An evaluation of the mechanical performance of extruded wheat starch loose fill

M. Lamb[1], V. Rouillard[2] and J. Milverton[3]

[1,2,3] *College of Engineering and Science, Victoria University, Melbourne, Australia*
PO Box 14428, MCMC 8001 Melbourne, Australia

[1]*Corresponding author. Email*: *matthew.lamb@vu.edu.au , Phone: (613) 9919 5591*

[2]*Co-author. Email: vincent.rouillard@vu.edu.au , Phone: (613) 9919 4602*

[3]*Co-author. Email: justin.milverton@live.vu.edu.au , Phone: (618) 7383 3389*

Abstract

During the distribution process, products are continuously exposed to dynamic forces resulting from vehicle vibrations as well as drops and shocks from various types of handling. In order to reduce the adverse effects of such loads, protective packaging or cushioning materials are used. Engineered packaging materials are generally petroleum based (plastics) and present significant environmental concerns after their disposal. The use of environmentally friendly, bio-compostable, alternatives is a logical development; however, if the salient protective characteristics of these materials is not well established their use may lead to greater losses and a larger environmental impact through product loss. This paper introduces a comprehensive approach for the mechanical characterisation of alternative cushioning materials, which includes the effects of environmental conditions. The procedure is used to compare the performance of loose fill starch beads with a commonly used engineering cushioning material, namely medium density, closed cell polyethylene. The results show that the starch beads can offer a viable alternative to the engineered cushioning materials as they provide reasonable overall cushioning character, albeit over a narrower stress range when compared with the polyethylene cushions. The loose fill was also shown to perform in terms of vibration damping and resistance to sustained dynamic loads for low static stress levels.

Keywords: Starch, natural frequency, damping, packaging, cushioning

Acknowledgments

The authors would like to acknowledge Dr Marlene Cran of Victoria University for her assistance with the Fourier transform infrared spectroscopy analysis and scanning electron microscopy images.

Introduction

Packaging is ubiquitous in modern societies, especially in developed economies. Without packaging, the ability to move products from the point of manufacture to the point of use can be, in most cases, impossible. During the distribution process, products are continuously exposed to dynamic forces resulting from vehicle vibrations as well as drops and shocks from various types of handling. In order to reduce the adverse effects of such loads on products during distribution and handling, protective packaging or cushioning materials are used. An example of the importance of protective packaging is food security and wastage during distribution. In developing countries which do not have access to adequate protective packaging materials, and where the road infrastructure is poor, a staggering 50% of food can be lost during transport between farms and markets [1]. Developed countries use synthetic protective packaging to mitigate the damaging effects of road transport (manifested as road-induced vibration and shocks) and these losses are able to be reduced. The majority of these synthetic cushioning materials are derived from petroleum based sources (plastics) due to their low cost, ease of manufacture and well-defined mechanical properties. However, there are many public concerns related to the use of these materials stemming from the overuse of plastics and difficulties associated with their disposal. The total amount of plastic produced to date is in excess of eight billion tons, of this total only nine percent has been recycled and 12 percent incinerated. The remaining 79 percent has ended up in landfills or the environment [2, 3]. The result of this is that by 2050 there will be more plastic than fish in the sea and 99 percent of all the seabirds on the planet will have consumed at least some plastic [3]. Protective packaging makes a significant contribution to these totals and because they are generally for single use, they are typically seen as wasteful. This perception has led to the development of government mandates and covenants which focus reducing packaging's environmental impact. In Europe, directive 94/62/EC on Packaging and Packaging Waste was introduced in December 1994 with the objective of reducing the volume and weight of packaging so that it is "limited to the minimum adequate amount to maintain the necessary level of safety, hygiene and acceptance of the packed product for the consumer" [4]. In 1999 the Australian National Packaging Covenant (NPC), a voluntary, co-regulatory agreement between the government and the packaging industry, was introduced to provide packaging companies with practical guidelines to evaluate the impact of new and existing packaging [5]. This attention coupled with public demand has lead to the development of a number of environmental alternatives which range greatly in terms of development method, environmental impact and mechanical performance. Some examples make use of moulded paperboard pulp [6, 7] and some even include fungal based alternatives [8, 9]; however, the majority are starch-based blends [10-15] or composites which use starch as the binding material [16]. The development of these alternatives is a positive for the future health of the planet; however, if the salient protective characteristics of these materials is not well established they may be misused, leading to greater losses and a larger environmental impact through product loss. This topic is discussed by Wikstrom et al. [17] who use life cycle assessment examples to demonstrate that, protective packaging with a higher direct climate impact can be beneficial if product loss (particularly if the product is food) can be reduced. An example is given in their article that suggests that the climate impact of bread packaging could be double if it resulted in a 5% reduction in bread waste [18]. Despite this, the large majority of newly developed eco-friendly materials have not been tested in terms of their mechanical protection attributes, specifically their cushioning and vibrational performance. Goodwin et al. [9] go further to suggest that, while current methods for measuring dynamic shock cushioning are adequate, established methods for measuring vibrational performance are not always suitable for obtaining the required data for cushion design.

It is of particular importance that the protective packaging performance of commercially available products be evaluated and some examples of this do exist. Arif et al. [19], for example, undertook a preliminary study of Green Cell® foam, a biodegradable foam manufactured from a corn starch blend. They measured a number of characteristics of the material including its cushioning performance over a range of relative humidity conditions and were able to provide some instructions for the materials use in packaging applications. They were also able to demonstrate that the foam is sensitive to variations in relative humidity. Given the potential for variations in environmental conditions in the distribution cycle and the water solubility of most starch based cushions, this is an important consideration and should be included in any evaluation testing of the materials.

There are also a small number of investigations into the performance of the various loose fill environmental packaging alternatives. Tatarka and Cunningham [20] published the results for a study of six starch based loose fill foams and compared their performance against two synthetic (expanded polystyrene) alternatives. They evaluated the materials for moisture content, cell structure, foam and bulk density, compressive strength, resilience and friability. A similar study was undertaken by Wang et al. [21] comparing two starch based loose fill foams with a commercial plastic loose fill foam. In neither study were the cushioning performance and vibration resistance properties of the materials directly measured. Singh et al. [22] performed a study on the direct cushioning performance of a range of loose fill options including recycled expanded polystyrene (EPS), two starch based variations, slit and rolled corrugated paperboard, moulded paper pulp, wood shavings and popped corn. The authors were able to determine that the EPS, moulded paper pulp and starch loose fill options provided the best alternatives in terms of weight and volume utilisation. However, the test did not investigate the influence of environmental conditions on the performance of the samples.

This paper focuses on the evaluation of the cushioning and vibration performance of a bio-compostable, wheat starch based loose-fill cushioning material and how such characteristics are affected by environmental conditions. The results of this study will contribute to the design procedure of protective packaging and provide a valuable reference for the correct use of bio-compostable, wheat starch based loose-fill as an alternative to petroleum based protective packaging materials. Results are presented in the form of compression and cushion curves, vibration response characteristic (namely natural frequency and damping) as well as loss of stiffness resulting from prolonged exposure to dynamic (vibration related) loads. Results from tests performed on a common petroleum based protective cushioning material, Ethafoam200^{TM}, will also be presented for comparison purposes.

