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Research on Poisson Ratio of Molded Pulp Material Based on DICM and Uniaxial Tensile Test

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Abstract

Green packaging, also known as sustainable packaging, is the use of materials and manufacturing methods for the packaging of goods that has a low impact on both energy consumption and on the environment. As a new type of green packaging materials, molded pulp is widely used in packaging industry. Molded pulp products have a widely range of materials, such as wood pulp, sugarcane pulp, recycled corrugated pulp, recycled newspaper pulp etc. The mechanical properties of molded pulp material are the basis of structural optimum design of the molded pulp products. An attempt were made by this paper on the relationship between Poisson's ratio and fiber structure, molding process and thickness, uniaxial tensile test and digital image correlation method were carried on samples made from wood pulp, bamboo pulp, sugarcane pulp, white mixed pulp, black mixed pulp, recycled corrugated paper pulp, recycled newspaper pulp and corrugated base paper. The fiber structure of the different molded pulp materials was observed by scanning electron microscope. The Poisson's ratio of each sample was analyzed. The result shows the Poisson's ratio of pulp material were related to fiber structure and drying method. Pulp material dried outside mould has smaller Poisson's ratio, while the pulp material dried inside mould has larger Poisson's ratio. SEM images shows that the molded pulp material has layered phenomenon. The outer layer is dense and the inner layer is loose. The research results can provide guidance for the production, design and numerical simulation analysis of molded pulp products.

Keywords: Molded pulp • Digital image correlation method • Poisson's ratio • Scanning electron microscope • Tensile test • Fiber structure

Introduction

Molded pulp product is an environmental-friendly packaging made from recycling corrugated paper, old newspapers and other plant fibers. Wang and Peng pointed out that unlike EPE, EPS and other foamed plastics, the cushioning performance of molded pulp product relies on its structure and material properties. Due to form (geometry) and aesthetic limitations, molded pulp products have been restricted to the egg tray market for many years. However, demand is now increasing due to their sustainable qualities. Being made of wood fibers, essentially cellulose, molded pulp products are in general, totally renewable and biodegradable. These qualities have enabled growing adoption within the packaging industry, with companies eager to embrace alternatives to oil-based forms of packaging due to government regulations as well as customer demands. Reviews of historical development of industrial applications of molded pulp packaging, recent manufacturing innovations in the field and an overview of industrial scenario in the UK are given respectively [1]. Zhong, Long, and Zhang studied the influence of molded pulp structural parameters on its properties by numerical simulation method. Zhang and Wang studied the dynamic cushioning performance of a molded pulp product. Comte, C. and J. Von Stebut tested the compressive properties of molded pulp materials and proposed the constitutive equation. However, the research on mechanical properties of molded pulp materials is still insufficient. With the wide application of numerical analysis technology in packaging structure optimization design, accurate determination of mechanical properties of molded pulp materials has become an important factor affecting product design accuracy. Comte and Von Stebut shows that molded pulp is a thin-walled material with low strength and little transverse deformation during uniaxial tension or compression [2]. The traditional strain measurement methods, such as mechanical method, acoustic method and electrical method, are difficult to meet the requirements. Digital Image Correlation Method (DICM) is a non-contact method for measuring displacement and deformation. The deformation information of test material is acquired by digital camera, and the image data is conducted by computer. It is especially suitable for mechanical properties measurement of thin-walled materials with low strength. Nieweglowski, Campbell and Haavisto successfully applied DICM in many fields.

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Materials

Four kinds of pulp materials were selected in the experiment. Raw pulp materials including wood pulp, bamboo pulp and sugarcane pulp, were produced by traditional papermaking process. The samples of raw pulp materials were cut from the original pulp board. Mixed pulp materials including white mixed pulp, and black mixed pulp, were dried in the drying mould under pressure and the samples were cut from molded pulp products. Recycled pulp materials including recycled corrugated pulp, recycled newspaper pulp, were dried outside the mould and the samples were also cut from molded pulp products. Corrugated base paper made from Old Corrugated Container (OCC), was used to compare with other pulp materials. Eight specimens were used for each pulp materials during the experiment. The size of the specimens refers to the standard ISO 1924-2. The parameters of the specimens are shown in Table 1. Before the test, the samples were placed in a constant temperature and humidity chamber for 24 hours [3].

Specimen type	Length/mm	Width/mm	Thickness /mm	Weight/mm	density kg/m^3
Wood pulp	100	25	1.35	1127	837.1
Bamboo pulp	100	25	1.509	981	650.1
Sugarcane pulp	100	25	0.674	520	771.1
White mixed pulp	100	25	0.72	541	751.9
Black mixed pulp	100	25	1.12	6781	699.6
Recycled corrugated pulp	100	25	2.07	960	307.1
Corrugated paper	100	25	0.35	174	482.2

Table 1. Specimen parameter.

