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Moisture dependent rheological properties measurement of porous materials during drying

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ABSTRACT
Drying is the most common food preservation method and it is practiced in both industry and household level applications. It increases the shelf life of plant-based food materials by removing water from high-moisture food. Significant changes takes place on the quality and nutrition of plant-based food materials due to the structural modification during the course of drying. Material properties including rheological properties and drying conditions are the main factors are responsible in microstructural changes of porous materials during drying; which eventually affect the dried food quality. However, limited study has been conducted to investigate the change of rheological properties of plant-based material during drying and its relationship with the change of moisture content. In this study, cylindrical shape potato samples having diameter and height of 25 mm and 12 mm respectively have been taken for the targeted observation. Convective dryer has been used to remove the moisture content from the sample. A mechanical testing machine has been used in order to compress the sample and a real time load measuring and data logging system was used to measure the developed stress for unit deformation. From this study, moisture content significantly affect rheological properties of porous plant-based food materials. At the early stage of drying, modulus of elasticity decrease from 0.3 MPa to 0.2 MPa with the decrease of moisture content from 85% to 81% wet basis. This result would help to design, and manufacturing of sustainable drying system for high-quality dried foods.

Keywords: moisture; mechanical properties; porous material; drying.

1. Introduction

Due to the absence of proper processing approximately 30% of globally produced food are wasting annually [1]. It is also reported that annually 30% to 40% of produced fruits and vegetable are wasting in developing countries [2]. Drying is one of the simplest methods that increase the shelf life of food material by removing moisture content from it, and thus it reduce the possibility of microbial spoilage of food [3].

Around 80% to 90% water are present in plant based porous material [4]. According to the spatial location of water in plant based porous material, water can be classified as free water (intercellular water) and bound water (intracellular water). Drying increases the shelf life of porous material by removing both free and bound water from the microstructure of porous material [5].

Rheological properties are generally used to understand the behavior of material under loading. For plant based porous materials these properties are used in manufacturing and operation of equipment's that are mainly used in post harvesting process [6, 7]. Young's modulus and stiffness are the most important rheological properties. Young's modulus of a material indicates the amount of stress it will develop for per unit strain of it, where stiffness represents the amount of resisting force develop in material for unit deformation of it. For porous materials, these two rheological properties give a clear picture of the behavior of these materials under loading. At the time of drying, these rheological properties affect the migration of water from porous materials [8]. Moreover, these rheological properties predict the load deformation behavior of porous materials and help to establish a relation between shrinkage and drying kinetics.

Moisture content, morphology and process method are some well-known factors which affect the rheological properties of porous materials [9]. During drying water in the porous materials (both free and bound water) migrates from it and decrease the moisture content, there will come a situation where the porous material will transfer from rubber like material to glassy state. This transition splits the behavior of material into two distinct state. In rubbery state, moisture content in the sample is generally high and porous materials are generally soft and can be treated as viscoelastic material. On the other side, sample at glassy state behaves like a solid elastic material [10].

When plant based porous materials are dried, their rheological properties such as Young's modulus, and stiffness change with moisture content. Limited study has been conducted to find out the relation of Young's modulus with change of moisture content in porous materials in drying environment. The objective of this research is to find out trends of different rheological properties with change of moisture content and also find the load-deformation behavior while compressing the samples in drying environment.

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2. Materials and Method

2.1 Sample preparation

In order to carry out the test, potato samples were bought from the local market of Rajshahi. Samples with consistent in size and free from any noticeable defects were select the samples. In order to maintain uniform initial conditions, all of the fresh potato were kept in a refrigerator at a temperature of 5±1 °C to maintain them as fresh as possible. Before the experiment, all the samples were taken from the refrigerator and kept them at room temperature for one hour.

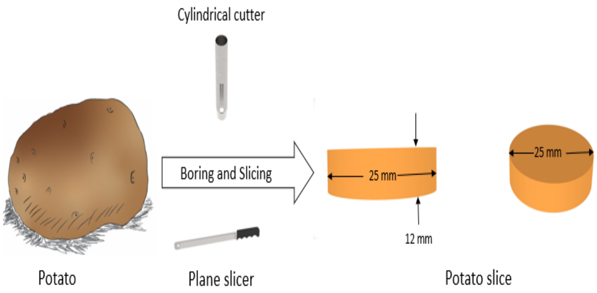

Fig.1 Preparation of sample for rheological properties measurement

A cylindrical steel tube cutter was used for preparing samples of cylindrical shape. Average diameter, height and mass were taken 24.5±0.5mm, 12±0.5mm and 5±0.5gm respectively for the preparation of the samples.

2.2 Drying

In order to change the moisture content in the sample, a hot air convective dryer was used. In order to maintaining uniform drying conditions the dryer was started about 30 min before the drying of the sample. With a temperature of 45 °C and an air velocity of 1m/s, the experiment has been conducted in the convective dryer. For measuring the air velocity of the convective dryer, a digital anemometer was used.