The Materials

The extruded wheat starch beads are biodegradable, water- soluble and are not known to present any hazards in their diluted form. The beads are manufactured using a system that mixes and extrudes the wheat starch into small log forms. Using gravimetric and thermo-gravimetric analysis (TGA), the beads were found to have an average moisture content of 7.57% ±0.17%, with the remaining composition consisting of approximately 79.5% starch and 12.9% inorganic filler (Silica, Si). The effect of these inorganic fillers may present opportunities for further research in chemical and environmental fields. The Fourier transform infrared spectroscopy (FTIR) spectrum of sample starch bead is shown in Fig. 1 and the associated structural assignments are presented in Table 1.

Insert: Fig. 1 Fourier transform infrared spectroscopy (FTIR) spectrum of sample starch bead

Insert: Table 1 Structural assignments of major FTIR peaks

Ethafoam220 is a medium-density (35.2 kg/m3), closed-cell polyethylene foam designed to provide strength and durability for packaging applications. It is specifically designed as a cushioning material for applications requiring shock-absorption and vibration-damping [23].

Scanning Electron Microscope (SEM) images revealing the significant difference between the microstructure of the starch beads and close-cell structure of the Ethafoam220 are shown in Fig. 2. Fig. 3 presents further SEM images of a typical starch bead showing increasing levels of detail.

Insert: Fig. 2 Microstructure of Ethafoam220 (left) [24] versus extruded starch bead (right)

Insert: Fig. 3 Scanning electron microscopy (SEM) images of starch beads at magnifications: (a) 100x, (b) 1100x, (c) 5000x and (d) 10,000x.

Experimental Design

As products can be shipped around the globe, it is important that the protective packaging retains its ability to protect the product when exposed variations in climatic conditions. To simulate such atmospheric hazards, the samples were pre-conditioned in a programmable environmental chamber prior to testing. The dynamic performance of the loose fill starch was evaluated for three climatic conditions. The conditions were selected to allow for a comparative evaluation for climates ranging from extreme humidity to extreme dry conditions that are relevant to Australian exports into the Asian markets for one. The International Safe Transit Association [25] provides a set of standard test schedules for pre-conditioning prior to testing. These standard schedules were used for the experiments performed in this study. The standard conditions used are outlined in Table 2.

Insert: Table 2 Conditioning table

After conditioning, the beads were subject to a series of compression, shock and vibration tests in order to estimate the performance of the beads for each set of conditions. The Ethafoam220 samples were subjected to the same testing regime but were not pre-conditioned as variations in relative humidity are not known to alter its performance. Each of these tests were performed under ambient laboratory conditions (23°C ±2°C and 45 % ±

5% relative humidity)

The loose fill starch beads required a containment system for each of the tests performed. This was achieved using a small, engineered polyvinyl chloride (PVC) pipe section with an internal diameter of approximately 147 mm. As can be seen in Fig. 4, the PVC section had a number of equally spaced holes drilled in its walls in order to eliminate pneumatic compression and suction. The beads were stacked two rows high (approximately 40 mm total thickness) with care applied to the placement of the beads to aid in the repeatability of the experiments. Nevertheless, the ability to consistently pack the containers at a constant density was restricted by variations in bead dimensions and human judgment; therefore, at least three repeats of each test were carried out and the mean values recorded. The Ethafoam220 samples were cut into a rectangular shape with a thickness of 40 mm to allow a direct comparison in performance with the starch beads (the other dimensions were set to achieve the desired stress level but were typically 50 mm long by 50 mm wide).

Insert: Fig. 4 Starch bead containment system

Compression Tests

To investigate the compressive resistance of the starch beads when subjected to alternative environmental conditions, a series of quasi-static and dynamic compression tests were performed using a programmable Universal Testing Machine. Quasi-static compression tests were performed at a rate of compression of 0.5 mm/s. The samples were compressed to approximately 90% strain. Each of the compression tests were performed using a circular piston with a diameter of 143 mm. Compression tests were also performed on the Ethafoam220 samples (at ambient laboratory conditions) for comparison purposes.

Shock Tests

A series of shock tests were performed using a solid cylinder (143 mm diameter) of known mass attached to a guided platen which was dropped from a set height of approximately 300 mm. During impact between the cylinder and the beads the acceleration of the platen was recorded using an accelerometer and data acquisition system. A schematic of the setup is presented in Fig. 5. The results will be presented in the form of cushion curves which are widely used for characterizing the shock absorption characteristics of cushioning materials [26].

Five equally spaced static stresses ranging from 1 kPa to 2.5 kPa were used for the starch beads to enable creation of a cushion curve. Five repeat tests were performed at each static stress to allow an average to be taken (required due to the loose fill nature of the starch beads). Cushion curves for the Ethafoam220 samples were developed for comparative purposes (published data is not available for 40 mm sample thickness). For both materials, the results from five consecutive drops were recorded for each static stress to allow the cumulative effect of the shocks to be measured.

Insert: Fig. 5 Shock testing experimental configuration

Vibration Tests

As indicated by Goodwin et al. [9], there is a deficiency in current testing methods when it comes to measuring the vibration isolation performance of protective cushioning materials. It is important to be able to accurately estimate the dynamic properties of cushions, namely their natural frequency (equivalently stiffness) and damping. It is perhaps even more important to know how these properties vary (as a result of damage to the cushion) when the cushion is subjected to the sustained dynamic loads created by vibrations during distribution. The authors have presented a number of articles on this topic [27-29] and have shown that Fourier analysis can be used to estimate the system’s frequency response function (FRF) from which the sample’s stiffness and damping can be extracted. The articles have also shown that variations in the loss of structural health of the cushion can be monitored using the system’s short-time FRF to extract continual relative estimates of cushion stiffness. The described used in these articles will also be used here.

In this study, two series of vibration tests were performed. One tests was designed to establish the dynamic properties (natural frequency and damping) of the samples for each of the environmental conditions while the other was to record the fatigue characteristics of the samples at standard laboratory conditions. For the dynamic properties test, the total exposure to the laboratory conditions (after pre-conditioning) was limited to 7 minutes (2 minutes settling time under random vibrations followed by 5 minutes data capture for FRF estimation).

Multiple samples of the starch beads were subjected to Band Limited White Noise (BLWN) random vibration (3-50 Hz) using an electrodynamic vibration shaker as shown in Fig. 6. The apparatus consists of a guided mass and piston located by a precision ground shaft and low friction pneumatic bearing. The use of the low friction pneumatic bearing is of particular importance as it allows for the accurate estimation of the damping within the sample which is not corrupted by friction between the bearing and shaft. The root-mean-squared (RMS) excitation for the dynamic properties tests was set at 1.5 m/s^2 to avoid inducing damage to the beads whilst providing sufficient deflection to allow the system's dynamic characteristics to be established. The fatigue resistance tests the excitation level was set to 2.5 m/s^2 RMS. Both tests were repeated for three different masses which were based on the cushions effective static load range as indicated by the measured cushion curves.

