

Study of Physical Properties and Shock Absorption Abilities of Starch Polymer Foam as Cushioning Material for Packaging

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Abstract. Lack of information about the formulation and fabrication process of starch polymer foam and lack of study in the shock absorption ability of starch polymer foam were the reasons this research was executed. In this project starch polymer foam was produced to be used as cushioning material for packaging. Starch polymer foam were developed from starch, polyvinyl alcohol (PVA), urea, citric acid, and deionised water. Water amount with drying and curing process were the variables manipulated to produce the best starch polymer foam. It was determined then, that the optimized ratio of starch:PVA: citric acid was 1:1:4. The amount of water used was 10 ml/gram of starch/PVA weight. The suitable foaming mixing was done at a speed of 1500 rpm for 40 minutes. Drying process was done at 70°C for 24 hours, followed by curing process at 100°C for 1 hour to produce closed-cell foam. While for the open-cell foam, the foam was dried and cured at 100°C for 6 hours. The open-cell and closed-cell foams produced were cut to 6 cm height x 6 cm width x 0.5 cm thick. The average density was calculated and then the foams were subjected to weight drop destructive test. The test was done by placing a foam on top of a piece of mirror, and a weight is dropped onto the foam, with increasing height until the mirror break. Three weights were used with mass of 50 g, 100 g and 200 g. The starch foams were compared to polyurethane and polystyrene foams in terms of the minimum height that can cause the mirror to break. The results showed that starch closed-cell foam absorbed the highest impact energy followed by polystyrene foam, starch open-cell foam and polyurethane foam.

1 Introduction

The packaging industry is growing broadly as it is linked to the growth of world's economy. Packaging has become an essential industry across wide range of industries like healthcare, food and drink, furniture, modern gadget and as well as in other industrial sectors. However, the markets of the packaging industries are relying upon the petroleum industries for the raw materials. The traders or retailers have to cope with the price fluctuations of raw material, depending on the supply and demand of their business.

Plastic foams are often used as cushioning materials for packaging because of its lightweight properties and shock absorption abilities. The most common polymer foam cushioning materials are made up of polystyrene, polyurethane, polyethylene and

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polypropylene. There are two major types of foams which are open-cell and closed-cell. Open-cell foam allows gases and liquids travel freely through the foam cells, while a closed-cell foam only allows gases and liquids to diffuse through very small boundaries between the foam cells [1].

Starch is an inexpensive, natural and renewable raw material that can be processed into a polymer. To produce starch polymer, the starch has to be plasticised with plasticizing agent such as urea. Plastic products containing starch are considered biodegradable because starch easily degrades into simpler compounds that can be metabolized by microorganisms such as fungi, bacteria and yeast [2]. The extruded starch polymer foam was patented by Ivan Tomka in 1996. Since that, several researches have been made to study the capabilities and properties of starch polymer foam to replace the petroleum based polymer foam.

Pure starch itself is poor in mechanical properties, process ability and dimensional stability to be used directly as end products. To improve the properties of starch, some physical and chemical modifications of starch have to be made by mixing the starch with other polymers, or with plasticizers and other additives. There are a lot of hydroxyl groups on starch chains, two secondary hydroxyl groups at C-2 and C-3 of each glucose residue, and one primary hydroxyl group at C-6 when it is not linked [3]. The existence of hydroxyl groups in the starch opens up the potential of the starch to have reaction with water and alcohols, so, starch can be oxidized and reduced, and may participate in formation of hydrogen bonds either ether or ester.

Distilled water can be used as the modifying agent because of the existence of hydroxyl group in starch chains which allow water molecules to modify the chains of starch polymer. Moreover, distilled water also performs as blowing agent for the starch, because when water evaporated, it will release steam to expand and reduce the density of the foam [4]. Therefore, the amount of water is very important in the production of starch polymer foam as it can change the properties of the foam.