2.3 Moisture content determination

Wet basis technique was used to measure the moisture content of each sample at different drying condition. According to wet basis technique moisture 2.3 Moisture content determination

Wet basis technique was used to measure the moisture content of each sample at different drying condition. According to wet basis technique moisture content is defined as

Moisture content (WB) = $\{(W_{wet} - W_{dry})/W_{wet}\}\times 100$ (1)

Where, W represents weight of the sample. A digital electronic balance having accuracy of 0.01gm and range of 0-100gm was used to measure moisture content of fresh sample Moisture content of fresh potato sample was found 85%. For each drying condition, three samples were taken and their average moisture content was considered as moisture content of the sample.

2.4 Measurement of mechanical properties

In this study the variation of moisture dependent mechanical properties (e.g. Young's modulus, stiffness) of plant-based food material were investigated. Young's modulus is calculated using the following relation.

$$\text{Young's modulus, } E = \frac{\text{Stress}}{\text{Strain}} = \frac{F/A}{\Delta L/L} = \frac{\frac{F}{\pi(D/2)^2}}{\frac{l}{L}} \quad (2)$$

Where D and L is the diameter and height of the cylindrical sample. Whereas, l is the axial deformation and applied force is F.
After getting Young's modulus of the sample, stiffness can be measured using the following expression.

$$\text{Stiffness } k = \frac{AE}{L} = \frac{F}{l} \quad (3)$$

2.4 System description

An experimental setup has been fabricated to investigate the mechanical properties (Young's modulus, stiffness) of plant-based food material under different drying condition. During the compression test of plant-based porous material, it was required to ensure that the setup is capable to run in an efficient way. For this reason, environment with convective drying condition and different moisture content was maintained to perform the whole process.

The experimental setup consists of four main components namely control unit, compression unit, deformation measuring unit, and drying unit. In the experimental set-up the control unit was used to control the speed of the actuator to maintain the desire compression speed. The actuator was used to apply the pressure force on the plant-based food material to measure the mechanical property in different moisture content. A combination of three load cells has been incorporated in the setup to measure the applied load. At the time of compression, the deformation was measured with the help of deformation measuring unit where an IR sensor was used to measure the deformation of the sample. A convective dryer has been used to change the moisture content of the sample and maintaining drying condition.The calibration of the device has been done using a standardized system entitled INSTRON 2kN.

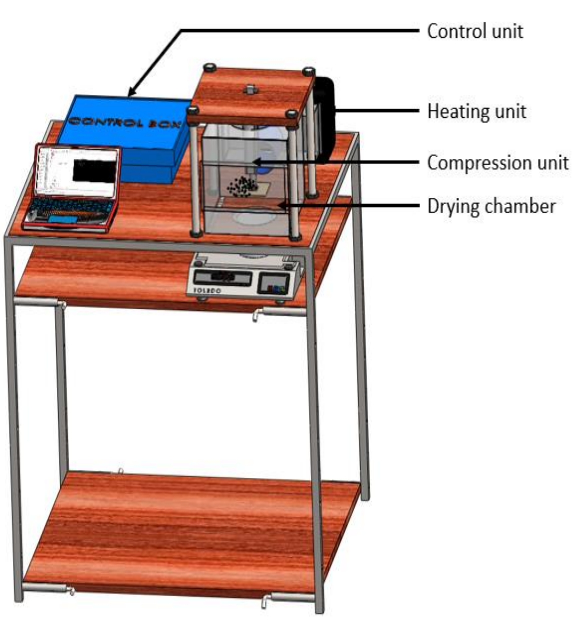

Fig.2 Experimental setup

3. Results and Discussion

3.1 Young's modulus

The variation of Young's modulus along with moisture content is shown in Fig.3. An increasing trend of Young's modulus along with increase in moisture content is found in Fig.3 .

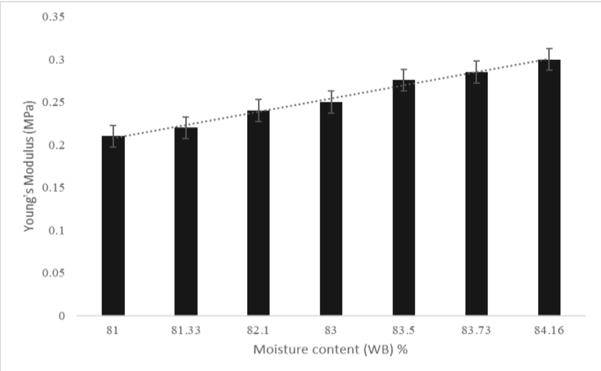

Fig.3 Trend of Young's modulus of potato along with change in moisture content.