Insert: Fig. 6 Vibration testing experimental configuration

Compression Test Results

The average quasi-static compression curves for each conditioning profile are shown in Fig. 7a. The most prominent differences between each profile are seen throughout the central regions of the curves, particularly when comparing profiles at standard room and extreme heat dry conditions. Prolonged exposure at high temperature and low humidity has resulted in a loss of moisture content. This loss is believed to have increased the brittleness and compressive resistance of the starch beads. Inspection of the beads during testing supported this hypothesis, with the visible difference between beads conditioned at extreme heat dry and standard room conditions displayed in Fig. 8. Fig. 8 shows that extreme heat and low humidity causes the beads to dry and become brittle, resulting in cracking and distortion of the beads structure.

The enlarged section (Fig. 7b) of the compression curve results also shows that the elevated humidity of the tropical conditions has caused some softening of the samples at their surface which is reflected as initial softening (below 1 kPa) when compared to the other samples. From 1 to 3.5 kPa each climatic conditioning results in similar sample stiffness.

Insert: Fig. 7 (a) Average quasi-static compression curves of each conditioning profile for dual layered (approx. 40 mm thick) starch beads (b) enlarged section of (a).

Insert: Fig. 8 Brittle starch bead resulting from extreme heat dry conditioning (left)

The untested beads that were subjected to extreme hot and dry conditioning were allowed to 'recover' at 23°C 50% relative humidity for approximately 48 hours to investigate the materials ability to re-absorb moisture. Compression tests were performed on these beads with the results compared in Fig. 9. These results suggest that the beads can recover with their compressive resistance returning back to that at standard conditions.

Insert: Fig. 9 Recovery of pre-conditioned hot dry starch beads after re-conditioning at 23°C 50% relative humidity for 48hrs

For the purposes of comparison, the compression characteristics of the Ethafoam220 samples is shown in Fig. 10.

Insert: Fig. 10 Ethafoam220 compression curve (40 mm thick) compared with equivalent for starch beads

Shock Test Results (Cushion Curves)

The results from the shock tests performed at standard laboratory conditions are presented in Fig. 11 in the form of cushion curves. The solid filled markers are the results for the first drop on the materials and the empty markers represent the average peak acceleration for drops two to five. For the starch results, each marker represent the average result from five independent tests. Using the available equipment, tests could not be performed at the low static stresses for the starch beads, thereby not allowing for the measurement of the full cushion curve. To overcome this limitation, the overall shape of the curve was predicted using data from the available static stress levels as well as the dynamic compression curves for various compression rates in accordance to the methods presented by Sek and Kirkpatrick [30], and Sek et al. [31]. This can only be easily achieved for the first drop results. The estimation is shown in Fig. 11 as a solid grey line.

Insert: Fig. 11 Cushion curves for dual layered starch beads and 40 mm thick Ethafoam220 for a drop height of 300 mm at standard laboratory conditions

The results show that the minimum peak acceleration for the starch beads was 35% higher than Ethafoam220 for the first drop and 55% higher for the average of drops two to five. In addition, the starch beads have a far narrower useful static load range with applications being limited to static loads of below 5 kPa for the 40 mm material thickness tested. The results show that the starch beads are only really of use for packaged artifacts of low density (large surface area compared to mass). For a given thickness, approximately 7-10 times more (by volume) of starch beads is required to offer similar shock absorption characteristics as those of Ethafoam220.

The results for the starch bead shock tests over a range of climatic conditions are shown in Fig. 12. Fig. 12a shows the results for the first drop and Fig. 12b shows the average results for drops two to five.

Insert: Fig. 12 Influence of climatic conditions on starch bead cushioning performance (a) first drop (b) average results drops two to five

It is evident that the variations in climatic conditions had negligible influence on the cushioning performance of the starch beads. However, increase moisture content does result in a marginal but consistent increase in transmitted acceleration levels for the initial drop suggesting that increased moisture content resulted in a loss of cushioning performance for first drop condition. For drops two to five the opposite is true with a general (albeit small) increase in performance for the hot humid condition when compared to the other conditions.

Vibration Test Results

For the vibration tests, the samples were tested for static stresses based on the useful cushioning range as indicated by the cushion curves presented in the previous section. This includes data from the right hand side starting from static stress relating to peak accelerations of approximately 30 G upwards for starch and 20 G for Ethafoam. For the starch beads this meant a static stress range of 1.8 kPa up to 3.7 kPa and for the Ethafoam 10 kPa to 30 kPa.

The dynamic properties tests results for the Ethafoam220 are shown in Table 3 and typical FRF estimates are shown in Fig. 13. The significant drop in stiffness for the 30 kPa samples is in part a result of the nonlinear stiffness character, but is also a result of a smaller 43 mm by 43 mm cross-section sample being used to achieve the higher static stress.

Insert: Table 3 Ethafoam220 dynamic properties

Insert: Fig. 13 FRF estimates for Ethafoam220 at various static stress loadings

The dynamic properties tests results for the starch beads for each environmental condition are shown in Table 4 and typical (selected based on the sample with the closest damping and natural frequency when compared to the average results) FRF estimates are shown in Fig. 14. The results in Table 4 show that the starch samples have nonlinear stiffness and damping coefficients which both increase with an increase in static stress. The results show only minor variations with changes in the climatic condition with the beads pre-conditioned at standard laboratory conditions having the lowest average stiffness and highest average damping coefficient for the static stresses tested.

Insert: Table 4 Starch beads dynamic properties (average results from three independent tests)

Insert: Fig. 14 Typical FRF estimates for starch beads at various static stress loadings and environmental conditions

The results presented in Fig. 14 also do not show a significant change in the dynamic properties of the starch beads. The most noticeable variations are a slight drop in natural frequency for the 2.85 kPa results for the tropical conditions and an upwards shift for the hot dry results at 3.65 kPa when compared to the other results. Notably, these results agree with the findings of the compression tests.

The results from the vibration endurance (fatigue) testing are presented in Figures 15 and 16 for the Ethafoam220 and starch samples respectively. All tests were carried out in ambient laboratory conditions 23±2°C and 45±5% RH. The results for the starch samples are mean results from three individual tests. The average difference between the minimum and maximum relative natural frequency estimate for each point in time is given in the figure legend (mean range). Notably, the Ethafoam220 samples are seen to experience a more rapid variation in stiffness than the starch samples (remembering that the static load is also higher for the Ethafoam); however, this variation tends to cease after the 80 minute mark for the two lower static stresses and after approximately 30 minutes for the 30 kPa test. The 30 kPa results also plateau at 85% relative stiffness when compared to approximately 80% for the other tests. This difference may be in part due to the smaller cross-section of the samples and the corresponding lower initial stiffness. The starch samples are shown to have a strong resistance to fatigue for static loads up to 2.85 kPa with a steady and only minor loss in stiffness. At 3.65 kPa their loss of stiffness as a function of time resembles that of the Ethafoam samples. The compression curve results show that the starch beads begin to soften at 4 to 5kPa (see Fig. 7a) which in part explains the more rapid stiffness loss for the samples tested at 3.65 kPa as they will have seen in excess of 4 kPa during the vibration test.