Experiment Methods and Instruments

Test system

The test system consists of a universal testing machine GB/T 1040-92-I, a digital camera NK D5300, two light source and a computer. Using the test system, the image before deformation (reference image) and the image after deformation (target image) of specimen were obtained respectively. The deformation field information of the specimen is obtained by correlation analysis between the reference image and the target image, and the Poisson ratio of the testing material can be calculated. The measured load-deformation curves of samples can be transformed into stress strain curves.

Test Results and Analysis

Result of DICM

Figure 1 shows the overall deformation of the reference image and the target image of the white mixed pulp. The red point and the blue point are the coordinate point of the reference image and the target image respectively, and the green line is displacement of the reference point. The local enlargement at the bottom of the specimen. The local enlargement at the top of the specimen. Figure 1 shows that the deformation of molded pulp is non-uniform. The top displacement is greater than the bottom displacement. It is because the base of the equipment is fixed during the tension test, so the bottom displacement of the sample is small. By processing the deformation information shown in Figure 1 with DICM, the maximum deformation in x direction and y direction can be extracted respectively [4].

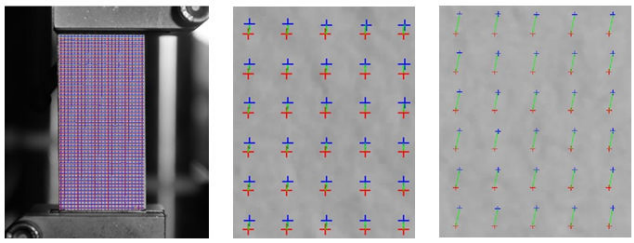

Figure 1. Deformation field diagrams of specimens.

The digital image processing results of the maximum displacement in x and y directions and Poisson ratio of the white mixed pulp are shown in Table 2. The stress-strain curves of the eight samples of white mixed pulp was shown in Figure 2. The stress-strain behavior of the specimen is nonlinear, but it is approximately linear under condition the strain less than 0.1. Therefore, image data with strain of 0.006 is selected as target image for digital image correlation processing. To ensure the accuracy of DICM, the displacement calculated by DICM is compared with the result measured by universal machine. In Table 2, $\triangle x$ and $\triangle y$ are the deformations in x and y directions obtained by DICM is the Poisson ratio, and $\triangle y$ is the deformations in y direction measured by tensile testing machine. Table 2 shows that the testing error between DICM and universal machine is less than 4%, which indicate that the DICM calculation result is credible. Tensile test can only obtain the deformation data in the tensile direction. The DICM method can obtain the deformation data in the longitudinal and transverse directions of the specimen.

Result of stress-strain

The average stress-strain curves of white mixed pulp shown in Figure 2 was obtained. Figure 3 shows that the yield strength of corrugated base paper, sugarcane pulp and white mixed pulp is higher, while the strength of recycled newspaper pulp and corrugated pulp is lower. It is due to the corrugated base paper, sugarcane pulp and white mixed pulp were dried in mould under pressure, which would make the material having smaller thickness and dense fiber structure. The recycled newspaper pulp and recycled corrugated pulp were thicker than other materials and were dried naturally outside [5].

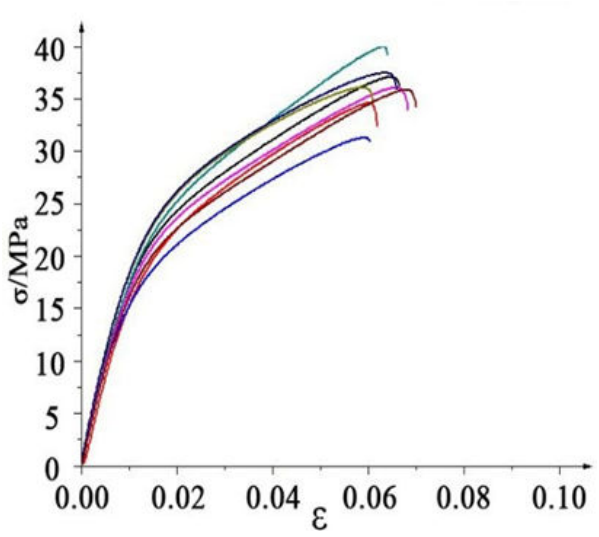

Figure 2. Stress-strain curves of white mixed pulp.