Decrease in moisture content can cause drop of the structural strength of the food sample. Empty spaces are created when water in the food sample travels outside and these results decrease of Young's modulus of the food sample. From the literature it has been found, with decreasing moisture content from the potato, Young's modulus increases [11–13].The Young's modulus of potato is varied from 1MPa to 0.1MPa when moisture content varies from 6% to 17% [12], and here when moisture of the sample is varied from 85% to 81% i.e. for decreasing moisture content 15% to 19% from potato, Young's modulus has been changed from 0.3MPa to 0.2MPa. Samples become harder at the end of drying when the Young's modulus increases with decrease of moisture content. Whereas, at the early stage of drying, sample becomes softer due to glass transition temperature. In this stage of sample, Young's modulus decreases with decrease of moisture content. This validates the system.

3.2 Stiffness

Similar to Young's modulus Fig.4 shows a increasing trend of stiffness along with the increase in moisture content in the sample.

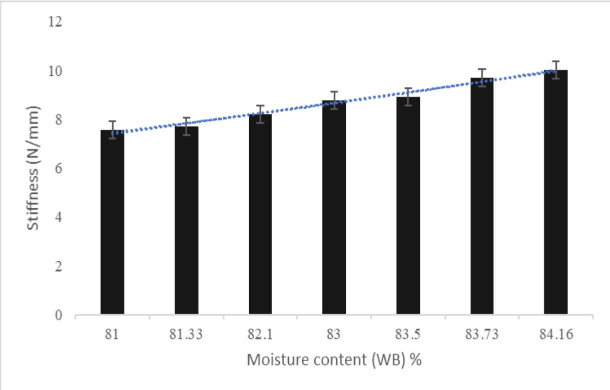

Fig.4 Trend of stiffness of potato along with change in moisture content.

Decrease in moisture content results to collapse of the structural integrity of the food sample. As stiffness of potato decreases with decreasing moisture content and increasing storage time [14, 15]. In literature, a positive relationship was found between water migration by mechanical and thermal energy of plant based porous materials and also mentioned that higher stiffness affect the rate of moisture migration from the cells of porous material [8], [16]. Because of the water present in the food material leave outside of the food sample causing empty spaces, stiffness of the specimen reduces.

3.3 Failure strength

Within the deformation zone ,the slope of the load-deformation curve is approximately linear for food materials [17]. The trend of increasing load linearly with increasing deformation within the deformation zone has been presented in Fig.5 .This linearity in load-deformation curve fails at a point which can be called failure strength.

As in the Fig.5, in order to achieve the same amount of deformation, sample 1 which have a moisture content of 84.16% requires more energy than sample 2 and 3 which have moisture content of 83.73% and 83.5% respectively. Due to compression, with increasing force deformation increases, and also when force decreases, deformation decreases [11], [18, 19].This trend can be described by Fig.5 .

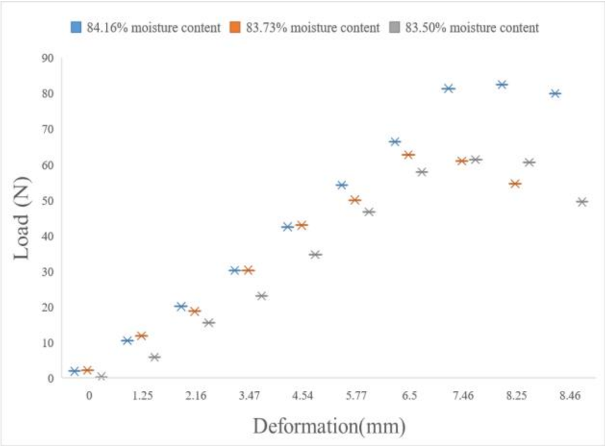

Fig.5 Compressive extension characteristics of porous materials.

4. Conclusion

Mechanical properties such as Young's modulus and stiffness of plant-based food material has been determined and their relation with moisture content has been investigated. Young's modulus for hard and soft sample has been examined. It decreases with decrease in moisture content for soft sample and it increases with decrease in moisture content for hard sample. In this study, sample has been tested at the early stage. For 84.16% moisture content, Young's modulus 0.3MPa and for 81% moisture content, Young's modulus 0.21MPa is found. So, Young's modulus has been decreased with decrease in moisture content at the early stage of drying when sample is soft. It has been found from this study that stiffness of the potato specimen increases with increase in moisture content. Same reason as Young's modulus is applicable for stiffness of the potato specimen. Successful application of this study can save both a substantial amount of energy and time in food drying system along with producing better quality dried food.

5. References

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NOMENCLATURE

E : Young's modulus, Pa
F : Force, N
A : Area, m^2
k : stiffness, N/m
D : Diameter, m
L : Length of the cylindrical sample, m
l : axial deformation, m