Insert: Fig. 15 Ethafoam220 fatigue endurance testing results

Insert: Fig. 16 Starch bead fatigue endurance testing results

Conclusion

In this paper, the performance of loose fill starch beads was compared with that of Ethafoam220. The results show that the starch beads offer a viable alternative to the engineered cushioning materials as they provide reasonable overall cushioning characteristics. However, for a given thickness, a volume increase of between 7 and 10 times is required to offer the same load-bearing capacity of Ethafoam220 in terms of shock and vibration absorption. Over its useful static load range, the starch-based material met or exceeded the performance of the Ethafoam samples in terms of vibration damping and resistance to sustained dynamic loads. It was also shown that the starch beads generally maintain their mechanical characteristics over a range of environmental condition and, importantly, have the ability to recover their geometric and compression properties when subjected to (relatively short term – days) variations in temperature and relative humidity.

In addition to providing a comparison between two materials, the paper also introduced a comprehensive approach for the mechanical characterisation of alternative cushioning materials, which includes the effects of environmental conditions. Such an approach can be applied to all alternative cushioning materials to better understand their performance when compared to traditional, petrochemical based, cushions. This will help to better evaluate their true environmental value. Future work that evaluates the dynamic nature of bio-compostable cushioning materials, such as the loose fill starch beads, is recommended for a range of material thicknesses. Such an evaluation will enable the selection of optimal material thicknesses depending on static load and will allow the benefits of the compostable materials to be truly measured.

References

1. Fox T & Fimeche, C (2013). Global food: waste not, want not. *London: Institution of Mechanical Engineers*.
2. Franzen H (2017). There are 8.3 billion tonnes of plastic in the world. *DW.com.* http://www.dw.com/en/there-are-83-billion-tons-of-plastic-in-the-world/a-39765670. Accessed 21 June 2017
3. Johnston I (2017). How plastic is damaging planet Earth. *Independent*. https://www.independent.co.uk/environment/plastic-how-planet-earth-environment-oceans-wildlife-recycling-landfill-artificial-a7972226.html. Accessed 18 June 2018
4. European Parliament and the Council of the European Union (EPCEU) (1994). European Parliament and Council Directive 94/62/EC of 20 December 1994 on packaging and packaging waste. *Official Journal of the European Union.* https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:31994L0062&qid=1534378302088&from=EN. Accessed 25 July 2018
5. Australian Packaging Covenant Organisation Ltd. (APCO) (2017). Australian Packaging Covenant. https://www.packagingcovenant.org.au/documents/item/1037. Accessed 1 August 2018
6. Eagleton D & Marcondes J (1994). Cushioning properties of moulded pulp. *Packaging Technology and Science*, *7*(2), 65-72.
7. Hoffmann J (2000). Compression and cushioning characteristics of moulded pulp packaging. *Packaging Technology and Science*, *13*(5), 211-220.
8. Holt G, Mcintyre G, Flagg D, Bayer E Wanjura J & Pelletier M (2012). Fungal mycelium and cotton plant materials in the manufacture of biodegradable molded packaging material: Evaluation study of select blends of cotton byproducts. *Journal of Biobased Materials and Bioenergy*, *6*(4), 431-439.
9. Goodwin D, Ge C, Kausch T, Diaz C & Gordon (2014). Vibration Performance for Biocushion Materials. *19th IAPRI World Conference on Packaging*
10. Fang Q & Hanna M (2000). Functional properties of polylactic acid starch-based loose-fill packaging foams. *Cereal Chemistry*, *77*(6), 779-783.
11. Ganjyal G, Reddy N, Yang, Y & Hanna M (2004). Biodegradable packaging foams of starch acetate blended with corn stalk fibers. *Journal of Applied Polymer Science*, *93*(6), 2627-2633.
12. Cinelli P, Chiellini E, Lawton J & Imam S (2006). Foamed articles based on potato starch, corn fibers and poly (vinyl alcohol). *Polymer Degradation and Stability*, *91*(5), 1147-1155.
13. Pushpadass H, Babu G, Weber R & Hanna M (2008). Extrusion of starch-based loose-fill packaging foams: effects of temperature, moisture and talc on physical properties. *Packaging Technology and Science*, *21*(3), 171-183.
14. Lee S, Eskridge K, Koh W & Hanna M (2009). Evaluation of ingredient effects on extruded starch-based foams using a supersaturated split-plot design. *Industrial Crops and Products*, *29*(2-3), 427-436.
15. Abinader G, Lacoste C, Baillif M, Erre D, & Copinet A (2015). Effect of the formulation of starch-based foam cushions on the morphology and mechanical properties. *Journal of Cellular Plastics*, *51*(1), 31-44.
16. Li C, Xiao S & Lin H (2011). Development of Biodegradable Wood Fiber Foam Packaging Material. In *Advanced Materials Research* (Vol. 204, pp. 58-61). Trans Tech Publications.
17. Wikström F, Williams H, Verghese K & Clune S (2014). The influence of packaging attributes on consumer behaviour in food-packaging life cycle assessment studies-a neglected topic. *Journal of Cleaner Production*, *73*, 100-108.
18. Williams H & Wikström F (2011). Environmental impact of packaging and food losses in a life cycle perspective: a comparative analysis of five food items. *Journal of Cleaner Production*, *19*(1), 43-48.
19. Arif S, Burgess G, Narayan R, & Harte B (2007). Evaluation of a biodegradable foam for protective packaging applications. *Packaging Technology and Science: An International Journal*, *20*(6), 413-419.

20. Tatarka P & Cunningham R (1998). Properties of protective loose-fill foams. *Journal of Applied Polymer Science*, *67*(7), 1157-1176.

21. Wang W, Flores R & Huang C (1995). Physical properties of two biological cushioning materials from wheat and corn starches. *Cereal chemistry*, *72*(1), 38-41.

22. Singh S, Chonhenchob, V & Burgess, G (1994). Comparison of various loose fill cushioning materials based on protective and environmental performance. *Packaging Technology and Science*, 7(5), pp.229-241.

23. Quality Foam Packaging (QFP) (2018) Dow Ethafoam 220 Foam. https://eur-lex.europa.eu/legal-content/en/TXT/?uri=CELEX:32005L0020. Accessed 25 June 2018

24. Atlanta Home Designers (AHD) LLC (n.d.) Closed Cell Foam. http://atlantahomedesigners.com/departments/energy-saving-products/spray-foam/. Accessed 03 October 2013

25. International Safe Transit Association (ISTA) (2011), ISTA Procedure 2A 11-11: Packaged-Products 150lb (68kg) or Less, p. 6.