However, poor water resistivity of starch polymer is one of the major disadvantages of the material. Although the tensile strength may be rather high, but it becomes too fragile after absorbing water [5-6]. Therefore, to increase water resistivity of the starch, it must be mixed with polyvinyl alcohol (PVA) which has good water resistivity, excellent film forming and high thermal stability [6]. The addition of PVA into starch reduces its brittle nature and increases the tensile properties [7]. There are other research that showed significant improvement in the Young modulus up to 500% for the starch/montmorillonite nanocomposite containing 5 wt% of clay.

Mixing with only water cannot make the starch usable and comparable with existing cushioning foam in terms of its mechanical properties and physical properties [8]. Therefore, citric acid should be added into the formula to increase the elongation at break.

Citric acid has polysaccharides containing hydroxyl groups that have the possibility to be cross-linking by poly-functional carboxylic acid. Therefore, this will slightly increase its rigidity and brittleness due to the cross linking reaction. Moreover, by reacting citric acid with the starch, the molecular weight of the starch will be reduced. As a result, the diffusion rate and permeability of the polymer will be increased [9-10].

In this paper, starch polymer foam was produced for potential use as cushioning material for packaging. Starch polymer foam were developed from starch, polyvinyl alcohol (PVA), urea, citric acid, and deionised water. Significant contribution of this research is the introduction of a simple destructive test to quantify shock absorption ability and comparison of impact energy between starch polymer foam and other polymer foams such as polyurethane and polystyrene.

2 Materials and methodology

2.1 Starch polymer foam formulation

Starch, which is inexpensive, natural and renewable raw material was therefore selected as one component to produce a new polymer foam. The materials used were starch powder, PVA, urea, citric acid and deionized water. Detail formulation and its composition is given in Table 1.

Table 1. Starch polymer foam formulation.

Materials	Amount
Starch	5 g (16.67%)
Polyvinyl alcohol (PVA)	5 g (16.67%)
Citric acid (CA)	20 g (66.67%)
Urea	3 g (10% from total weight of starch/PVA/CA)
Deionized water	100 ml

2.2 Sample preparation

For mixing process, firstly PVA is poured into flask together with 50 ml of distilled water and the flask is immersed in water bath at temperature of 90°C and is stirred with magnetic stirrer at 300 rpm until the PVA is completely dissolve. Then, starch and urea are mixed with 50 ml of distilled water in a separate beaker. After that, the starch/urea/water mixture is poured into the flask and then the mixture is stirred with magnetic stirrer for 45 minutes at 300 rpm. The gel-like mixture is cooled down to room temperature before started foaming it.

Before the foaming process, citric acid is added into the cooled gel-like mixture. After that, the mixture is stirred with mechanical stirrer or mixer at 1000 rpm for 45 minutes, when mixture is foamed after that process. Then, the foamed mixture is poured into a plastic mold. The mold is put inside an oven for drying and curing process. These processes are illustrated in Figure 1.

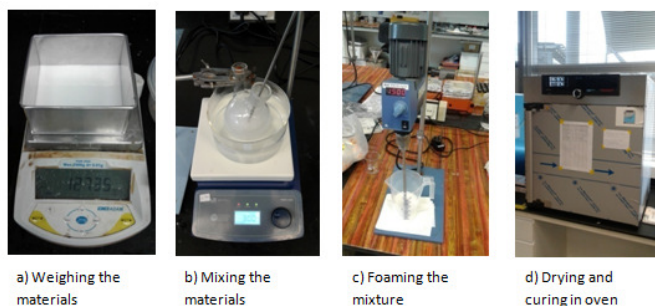


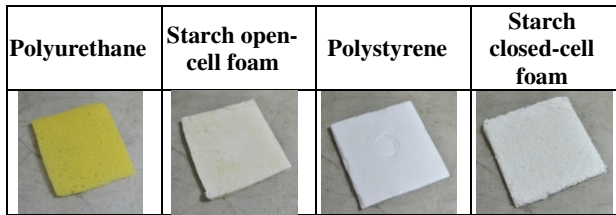
Fig. 1. Summary of sample preparation.

