavior of the target molded pulp cushion was investigated in four stages: elastic, first buckling, subbuckling, and densification. Compared to that of EPS or MLCS, its rigidity was high in the early stages of deformation; then, owing to plastic deformation, the rigidity was notably reduced. The compression behavior of the target molded pulp cushion was also largely influenced by structural factors such as the geometric shape and depth of the structural unit and environmental conditions, rather than the properties of the material.

4. The yield strength of the target molded pulp cushion

increased with an increase in the depth of the structural unit; however, the yield strain decreased. The difference in yield strength between 50% and 90% of the relative humidity was approximately 24~30%, and the difference in yield strength between 1.3T and 1.5T of wall thickness significantly decreased with an increase in the depth of the structural unit.

5. molded pulp cushions are manufactured in various forms depending on the characteristics of the product and the mechanisms and degrees of reaction to external forces may differ depending on their structure. As the data presented here are limited to the target molded pulp cushion of this study, limitations exist in applying the data. In the future, more comprehensive design data must be established for the cushioning packaging design of molded pulp cushions.

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