26. Brandenburg R & Lee J (2001), Fundamentals of Packaging Dynamics, *L.A.B. Equipment, Inc.*, Illinois

27. Lamb M, Rouillard V & Sek M (2012). Monitoring the evolution of damage in packaging systems under sustained random loads. *Packaging Technology and Science*, *25*(1), 39-51.

28. Lamb M & Rouillard V. (2012). Assessing the influence of Fourier analysis parameters on short-time modal parameter extraction. *Journal of Vibration and Acoustics*, *134*(3), 031002.

29. Lamb, M & Rouillard V. (2017). Static and Dynamic Strength of Paperboard Containers Subjected to Variations in Climatic Conditions. *Packaging Technology and Science*, *30*(3), 103-114.

30. Sek M & Kirkpatrick J (1997). Prediction of the Cushioning Properties of Corrugated Fibreboard from Static and Quasi-dynamic Compression Data, *Journal of Packaging Technology and Science*, vol. 10, pp. 87-94.

31. Sek M, Minett M, Rouillard V & Bruscella B (2000). A New Method for the Determination of Cushion Curves, *Journal of Packaging Technology and Science*, vol. 13, pp. 249-255.

Table 1. Structural assignments of major FTIR peaks

Wave number (cm^{-1})	**Peak assignment**
839	C-O-C
932*	Si-H
997	C=C
1017	C-O
1080	C-O
1150	C-O
1252*	$Si-CH_3$
1337	C-H
1368	H-C-H, C-H, O-H
1416	H-C-H, C-H, O-H
1451	O-H
1638	COOH
2851	C-H
2924	C-H
3246	O-H
3312	O-H

*Indicates the presence of inorganic pigment/filler, silica or talc.

Table 2. Conditioning table [25]

Conditions	Minimum Conditioning Time (hrs)	Temperature (°C ±2°C)	Relative Humidity (% ± 5%)
Standard	72	23	50
Hot Humid	72	38	85
Extreme Heat, Dry	72	60	15

Table 3. Ethafoam220 dynamic properties

Static Stress (kPa)	Natural Frequency (Hz)	Damping Ratio (%)	Stiffness (kN/m)	Damping Constant (N.s/m)
16.5	27.5	7.3	119	101
23	22.2	8.1	109	127
30	14.6	9.7	47	100

*note that the 30 kPa sample was a 43x43 mm cross section. Thickness remained at 40 mm

Table 4. Starch beads dynamic properties (average results from three independent tests)

Static Stress (kPa)	Climatic Condition	Natural Frequency (Hz)	Damping Ratio (%)	Stiffness (kN/m)	Damping Constant (N.s/m)
1.85	Standard	21.8	10.7	56	88
	Tropical	22.0	9.5	58	79
	Hot Dry	22.4	8.9	59	75
2.85	Standard	20.8	8.8	79	106
	Tropical	19.9	9.4	72	108
	Hot Dry	20.9	8.7	79	105
3.65	Standard	18.5	11.1	81	155
	Tropical	19.4	9.3	89	136
	Hot Dry	19.6	9.9	91	146

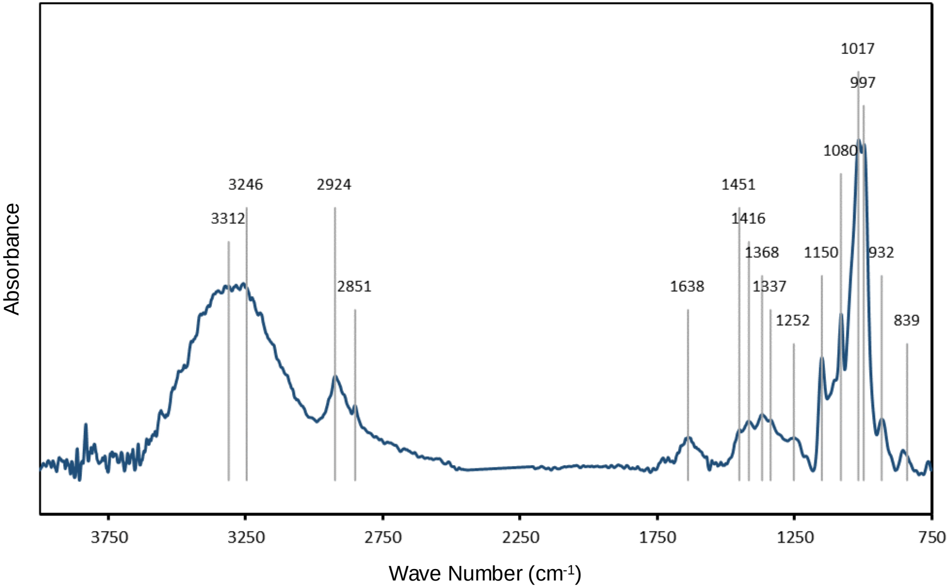


Fig. 1 Fourier transform infrared spectroscopy (FTIR) spectrum of sample starch bead

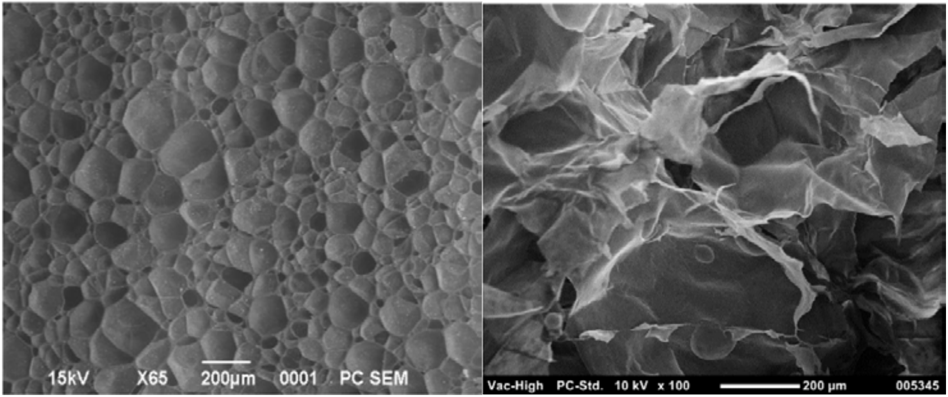


Fig. 2 Microstructure of Ethafoam220 (left) (AHD LLC n.d.) versus extruded starch bead (right)