To produce starch open-cell foam and starch closed-cell foam, the drying and curing procedure was varied as shown in Table 2. Starch foam developed in Method 1 was however, not suitable for the research. All foams were cut into square pieces of 6.0 cm (height) x 6.0 cm (width) x 0.5 cm (thick) as displayed in Table 3.

Table 2. Drying and curing methods for starch foams.

Method 1	Method 2	Method 3
Drying and curing for 4 hours at 120°C	Drying and curing for 6 hours at 100°C	Drying for 24 hours at 70 °C Curing for 1 hour at 100°C
Produced a foam that is very fragile	Produced an open cell foam	Produced a closed cell foam

Table 3. Foams cut into pieces of 6 cm x 6 cm x 0.5 cm.



2.3 Weight drop destructive test

To determine the shock absorption ability of the foams, a weight drop destructive test was conducted. This test was done to compare the performance of different types of foams in terms of their ability to absorb impact energy from a free fall weight. These foams were subjected to weight drop destructive test as shown in the Figure 2.

A rectangle mirror of 1 mm thick was placed on a flat concrete surface below the PVC pipe. The weight was dropped in free fall condition through the PVC pipe starting at 2.0 cm height from the mirror, and was kept increasing by 2.0 cm until the mirror breaks or at the highest point on the pipe of 1 m. The height where the mirror breaks was recorded. A control reading was taken when the test was conducted without polymer foam on top of the mirror.

The impact energy that caused the failure was calculated by the formula of gravitational potential energy, given in Eq. (1):

$$E = mgh \tag{1}$$

where m = mass of the weight, g = gravitational acceleration (10 or 9.81 m/s²), and h = height. The steps were repeated by placing polymer foam on top of the mirror. The impact energy that causes mirror breaks by different foams was compared.

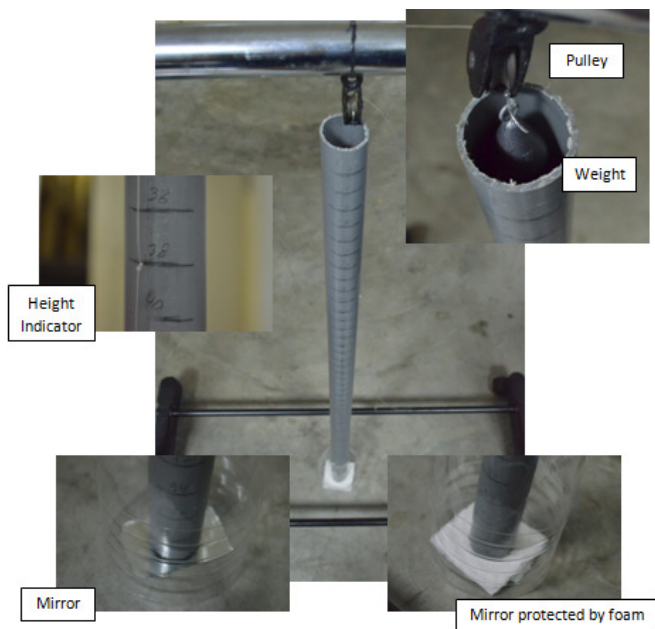


Fig. 2. Weight drop destructive test apparatus set up.

3 Results discussion

3.1 Physical properties of the polymer foams

From the properties of the foams, starch open-cell foam was comparable to polyurethane foam because of its flexibility and low density. While closed-cell foam can be compared with polystyrene because of its rigidity. The major drawback of the starch polymer foams was that their density were slightly higher than the competitors as tabulated in Table 4. Compared to the lightest foam in this research, which was polystyrene, starch closed-cell and open-cell foams were 2050% and 361% greater in density, respectively.

Excessive amount of water can cause the foaming process fail and the foam will not dry perfectly. The suitable amount of water to produce starch polymer foam was at 10 ml of water per 1 g of starch/PVA.