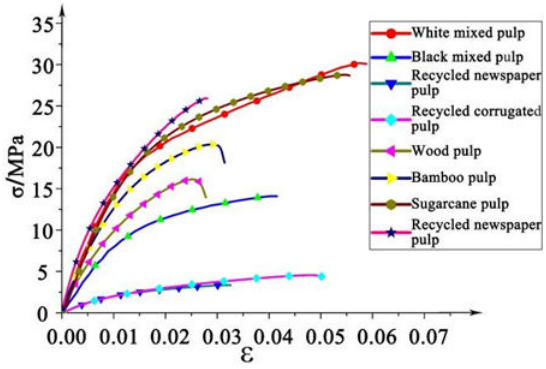

Figure 3. Stress-strain curves of various pulp.

Result of poisson ratio

Poisson ratio parameters of other seven materials can also be obtained, as shown in Table 3. Table 3 shows that the Poisson ratio of sugarcane pulp is about 0.202, which is the largest. The Poisson ratio of wood pulp, bamboo pulp, white mixed pulp, black mixed pulp, recycled corrugated pulp, recycled newspaper pulp, and corrugated base paper is 0.169, 0.017, 0.12, 0.167, 0.098, 0.044 and 0.111 respectively. The coefficient of variation of test data of sugarcane pulp, black mixed pulp, recycled corrugated pulp and recycled newspaper pulp is larger. It is due to the four materials are formed by three-dimensional forming method, and the thickness is not uniform. The sample is cut directly from the molded pulp products, which will lead to large errors. The other materials are formed by plane forming method with uniform thickness and small sampling errors.

Specimen	Wood pulp	Bamboo pulp	Sugarcane pulp	White mixed pulp	Black mixed pulp	Recycled corrugated pulp	Recycled newspaper pulp
1	0.172	0.119	0.204	0.134	0.144	0.118	0.04
2	0.17	0.107	0.199	0.121	0.189	0.099	0.058
3	0.167	0.11	0.211	0.118	0.146	0.099	0.03
4	0.172	0.108	0.212	0.108	0.181	0.105	0.039
5	0.164	0.116	0.198	0.123	0.161	0.088	0.049
6	0.169	0.099	0.203	0.108	0.14	0.09	0.041
7	0.167	0.091	0.193	0.126	0.189	0.098	0.046

Table 2. Poisson's ratio parameters of pulp molded materials.

Result of SEM

To study the relationship between fiber structure and Poisson's ratio, the fiber structural characteristics at surface and fracture of the molded pulp materials shown in Table 1 was observed by SEM. The Scanning Electron Microscope Image (SEMI) were shown in Figure 4. It is concluded that the long fibers of wood pulp material tightly interlaced in bending and flattening shape can produce greater fiber bonding strength. There are many fillers between the fibers, and has a significant stratification phenomenon at the fracture.

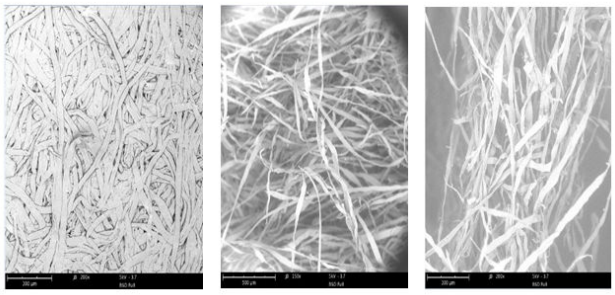

Figure 4. Scanning electron microscopic image (SEMI) of wood pulp.

Conclusion

The paper shows that the deformation error measured by DICM and the universal machine was less than 4%, which proves the accuracy of DICM in measuring the deformation of paper materials. The Poisson ratio parameters and strength of molded pulp materials are related to the thickness, fiber structure and manufacturing method. The Poisson ratios of wood pulp, bamboo pulp, sugarcane pulp, white mixed pulp, black mixed pulp, recycled corrugated pulp, recycled newspaper pulp and corrugated base paper are 0.169, 0.107, 0.202, 0.12, 0.167, 0.098, 0.044 and 0.111, respectively. In addition to wood pulp and corrugated base paper, there are different degrees of delamination at tensile fracture of other pulp materials. With the increase of thickness, the delamination phenomenon becomes more obvious. The outer material is compact and the inner material is loose. In general, recycled materials have smaller Poisson ratio. The tighter fiber structure will lead to larger Poisson ratio, the looser fiber structure will lead to small Poisson ratio.

Production process is the key factor affecting the performance of molded pulp. Materials made by traditional drying method under pressure such as white mixed pulp and black mixed pulp has higher strength and Poisson ratio. The pulp material produced by external drying method such as recycled corrugated pulp, recycled newspaper pulp has smaller strength and Poisson's ratio. Therefore, it is not scientific to increase the strength of molded pulp products only by increasing the thickness of materials.

Availability of Data and Material

"Data sharing is applicable to this article.

Competing Interests

The authors declare that there are no competing interests.

Authors' Contributions

Individual contribution.

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