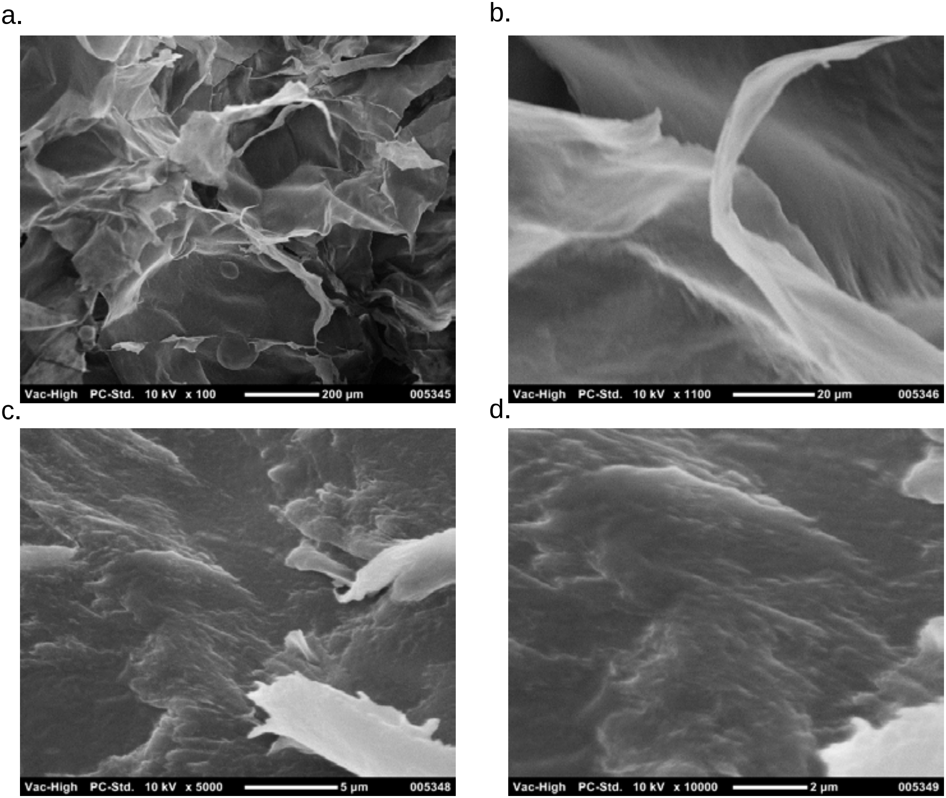


Fig. 3 Scanning electron microscopy (SEM) images of starch beads at magnifications: (a) 100x, (b) 1100x, (c) 5000x and (d) 10,000x.

Fig. 4 Starch bead containment system

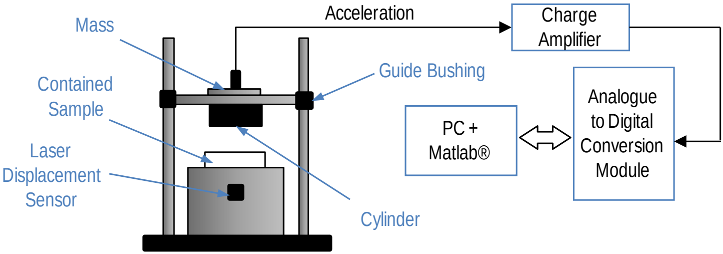


Fig. 5 Shock testing experimental configuration

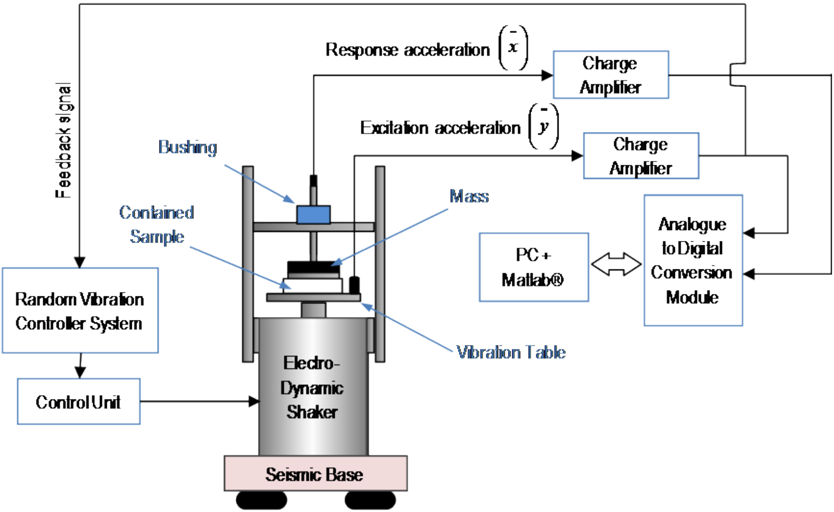


Fig. 6 Vibration testing experimental configuration

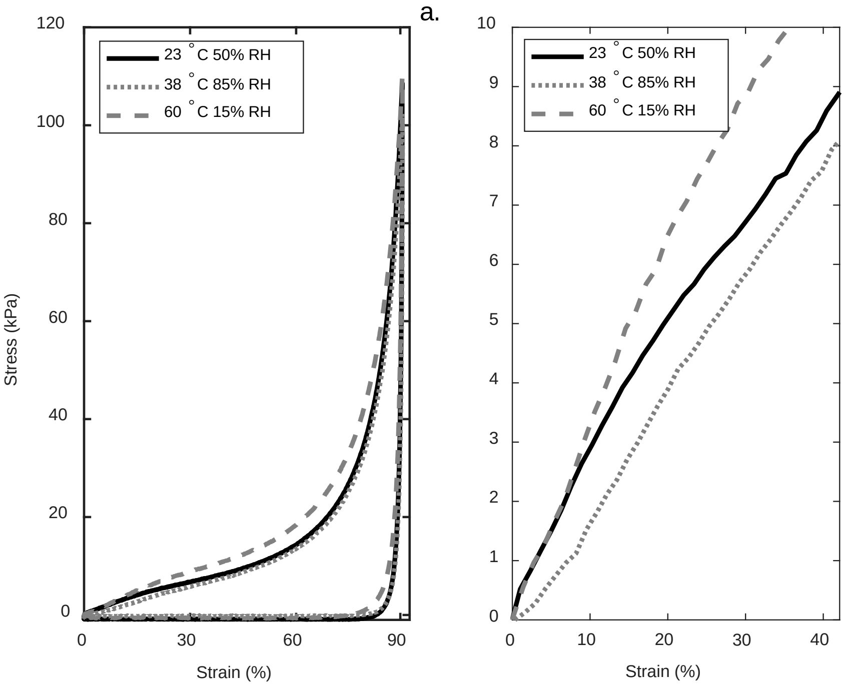


Fig. 7 (a) Average quasi-static compression curves of each conditioning profile for dual layered (approx. 40 mm thick) starch beads (b) enlarged section of (a).