Different drying and curing process will cause different foam properties. If a foam was dried and cured at 100°C for 6 hours, it will produce open-cell foam because water boils at that temperature and causes steam bubbles to create bigger pores to the foam.

If a foam was dried at 70°C for 24 hours and cured at 100°C for another 1 hour, the foam produced was closed-cell foam because the foam was slowly dried. The property of the foam produced was rigid and less flexibility, an attribute of closed-cell foam.

Table 4. Physical properties and formulation of the best foams produced and existing cushioning material.

Samples	Starch closed-cell foam	Polystyrene	Starch open-cell foam	Polyurethane
Volume (after being cut)	18 cm ³	18 cm ³	18 cm ³	18 cm ³
Average weight (g)	10.827	0.496	2.329	0.716
Density (g/cm ³)	0.602	0.028	0.129	0.040
Form	rigid	rigid	flexible	flexible

3.2 The minimum height of the weight to break the test mirror

The weight used in the first iteration of the test was 50 g of mass. With that weight, the minimum height for the weight to cause unprotected (no foam) mirror to break was 0.38 m. This is the control's result.

After a polyurethane foam is placed on top of the mirror, the minimum height for the weight to cause the mirror to break increased to 0.46 m. It shows that, polyurethane foam was absorbing the impact force because there was some small difference (21.1%) in the minimum height between having or without the cushioning material (foam).

However, for this iteration, the weight was not enough to break the mirror within 1.0 m of height while the starch open-cell, polystyrene and starch closed-cell foams were placed on top of the mirror as exhibited in Figure 3.

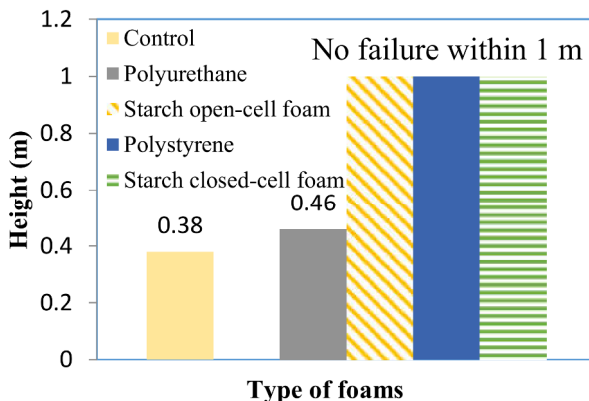


Fig. 3. The minimum height of the weight that can cause the mirror to break using 0.05 kg weight.

Therefore, the weight was increased to 0.1 kg after that. In this iteration of using 100 g weight, some reductions in height for weight drop to break the mirrors without foam and with the polyurethane foam were observed. This happened due to increasing mass that caused higher impact energy. For the starch open-cell foam, the mirror broke at the height of 0.52 m. So, it is better than polyurethane foam by 117% implying its ability to absorb greater impact force. The mirrors placed below the polystyrene and starch closed-cell foams still did not break in this iteration as shown in Figure 4.

Thus, the weight was increased to 0.2 kg. In this iteration of 200 g weight, all mirrors used were finally broken. Starch closed-cell foam yielded the highest minimum height at 0.8

m while the polystyrene minimum height was 0.6 m, thus proven that starch closed-cell foam has more shock absorption ability (33.3%) compared to polystyrene foam.

In other words, the minimum height of the weight to cause failure on starch closed-cell foam covered mirror were actually 300% higher than the unprotected mirror. These results are shown in Figure 5.

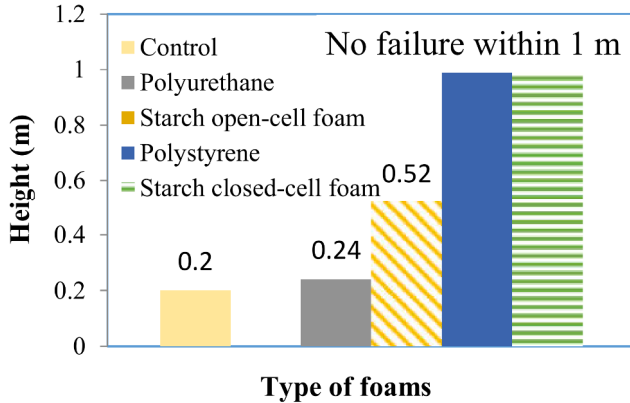


Fig. 4. Minimum height of 0.1 kg weight that can cause the mirror to break.