Fig. 8 Brittle starch bead resulting from extreme heat dry conditioning (left)

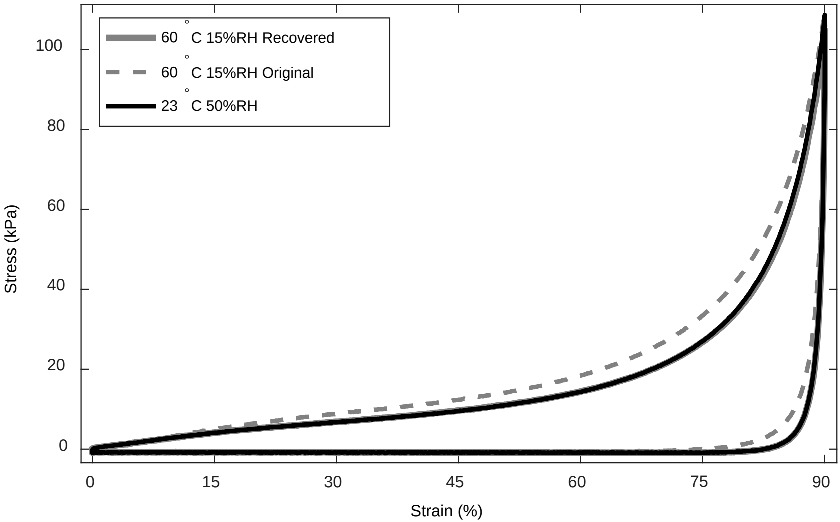


Fig. 9 Recovery of pre-conditioned hot dry starch beads after re-conditioning at 23°C 50% relative humidity for 48hrs

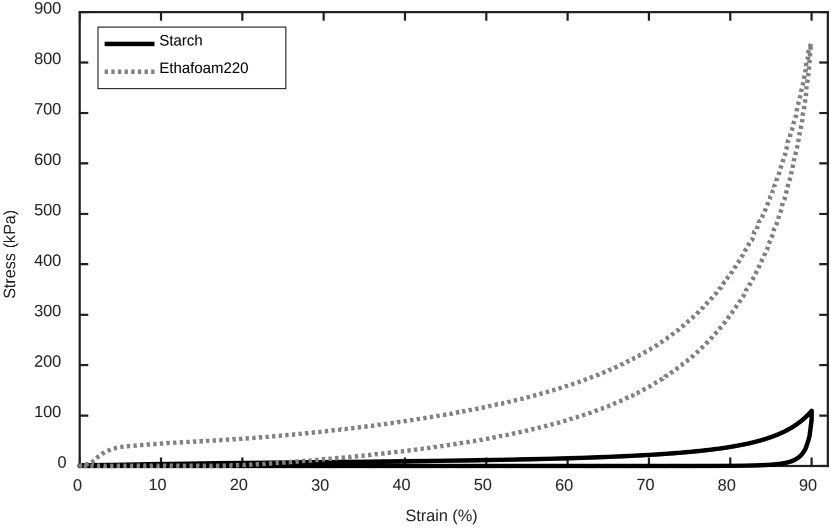


Fig. 10 Ethafoam220 compression curve (40 mm thick) compared with equivalent for starch beads

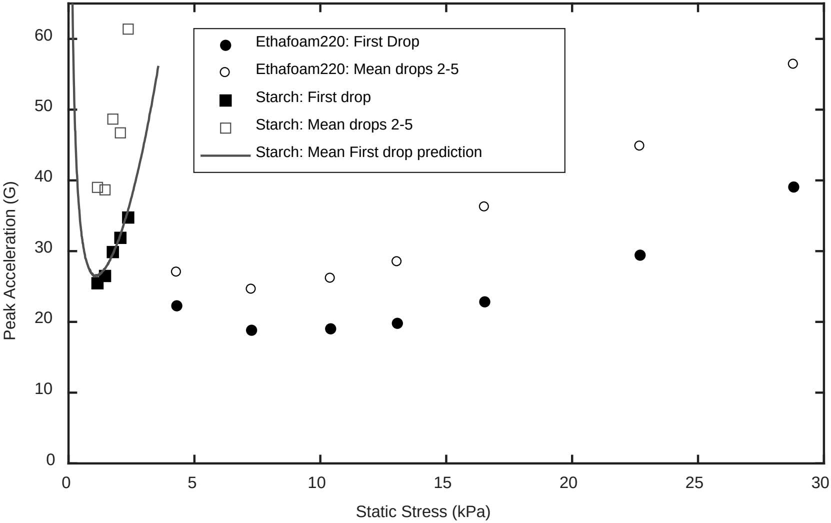


Fig. 11 Cushion curves for dual layered starch beads and 40 mm thick Ethafoam220 for a drop height of 300 mm at standard laboratory conditions

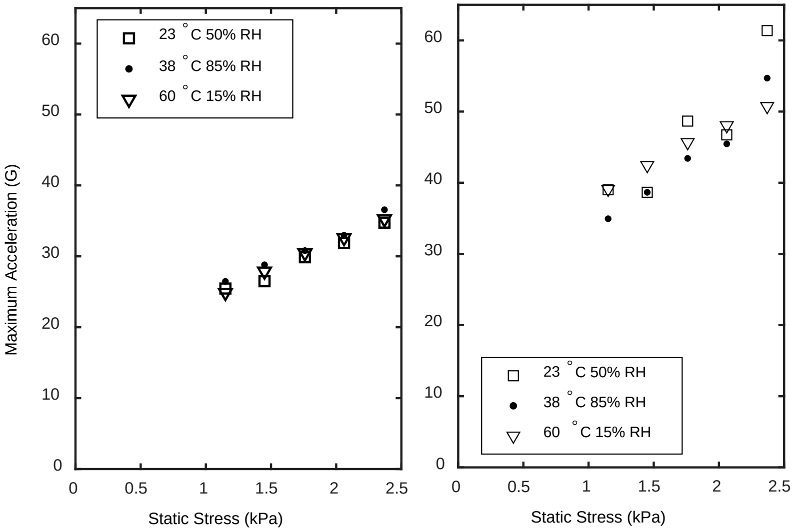


Fig. 12 Influence of climatic conditions on starch bead cushioning performance (a) first drop (b) average results drops two to five