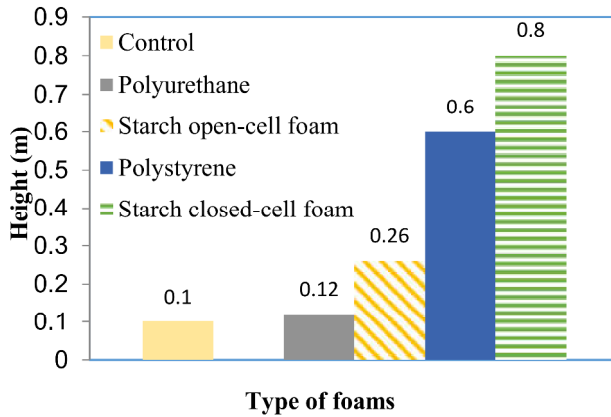


Fig. 5. Chart of minimum height of weight that can cause the mirror to break using 0.2 kg weight.

3.3 Impact Energy and Shock Absorption Performance

In summary, the maximum heights of the 200 g weight that can be dropped on top of the polymer foams protecting the mirror without breaking were 0.78 m, 0.58 m, 0.24 m and 0.1 m for starch closed-cell, polystyrene, starch open-cell and polyurethane, respectively.

From the graphs discussed earlier, the performances of the starch polymer foams in terms of shock absorption abilities were better than the existing cushioning materials; polystyrene and polyurethane.

The starch closed-cell foam can absorb impact force, 33.3% higher than the polystyrene foam. While starch open-cell foam can absorb impact force at 131.8% higher than polyurethane foam. The maximum gravitational potential energy that can be absorbed by the foams without failing the material they are protecting are shown in Figure 6.

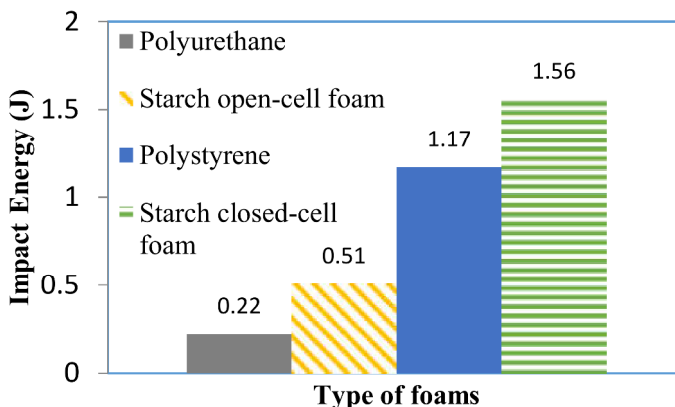


Fig. 6. Maximum impact energy absorbed that each foams can withstand without breaking the mirror.

4 Conclusions

In conclusion, starch polymer foams were compared with the existing cushioning material foams which are polystyrene and polyurethane foams. However, the produced starch foams were higher in density the two polymer foams mentioned earlier.

From the packaging drop test, starch closed-cell foam demonstrated higher shock absorption ability compared to polystyrene because it can withstand higher impact force to protect the mirror from breaking. On the other hand, starch open-cell foam also showed higher shock absorption ability compared to polyurethane foam. Therefore, it proved that both of the starch polymer foams were better than the existing cushioning material foams in terms of shock absorption ability.

The constructed weight drop destructive test was able to demonstrate the shock absorption abilities of the foams. The collected data was analysed for the minimum height of a particular weight that can caused foam-protected mirror to break, as well as the maximum impact energy that can be absorbed by the foams without breaking the mirror.

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