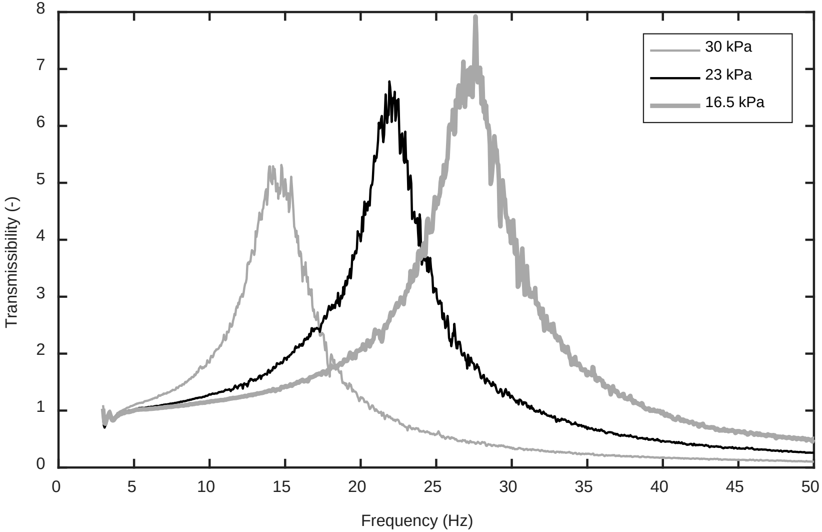


Fig. 13 FRF estimates for Ethafoam220 at various static stress loadings

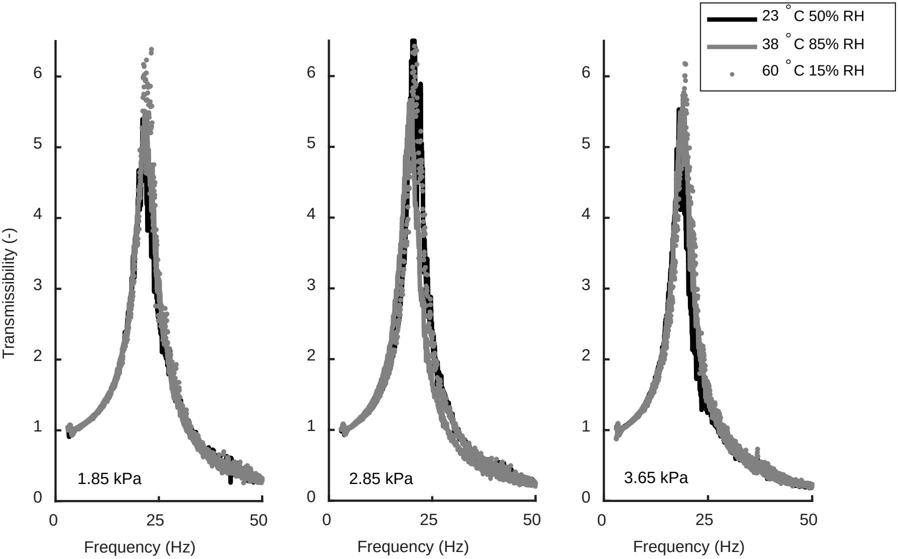


Fig. 14 Typical FRF estimates for starch beads at various static stress loadings and environmental conditions

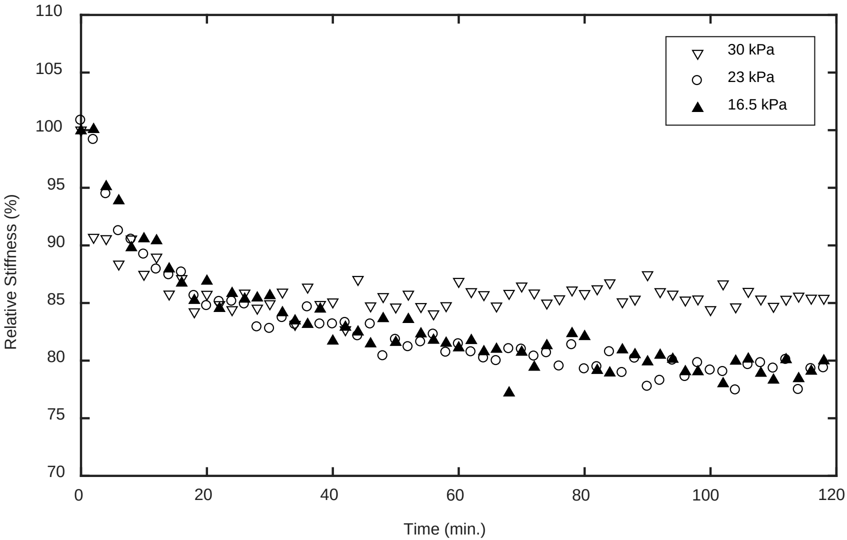


Fig. 15 Ethafoam220 fatigue endurance testing results

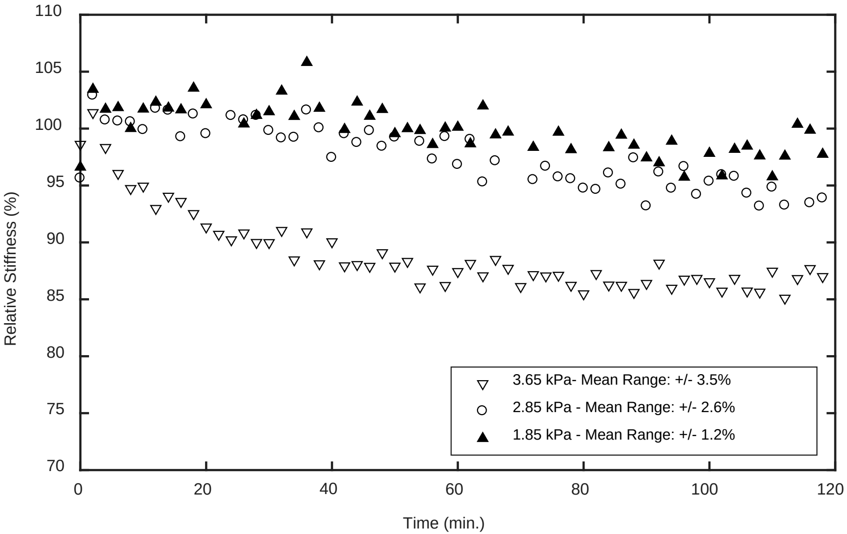
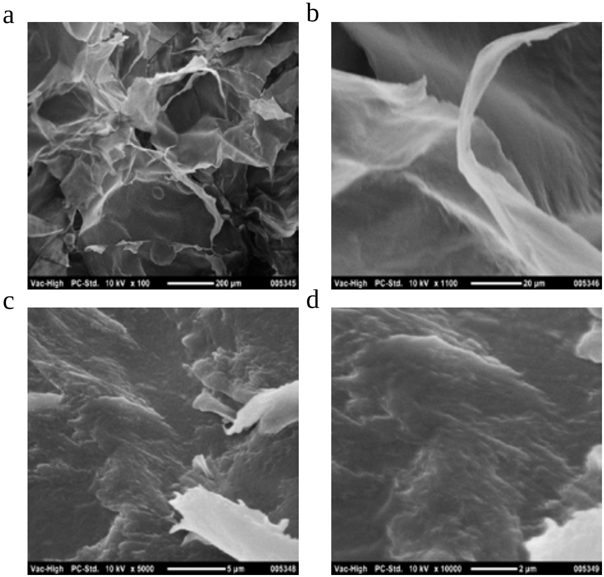


Fig. 16 Starch bead fatigue endurance testing results

An evaluation of the mechanical performance of extruded wheat starch loose fill

M. Lamb*, V. Rouillard and J. Milverton

College of Engineering and Science, Victoria University, Melbourne, Australia



This paper introduces an approach for the characterisation of alternative cushioning materials. The procedure is used to compare the performance of loose fill starch beads with a closed cell polyethylene. The results show that the starch beads can offer a viable alternative as they provide reasonable cushioning character, albeit over a narrower stress range. The loose fill was also shown to perform in terms of vibration damping and resistance to sustained loads for low static stresses.